Jackson PALEOSEISMOLOGY OF UTAH, VOLUME 3: HOLOCENE PALEOSEISMIC EVENTS ON NEPHI & LEVAN SEGMENTS UGS SPECIAL STUDY 78

Paleoseismology of Utah, Volume 3

THE NUMBER AND TIMING OF HOLOCENE PALEOSEISMIC EVENTS ON THE NEPHI AND LEVAN SEGMENTS, WASATCH FAULT ZONE, UTAH

by
Michael Jackson
Cooperative Institute for Research in the Environmental Sciences
University of Colorado

SPECIAL STUDY 78
UTAH GEOLOGICAL SURVEY
a division of
UTAH DEPARTMENT OF NATURAL RESOURCES

1991

UTAH GEOLOGICAL SURVEY
2363 Foothill Drive
Salt Lake City, Utah 84109-1491

THE UTAH GEOLOGICAL SURVEY is organized into three geologic programs with Administration, Editorial, and Computer Resources providing necessary support to the programs. The ECONOMIC GEOLOGY PROGRAM undertakes studies to identify coal, geothermal, uranium, hydrocarbon, and industrial and metallic mineral resources; to initiate detailed studies of the above resources including mining district and field studies; to develop computerized resource data bases; to answer state, federal, and industry requests for information; and to encourage the prudent development of Utah's geologic resources. The APPLIED GEOLOGY PROGRAM responds to requests from local and state governmental entities for engineering geologic investigations; and identifies, documents, and interprets Utah's geologic hazards. The GEOLOGIC MAPPING PROGRAM maps the bedrock and surficial geology of the state at a regional scale by county and at a more detailed scale by quadrangle. Information Geologists answer inquiries from the public and provide information about Utah's geology in a non-technical format.

THE UGS manages a library which is open to the public and contains many reference works on Utah geology and many unpublished documents on aspects of Utah geology by UGS staff and others. The UGS has begun several computer data bases with information on mineral and energy resources, geologic hazards, stratigraphic sections, and bibliographic references. Most files may be viewed by using the UGS Library. The UGS also manages a sample library which contains core, cuttings, and soil samples from mineral and petroleum drill holes and engineering geology investigations. Samples may be viewed at the Sample Library or requested as a loan for outside study.

The UGS publishes the results of its investigations in the form of maps, reports, and compilations of data that are accessible to the public. For information on UGS publications, contact the UGS Sales Office, 2363 Foothill Drive, Salt Lake City, Utah 84109-1491, (801) 467-7970.

Paleoseismology of Utah, Volume 3

THE NUMBER AND TIMING OF HOLOCENE PALEOSEISMIC EVENTS ON THE NEPHI AND LEVAN SEGMENTS, WASATCH FAULT ZONE, UTAH

by
Michael Jackson
Cooperative Institute for Research in the Environmental Sciences
University of Colorado

SPECIAL STUDY 78 1991
UTAH GEOLOGICAL SURVEY
a division of
UTAH DEPARTMENT OF NATURAL RESOURCES

FOREWORD

This report on the Holocene history of ground-rupturing earthquakes on the Nephi and Levan segments of the Wasatch fault zone is the third in the Utah Geological Survey's "Paleoseismology of Utah" Special Studies series. The study was jointly supported by the U.S. Geological Survey under the National Earthquake Hazard Reduction Program, and by the UGS as part of the Wasatch Front Earthquake Hazard Assessment Program, a cooperative five-year research effort to evaluate earthquake hazard and risk along Utah's heavily populated Wasatch Front. Fault-trenching studies, like the one presented here, provide information on earthquake timing and recurrence, fault displacement, and fault geometry that is used to characterize seismic-source zones and to evaluate the long-term earthquake potential of active faults.

This study is of particular interest because it makes extensive use of the relatively new thermoluminescence (TL) technique to date past ground-rupturing earthquakes. Efforts to adapt the TL technique, originally developed by archaeologists for dating pot shards, as a tool for dating paleoearthquakes are exciting because the TL method can be applied to mineral grains in commonly abundant silt and fine sand deposits. In the dry, sparsely vegetated regions of western Utah, organic material required for conventional radiocarbon dating is generally rare or absent. The availability of a reliable dating technique that can be readily applied in organic-poor arid environments represents a significant advance in our ability to interpret the earthquake history of active faults.

William R. Lund, Series Editor
Utah Geological Survey

also in the series

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

Paleoseismology of Utah, Volume 2: Paleoseismic analysis of the Wasatch fault zone at the Brigham City trench site, Brigham City, Utah and Pole Patch trench site, Pleasant View, Utah by Stephen F. Personius

TABLE OF CONTENTS

ILLUSTRATIONS

THE NUMBER AND TIMING OF HOLOCENE PALEOSEISMIC EVENTS ON THE NEPHI AND LEVAN SEGMENTS, WASATCH FAULT ZONE, UTAH

by
Michael Jackson
Cooperative Institute for Research in the Environmental Sciences
University of Colorado

ABSTRACT

The thermoluminescence (TL) and radiocarbon dating methods were used to constrain the paleoseismic history of the Nephi and Levan segments of the Wasatch fault zone (WFZ), Utah. Samples for dating were taken from the Deep Creek natural exposure and the Skinner Peaks trench, both on the Levan segment, and from the Red Canyon trench on the southern end of the Nephi segment.

At Deep Creek, a TL sample was taken from a soil buried by a large block of colluvium that spalled off the fault free face soon after rupture. The TL sample yielded an age estimate of 1000 ± 100 yrs B.P. and provides a close maximum for the event. Offset stratigraphic layers, the amount of graben formation, and fault-scarp morphology suggest this earthquake produced 1.8 m (5.9 ft) of net vertical tectonic displacement (NVTD). A trench excavated near Skinner Peaks revealed evidence for 2 earthquakes that caused a minimum of 2.8 m (9.2 ft) of NVTD. The most recent event (MRE) is placed between 1500 and 1000 yrs B.P. based on a TL age estimate of 2000 ± 300 years and a radiocarbon date of 1700 ± 200 yrs B.P., both from a burn horizon in the trench that is displaced by the MRE. The preferred time of faulting for the MRE is based on an estimate of the time required for an additional 0.5 m (1.7 ft) of sediment to accumulate on the burn horizon prior to the faulting event. An older event is inferred due to a greater thickness of depositional units on the down versus the upthrown block of the fault. Age constraints on this event are provided by a TL age estimate of 3100 ± 300 yrs B.P. and a radiocarbon date of 3900 ± 300 yrs B.P. These data and stratigraphic relations suggest that the older event occurred after 3900 yrs B.P. The dates for both events are in agreement with previous work on the segment.

The Red Canyon trench was cut across a scarp 5.5 m (18.0 ft) high near the southern terminus of the Nephi segment. Offset stratigraphy suggests three surface-rupturing earthquakes are responsible for approximately 5 m (16.4 ft) of NVTD. A maximum age for the MRE is provided by a TL age estimate of 1300 ± 500 and 1500 ± 400 yrs B.P. (most probable time of event 1200 yrs B.P.). The amount of displacement for this event is 1.4 ± 0.3 m (4.6 ± 1.0 ft). The penultimate event is constrained by maximum limiting radiocarbon ages of 3600 ± 400 and 3900 +500/-400 yrs B.P. (most probable time of event 3000-3500 yrs B.P.). The NVTD for this event is estimated at 1.5 ± 0.2 m (4.9 ± 0.66 ft). The oldest event has a maximum constraint of latest Pleistocene in age based on the morphology of the soil formed on the displaced alluvial-fan surface (most probable time of event 4000-4500 yrs B.P.). The amount of offset for this event is 1.7 ± 0.3 m (5.6 ± 1.0 ft). Data from the Red Canyon trench are in general agreement with the three events in 5000 years determined at North Creek 20 km (12.5 mi) to the north.

INTRODUCTION

The Wasatch fault zone (WFZ) delimits the boundary between the Basin and Range physiographic province to the west, and the Colorado Plateau and middle Rocky Mountain provinces to the east. The fault zone is approximately 320 km (200 mi) in length along strike starting near Malad City, Idaho in the north and terminating near Fayette, Utah in the south (figure 1). Over eighty percent of the population of Utah reside near the fault trace in a large zone of urban growth stretching from Ogden south to Payson. This zone, which comprises the central two-thirds of the WFZ, shows the highest slip rates, shortest recurrence intervals, and the most recent fault activity compared to the northern and southern segments (Machette and others, 1987).

Trench excavations and paleoseismic studies (Swan and others, 1980; Schwartz and Coppersmith, 1984, 1986; Machette, 1984; Machette, 1987; Machette and Lund, 1987; Nelson and others, 1987; Lund and Schwartz, 1987; Personius and Gill, 1987) confirm that the WFZ is composed of numerous, discrete segments which are thought to behave independently during large, ground-rupturing earthquakes. Ground-rupturing earthquakes have occurred on all WFZ segments during the late Pleistocene and on the central five to six segments during the Holocene. The scope of this work is to provide an independent estimate of the number and timing of past earthquakes on the southern portion of the WFZ on the Nephi and the Levan fault segments.

The evaluation of seismic hazards depends on a knowledge of the rate and frequency of rupture activity on a seismogenic fault. Determining an accurate age of characteristic deposits, either offset during deformation or generated during a ground-rupture event, is crucial to such evaluations. The radiocarbon method has been widely applied to the dating of Holocene and latest Pleistocene paleoseismic events (Swan and others, 1980; Schwartz and Coppersmith, 1984; Sieh and others, 1989); however, the lack of carbonaceous material in tectonic deposits often precludes its use in dating past earthquakes. This point underscores the need to develop new, and refine existing, Quaternary dating techniques to address the timing of seismic events in the geologic record. Therefore, a further aim of this study is to assess the use of the thermoluminescence (TL) method to provide age estimates for prehistoric earthquake events on Nephi and Levan segments of the WFZ.

The TL method is still experimental, but it has been used to provide geochronologic control on a variety of sediments in numerous geologic settings. The method directly dates mineral grains and provides an estimate of the time since the minerals were last exposed to sunlight. The TL technique has been applied to date paleoseismic events on the Weber (Forman and Nelson, unpublished data, 1988) and the American Fork (Forman and others, 1989) segments.

The TL age estimates provided by Forman and others (1989) on the American Fork subsegment of the fault show a close correlation to radiocarbon dates, suggesting that the TL method can be used to independently date paleoseismic events. In this study, TL age estimates will be used in conjunction with radiocarbon dates to constrain paleoseismic events on the Nephi and Levan segments of the WFZ.

This report will begin with a brief introduction to the structure of the WFZ followed by a synopsis of previous paleoseismic investigations on the Nephi and Levan segments. A section on the dating methods used in this study will be followed by a detailed discussion of trench excavations at the Red Canyon site (Nephi segment) and the Deep Creek natural exposure and the Skinner Peaks trench site (both on the Levan segment).

WASATCH FAULT ZONE

Mapping of bedrock exposed in the Wasatch Range was compiled by Hintze (1980). Machette and others (1986) mapped Quaternary deposits along the WFZ from Fayette in the south to Honeyville near the northern terminus of Holocene faulting. Gravity surveys by Zoback (1983) and seismic reflection profiles by Smith and Bruhn (1984) outline the subsurface geometry of the Bonneville and adjacent basins. Fission track dating of apatite collected from bedrock scarps along the fault provide a late Cenozoic uplift rate of 0.4 mm/yr (0.002 in/yr) (Naeser and others, 1983). Parry and Bruhn (1987) used fluid inclusions from Oligocene quartz monzonite in the Little Cottonwood stock to infer a total Cenozoic uplift of 11 km (6.9 mi) and an average slip rate of 0.67 mm/yr (0.003 in/yr) for the last 17.6 million years. Machette and others (1987) provide a synthesis of information regarding the late Pleistocene and Holocene geologic history of the Wasatch Front. Their summary suggest that the Quaternary geologic history is recorded in alluvial, colluvial, fluvial, lacustrine, and eolian sediments deposited in response to climatic cycles of excessive moisture (glacial or pluvial intervals) or restricted moisture (interglacial or interpluvial intervals).

The recognition of offset lake deposits, associated with advance and retreat of Lake Bonneville, can assist in determining maximum and minimum ages of fault events. Machette and others (1987) provide a complete summary of the fluctuations of Lake Bonneville. The Little Valley lake cycle of Scott and others (1983) is approximately 150 thousand years old with the high stand duration between 160 to 132 thousand years (marine oxygen isotope stage 6). This lake cycle seems to be contemporaneous with the Dry Creek glacial advance (Oviatt and others, 1987). An intermediate high stand of the lake, named the Cutler Dam lake cycle, occurred between 60-75 thousand years ago (McCalpin, 1986; Keaton and others, 1987; Oviatt and others, 1987). No evidence has been found for a glacial advance corresponding to the Cutler Dam lake high stand. The Bonneville lake cycle started by an increase in lake level around 32 thousand years ago, reaching a high stand at 15 thousand years ago. This high stand resulted in the cutting of the ubiquitous Bonneville shoreline. The expansion of Lake Bonneville coincides with a glacial advance in the Wasatch Range before 22 thousand years ago (Madson and Currey, 1979; Currey and Oviatt, 1985). After the lake reached the high stand of 1552 m (5092 ft), it overtopped its natural sill near Red Rock Pass, Idaho, and rapidly downcut to the level of the Provo shoreline. By 11 thousand years ago, the lake had fallen to a level close to that of the present Great Salt Lake.

SEGMENTATION AND PALEOSEISMIC HISTORY

A summary of the neotectonic history of the WFZ is presented by Machette and others (1987,1989). The WFZ was initially divided into six discrete segments which were thought to behave independently during large ground-rupture events (Schwartz and Coppersmith, 1984). Segment boundaries were based on a combination of geomorphic, geophysical, paleoseismic, and geodetic data. Recent trench excavations, combined with U.S. Geological Survey mapping of Quaternary units, led Machette and others (1986) to further subdivide the WFZ into ten to twelve segments (figure 1). Machette and others (1986) modified the number of segments based on recency of fault movement determined from fault-scarp morphology, and the relations between late Holocene deposits and the rupture trace of the WFZ.

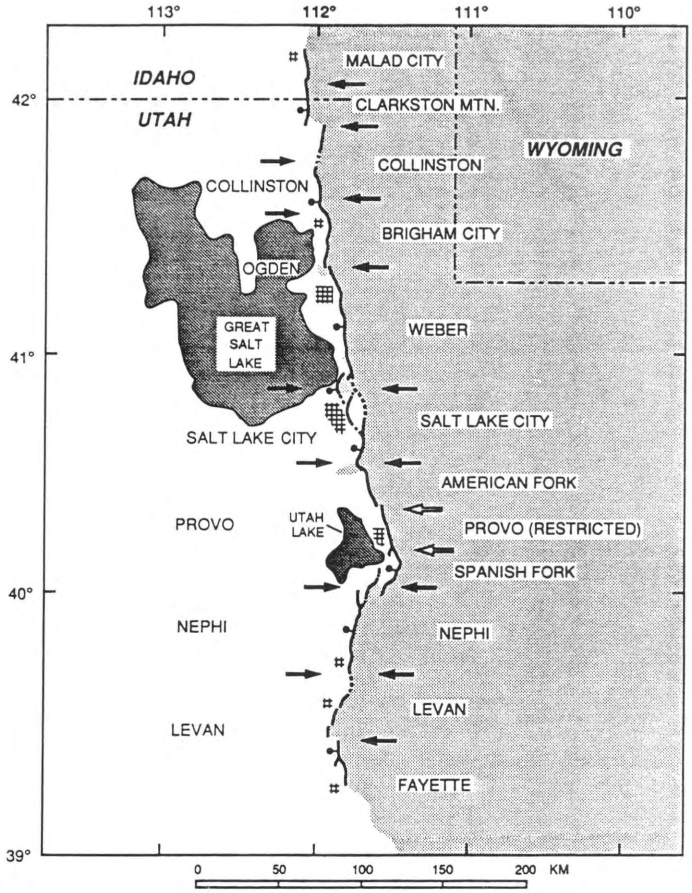


Figure 1. *Names and positions of the Wasatch fault zone (WFZ) segments as proposed by Schwartz and Coppersmith (1984; left column) and Machette and others (1987, 1989; right column). Solid arrows indicate segment boundaries; hollow arrows show two segment boundaries proposed by Machette and others (1986) which are not persistent (subsegments). Machette and others (1989) prefer a single Provo segment, like that proposed by Schwartz and Coppersmith (1984), but they do not rule out the possibility of ground rupture on the subsegments. Major towns are shown by cross hachure symbol. Modified from Machette and others (1989).*

Controversy existed in the way Machette and others (1986) subdivided the Provo segment into three shorter segments, the American Fork, restricted Provo, and Spanish Fork segments. However, a consensus was reached by Machette and others (1989), whereby the authors again group the American Fork, Provo, and Spanish Fork segments into a single Provo segment as originally proposed by Schwartz and Coppersmith (1984). Machette and others (1989) prefer a single Provo segment 70 km (43.8 mi) long, but suggest the possibility of future surface rupturing on two distinct subsegments, the Spanish Fork subsegment (which includes the restricted Provo and Spanish Fork segments of Machette and others, 1987) and the American Fork subsegment. Thus, their conclusions leave a total of 5 (Brigham City, Weber, Salt Lake City, Provo, and Nephi) or 6 (Brigham City, Weber, Salt Lake City, American Fork, Spanish Fork, and Nephi) central segments which display two to three ground-rupturing events per segment during the last six thousand years.

Machette and others (1987) also define three distal segments to the north (Malad City, Clarkston Mountain, and Collinston), which show evidence for pre-Holocene ground rupture. To the south, they identified the Levan segment, which displays evidence for a single ground-rupture event within the last 7.3 thousand years, and the Fayette segment where the latest movement is pre-Holocene.

Slip rates on the WFZ appear to be the greatest on the central segments, with slip decreasing toward the fault terminus (Schwartz and Coppersmith, 1984). In addition, slip rates vary through time on individual segments. Data presented by Machette and others (1987) suggest an increase in Holocene versus late Pleistocene slip rates along the northern and central segments of the WFZ (Machette and others, 1987). For example, at Gardner Creek on the Nephi segment, Machette (1984) calculated an average slip rate of between 0.12 and 0.20 mm/yr (0.0005-0.0008 in/yr) during the past 150-250 thousand years. At the same site a slip rate of 0.8 to 1.0 mm/yr (0.003-0.004 in/yr) is calculated for offset middle Holocene sediments, suggesting a five-fold increase in slip rate during the Holocene. Similar increases in Holocene slip rate have been found on the American Fork, Salt Lake City, and Brigham City segments and on the West Valley fault zone. Machette and others (1987) and Machette (1987) relate this increase in slip rate to rapid crustal rebound of the Bonneville basin after catastrophic draining of Lake Bonneville approximately 15 thousand years ago.

The Malad City and Clarkston Mountain segments of the fault show no latest Quaternary movement. The Collinston segment, the next segment to the south, displays no movement younger than about 15 thousand years. The Brigham City segment is the northernmost portion of the fault which displays evidence for repeated Holocene movement (Personius, 1988). Personius and Gill (1987) suggest that, near Brigham City, the WFZ displaced a middle Holocene fan surface at least three and possibly four times. Along the southern portion of the segment, there is evidence for as many as eight to ten fault events during the past 14 thousand years, but only a few discontinuous scarps are thought to be late Holocene in age. The lack of young, late Holocene fault scarps on the Brigham City segment contrasts sharply with the three late-Holocene surface-faulting events on the Weber segment to the south (Nelson and others, 1987).

On the Weber segment, the fault displaces Holocene-age deposits and forms a nearly continuous young scarp along the entire length of the segment. Scarp heights measured along the fault suggest slip rates of 1.0-1.5 mm/yr (0.004-0.006 in/yr) over the past 15 thousand years. At Gardner Canyon, near the northern portion of the segment, Nelson and others (1987) suggest that the last two events occurred prior to 2.0 and 1.1 thousand years ago based on radiocarbon dates of concentrated organics from buried soil A horizons. At the East Ogden site, Nelson and others (1987) document two middle Holocene events followed by an event in the late Holocene. At Kaysville, close to the southern boundary of this segment, Swan and others (1980) give evidence for three surface-faulting events during the last 8 ± 2 thousand years. The two youngest events occurred within the past 1580 ± 150 ^{14}C yrs B.P. Geomorphic evidence suggests that the most recent event (MRE) may be younger than 500 years, but older than settlement of the valley in 1847. Mapping of the Salt Lake City segment (Scott and Shroba, 1985: Personius and Scott, 1990) suggests that the most recent faulting occurred along the Warm Springs and East Bench faults and along that portion of the WFZ which bounds the range front from Olympus Cove south to Corner Canyon.

Trench exposures at Dresden Place, on the Salt Lake City segment, (written communication, from J. Garr to M. Machette, 1987) reveal 7 m (23 ft) of deformation in sediments deposited during the Bonneville lake cycle (about 26-15 thousand years ago). Of the 7 m (23 ft) of sediment, the lower 3 m (9.8 ft) show plastic deformation suggesting a fault event occurred prior to the recession of Lake

Bonneville about 12.5 thousand years ago. The upper 4 m (13.2 ft) of sediment display brittle deformation, which, although undated, is probably contemporaneous with the young deformation mapped by Scott and Shroba (1985). At the mouth of Little Cottonwood Canyon, also on the Salt Lake City segment, Swan and others (1980) document multiple surface-faulting events during the last 19 thousand years with at least one event in the last eight thousand years. At Dry Creek, 2 km (1.3 mi) further south, evidence was found for two surface-faulting events, with movement during the MRE constrained to a maximum of shortly after 1.8-1.1 thousand years ago and a minimum time contraint of 6.0-5.5 thousand years ago for the older event (Lund and Schwartz, 1987; Schwartz and Lund, 1988).

Keaton and others (1987) suggest that the two principal strands of the West Valley fault zone, the Granger and Taylorsville faults, show evidence for Holocene movement. They found the Granger fault has 4.5 to 12.2 m (14.8-40.0 ft) of normal slip during the past 12 thousand years, and the Taylorsville fault shows 1.5 m (4.9 ft) of monoclinal flexure with minor, laterally discontinuous faulting during the past 5 to 7 thousand years.

Paleoseismic events on the Provo segment are difficult to recognize because many of the fault scarps have been destroyed by the rise and fall of Lake Bonneville and because many of the Quaternary deposits have been disturbed by urban growth and gravel mining. Three surface-fault events are recorded as 7-8 m (23-26.2 ft) of displacement on a middle Holocene alluvial-fan surface at the American Fork Canyon trenches on the American Fork subsegment (Machette and Lund, 1987). Machette and others (1987) and Forman and others (1989) document the oldest event as occurring about 5.2 thousand years. Thermoluminescence and radiocarbon dates suggest the middle event occurred around 2.7 ± 0.3 thousand years. Charcoal and concentrated organic radiocarbon dates and TL dates from two trenches suggest that the MRE occurred at 0.5 ± 0.2 thousand years (Forman and others, 1989).

Swan and others (1980) found evidence for six to seven surface-faulting events which produced 11.5 to 13.5 m (38-44 ft) of net vertical tectonic displacement (NVTD) at Hobble Creek on the Spanish Fork subsegment. The younger three events are identified by three colluvial wedges in trenches at Dead Mans Hollow, 2 km (1.3 mi) to the west of Hobble Creek. The MRE was suggested to be about 1 thousand years by Swan and others (1980). Lund and others (1989) excavated five trenches on the Spanish Fork subsegment near the town of Mapleton. They uncovered evidence for two ground-rupture events with the MRE occurring between 800-500 yrs B.P. and the older event dated shortly after 2810 ± 95 yrs B.P. Two trenches near Water Canyon on the southern Spanish Fork subsegment suggest greater than three Holocene ground-rupture earthquake events (Ostenaa, 1990). The MRE is estimated between 0.54-0.15 thousand years, with the middle event occurring between 0.94-0.70 thousand years. The oldest event is constrained between 5.0-3.5 thousand years, with an older event postdating an alluvial fan dated at 9425 ± 105 ^{14}C yrs B.P.

At Rock Creek on the medial Provo segment, a trench excavation by Lund and others (1990) revealed 3.1 m (10.2 ft) of NVTD attributed to the MRE. Radiocarbon dates from soils faulted and buried by the MRE colluvium suggest that the event occurred just prior to 950-659 yrs B.P. The MRE at Rock Creek is in general agreement with the MRE at American Fork (north) and Mapleton (south) trench sites, suggesting that a single through-going rupture, which defines the Provo segment, occurred sometime between 1000-500 yrs B.P. (Lund and others, 1990).

The paleoseismic histories of the Nephi and Levan segments will be presented in a later section. The Fayette segment, which is the southernmost segment of the WFZ, shows evidence for early Holocene or late Pleistocene faulting (Machette and others, 1987).

THE APPLICATION OF THE THERMO-LUMINESCENCE (TL) TECHNIQUE TO DATING PAST EARTHQUAKES IN AN EXTENSIONAL TERRAIN

The TL dating technique has been used with success by Jackson (1988) and Forman and others (1989) for dating paleoseismic events on the WFZ. Since TL age estimates are crucial to establishing the fault chronology on the Nephi and Levan segments, the methods and assumptions used in generating TL age estimates are reviewed here. The dating of past earthquake events using the TL method is based on quantifying the time-dependent dosimetric properties of minerals, mainly quartz and feldspar, from characteristic tectonic deposits (McCalpin, 1986; Jackson, 1988; Forman and others, 1989). The TL signal of these minerals is reduced (bleached; figure 2) to a near-zero level (henceforth called the residual TL level) by direct sunlight exposure of the sediment after an earthquake event. Bleaching of the TL signal by sunlight provides a "zero time" datum for determining the timing of an earthquake event.

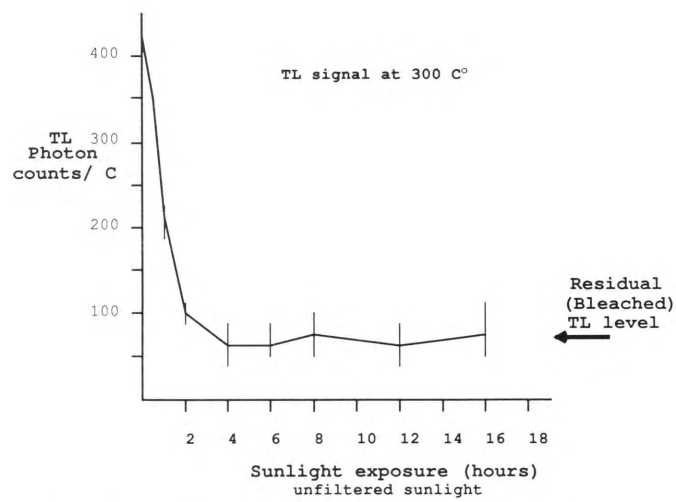


Figure 2. Plot of TL signal with increasing amounts of sunlight exposure. The residual TL level for this sample (ITL-48) was reached after 4 to 8 hours of unfiltered sunlight. Similar results were obtained for sample ITL 65 from the Skinner Peaks trench. Error bars of one sigma show the spread in TL signal over a five-sample population.

THERMOLUMINESCENCE METHOD

Thermoluminescence dating was developed in the early 1950s to date pottery (Aitken, 1974, 1985) and during the past decade has been applied to the dating of sediments in a variety of depositional settings. The TL dating of sediments was first proposed by Shelkoplyas and Morozov (1965) in Kiev, USSR. However, it was not until 1979 that Wintle and Huntley (1979) realized the effectiveness of sunlight exposure in zeroing, or resetting, the TL signal of sediments. This discovery ushered in the use of the TL method to date a broad range of terrestrial and ocean sediments (Forman and others, 1987).

McCalpin (1986) first applied the TL technique to date lacustrine sediments disturbed during earthquake events on the Hansel Valley fault, Utah. He established a chronology of three discrete fault events based on stratigraphic relations, TL age estimates, and limited amino acid and radiocarbon age control. However, he failed to address the sunlight bleaching mechanism for the lake sediment samples and did not provide adequate independent chronologic control to substantiate the TL age estimates. Forman and others (1989) used a combination of TL and radiocarbon age estimates to identify three major faulting episodes on the American Fork subsegment of the WFZ. They concluded that Holocene deposits such as loess, buried soil A horizons, and sag-pond muds, which are commonly found in normal-faulted terrain, are fully sunlight bleached prior to deposition and yield TL age estimates in agreement with radiocarbon dates. Jackson (1988, this study) used TL and radiocarbon age estimates to reconfirm three major fault events on the Nephi segment and to provide age control for the MRE on the Levan segment. Jackson (1988) also provided TL age estimates for soil A horizons buried by fault colluvium on the Spanish Fork subsegment of the WFZ.

Thermoluminescence dating of buried soil A horizons assumes that the TL signal of the buried horizon is reduced by sunlight bleaching and possibly by chemical weathering (Huntley and others 1983). Wintle and Catt (1985) address bioturbation as a mechanism for bleaching the TL signal of soil A horizons, and the effects of decalcification, gleying, and silt translocation on the stability of the TL signal. Forman and others (1988) discuss the time dependence of sunlight bleaching and effect of well-bleached eolian additions for soil A horizons formed on fluvial and colluvial sediments from Utah and Colorado.

Thermoluminescence is the light energy emitted upon heating minerals which have been subjected to ionizing radiation. The TL signal accumulates in response to ionizing radiation in the form of alpha, beta, and gamma particles from the decay of uranium, thorium (and their daughter products), and potassium-40 in the surrounding sediment. As the charged particles interact with mineral grains, they remove electrons from atoms (ionization), some of which are subsequently trapped in lattice charge defects. The density of trapped electrons depends on the number of lattice charge defects and the total radiation dose the sediment has been subjected to during the burial history. Heating or sunlight exposure of the sediment causes vibration of the crystal lattice and eviction of a majority of the trapped electrons. A population of these evicted electrons may recombine at 'luminescent centers' to release their energy as a measurable TL light signal. In the laboratory, the TL light signal is defined by the heating temperature of the sediment, light intensity given off during heating, and the wavelength of light emitted. For this study, the ultraviolet regions are isolated for analysis. This wavelength, presumably from feldspars, provides the most time-dependent TL signal (Debenham and Walton, 1983).

Thermoluminescence dating is based on the quantification of two parameters, the sample paleodose and the dose rate. When exposed to ionizing radiation, a sediment behaves like a long-term radiation dosimeter. Thus, the TL signal given off during heating is a measure of the accumulated radiation exposure of the sediment. This accumulated radiation is called the paleodose and is reported in units of grays (1 gray = 100 rads). The sample dose rate is an estimate of the environmental radioactivity of the sediment received during the burial period. In its simplest form, the TL age equation is given by:

$$\text{TL age} = \frac{\text{Paleodose (Gy)}}{\text{Doserate } \left(\frac{\text{Gy}}{\text{yr}}\right)}$$

Thus, if the sample dose rate and paleodose can be quantified, the equation can be solved for sample age.

PALEODOSE

The TL signal of a sample is a function of age; the older the sample the greater the TL intensity. The primary data set used in TL dating are plots of TL intensity with increasing temperature called glow curves (figure 3). Glow curves are produced by heating the sediment, which has been subjected to increasing amounts of artificial radiation, over a broad temperature range and simultaneously recording TL intensity. Paleodose is determined by fitting a regression to TL intensity (at an isolated temperature) versus artificial radiation dose data (figure 3). The paleodose value used in the above equation is estimated over a broad temperature range. Three methods are used to determine the sample paleodose: the total bleach (Singhvi and others 1982), the partial bleach (Wintle and Huntley, 1980), and regeneration method (Wintle and Proszynska, 1983). These methods are based on the addition of increasing amounts of radiation, from a calibrated radiation source, to the natural sediment (total bleach) or to a sediment whose TL has been bleached to a low level (partial bleach). All three methods were used to calculate paleodose values for samples from the Wasatch fault zone.

Problems which affect the determination of the paleodose include the intensity, duration, and spatial variation of sunlight bleaching and the short- and long-term stability of the TL signal. The accurate determination of a paleodose is dependent on establishing the Io level of the sediment. Sediment bleaching is controlled by the mode of sedimentation, the duration of sunlight exposure, and the sunlight intensity.

Huntley and others (1983) and Wintle and Catt (1985) hypothesize that soil A horizons are bleached by direct sunlight exposure, pedoturbation, and chemical weathering. Forman and others (1988) further suggest that the TL signal is reduced by the incorporation of well-bleached eolian material into the surface soil. Forman and others (1988) indicate that brief periods of pedogenesis (days to years) are insufficient to result in complete sunlight bleaching of a soil A horizon. They further hypothesize a 'mean residence time' of a few hundred years, which is dependent on pedoturbation and eolian influx rates, for modern soil A horizons in Utah and Colorado.

DOSE RATE

The dose rate is the radiation flux the TL sample is subjected to by the decay of uranium, thorium, their daughter products, and potassium-40 during the burial history of the sediment (reported in grays/ka). For samples in this study, U and Th content was estimated by thick-source alpha counting (Giffen and others, 1963), which measured the total number of alpha particles produced from the sample, and the total paired counts associated with the 232Th decay chain (Huntley and Wintle, 1981). The alpha-count method assumes secular equilibrium in the sample with no loss of radon; loss of radon in the sample reduces the accuracy of the alpha-count technique.

To determine if radon loss occurred in the Wasatch sediments, alpha counts were measured twice (counts > 2300), once sealed and once unsealed, to provide a path for radon escape. A ratio of unsealed to sealed sample count rates equal to 1.0 ± 0.05 suggests little or no diffusion of Rn. The loss of radon was not significant for the samples along the WFZ (see appendix 1). Potassium-40 contribution to the dose rate was measured by atomic absorption spectrophotometry.

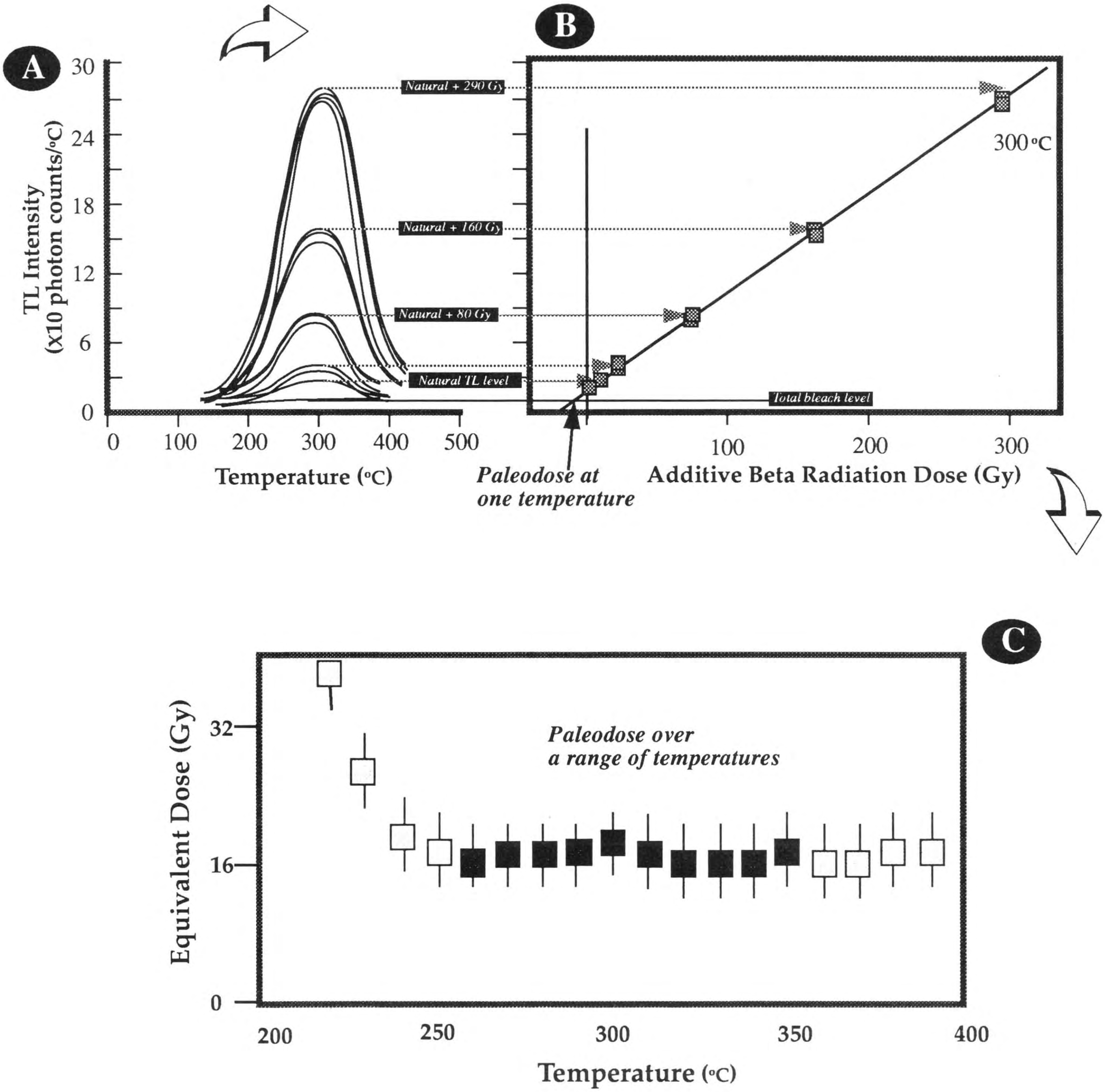


Figure 3. *Thermoluminescence glow curves (A) are produced by irradiating the natural sediment with increasing amounts of beta radiation. The sediment is then heated over a broad temperature range and the light emitted from the samples is plotted as a function of temperature. Paleodose (using the total bleach method) at a single temperature (B) is calculated by fitting beta dose versus TL intensity data (at a constant temperature) with a linear regression. Where the regression line meets the sample total bleach level is the paleodose at that temperature. The paleodose is then estimated over a broad temperature range (C) and an average value is used in the age calculation (black squares). Other methods for determining paleodose include the partial bleach (Wintle and Huntley, 1980) and regeneration methods (Wintle and Proszynska, 1983).*

One of the largest sources of error in determining the sample dose rate is the temporal variation of moisture content during the burial history. Forman and others (1989) suggest that the uncertainty in past water content and errors associated with the paleodose and dose rate analysis render the accuracy level of the TL method to ± 500 years for Holocene deposits.

The historic moisture contents of the Red Canyon and Skinner Peaks samples are estimated at 15 ± 3 and 10 ± 3 percent respectively. The Red Canyon trench site is located at the toe of an alluvial fan formed by streams heading in Red Canyon. The site is above the highest shoreline of Pleistocene Lake Bonneville, and consequently was not influenced by the fluctuating water table associated with the rise and fall of the lake. The water content for the Red Canyon samples is estimated at 15 ± 3 percent, or essentially the modern moisture content. The Levan segment was also isolated from the fluctuating effects of Lake Bonneville. However, at the Skinner Peaks trench site climatic conditions are slightly more arid and water content is estimated 10 ± 3 percent.

RADIOCARBON AND TL SAMPLING STRATEGY

Movement on a normal fault produces an unstable scarp, which degrades over time to form a colluvial wedge at the scarp base (Schwartz and Coppersmith, 1984). If movement occurs after a period of alluvial-fan stabilization, the fault-generated colluvium may bury a soil A horizon formed on the pre-fault fan surface (figure 4). During periods of fault stability, soil A horizon formation begins on the colluvium and is characterized by the addition of sunlight-bleached loess (Forman and others, 1988) and the bioturbation of unzeroed material to the surface by burrowing organisms (Huntley and others, 1983; Wintle and Catt, 1985). Renewed movement on the fault produces a second unstable scarp, which again degrades over time to form another colluvial wedge which buries the sunlight-bleached A horizon developed on the first colluvial wedge (figure 4). Therefore, Forman and others (1989) hypothesized that these buried soil A horizons represent zero time surfaces, which, due to the effects of direct sunlight bleaching, bioturbation, and the addition of well-bleached loess, have a TL signal which is reduced to a residual level (Huntley and others, 1983; Wintle and Catt, 1985). Consistency between TL and radiocarbon age estimates determined by Forman and others (1989) indicates adequate bleaching of the soils prior to burial and suggests the applicability of the TL method to dating paleoseismic events. A combination of TL and radiocarbon age estimates can be used to provide minimum and maximum constraints for paleoseismic events.

Dating of a buried A horizon provides a close maximum age estimate for the rupture which produced the overlying colluvial wedge. The sampling strategy employed to garner the maximum age control from a minimum number of TL samples is illustrated in figure 5. The TL signal actually starts to accumulate after the deposition of colluvium (burial of the soil). The time lapse between fault movement and colluvial wedge formation is dependent on factors such as fault scarp aspect, angle of scarp free face, and the type of material faulted. Evidence from the 1983 Borah Peak, Idaho rupture suggests that a colluvial wedge can form in as little as one to three years after an earthquake (Crone and Machette, 1984), but may be as great as 500 years (Wallace, 1977; Schwartz and Coppersmith, 1984).

In this study, the successful application of the TL method is based on the reduction of the TL signal in soil A horizons to a residual level prior to burial by colluvium. Therefore, it is imperative that TL samples be taken only from those horizons which assure sediment bleaching prior to burial. If the sediment bleaching hypothesis is violated by sampling the lower part of the A horizon or B or C horizons, an overestimate of sample age will result.

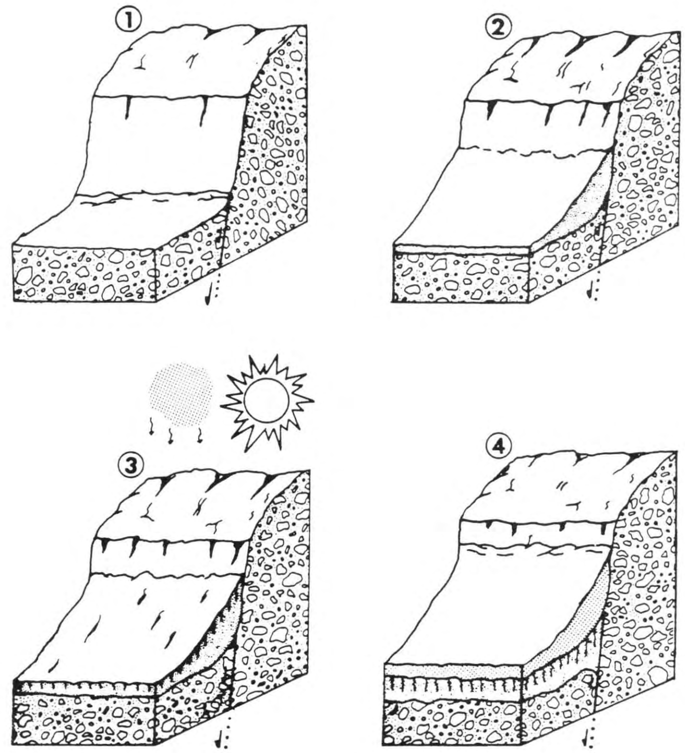


Figure 4. *Colluvial-wedge formation and bleaching mechanisms for soil A horizons. Movement on a normal fault produces an unstable scarp on the upthrown block (1). Over time the scarp degrades to form a colluvial wedge (2). Soil-forming processes are initiated on the wedge and the TL signal of the A horizon is reduced by bioturbation, well-zeroed eolian additions, and direct sunlight exposure (3). Subsequent movement on the fault produces another colluvial wedge which buries the soil. A TL age estimate from the buried A horizon provides a close maximum age for the most recent fault event (4).*

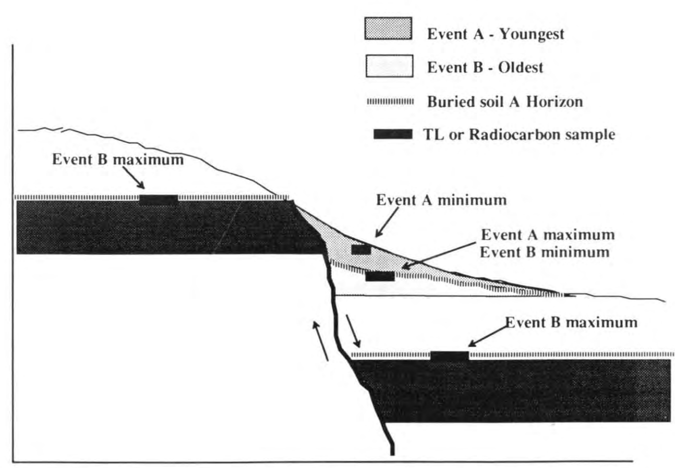


Figure 5. *Thermoluminescence and radiocarbon sampling strategy for a two-event normal fault scarp. All samples provide close, but slightly minimum and maximum age constraints on faulting.*

REPORTING THERMOLUMINESCENCE AND RADIOCARBON AGE ESTIMATES

THERMOLUMINESCENCE AGE ESTIMATES

Thermoluminescence age estimates are reported in years, which are assumed to be calendar years from the date of collection (Forman and others, 1989). Several parameters used in the calculations of TL age are still poorly understood, including the temporal variation in dose rate due to fluctuating water content of the sediment. Therefore, TL ages should be considered broad age estimates rather than absolute dates. If all three of the TL bleach methods provide the same equivalent dose estimate, then the TL age is calculated using the average of the three methods rounded to the nearest 100 years. Thus, three samples, from the same stratigraphic horizon, which date at 3000 ± 400, 3500 ± 200, and 3300 ± 300 would be reported as 3300 ± 300 years.

RADIOCARBON DATES

Bulk soil A horizon radiocarbon dates are composite ages for humic acids and other organics of differing ages accumulated over time. The interpretation of the dates is complicated because the age (and the age span) of the carbon compounds are unknown and difficult to estimate. Bulk soil-organic radiocarbon dates are reported from the laboratory with a one sigma error based solely on counting statistics which do not account for the mean residence time of organic carbon in the soil. Ignoring the mean residence time for organic carbon in the soil can lead to an overestimate of the soil age. Little is known about the mean residence of time or organic matter in the soils along the WFZ. Data by Nelson (personal communication, 1988) suggest that the upper 5-10 cm (0.02-0.39 in) of buried soils from the Weber segment of the WFZ date 100-300 years older than carbonized wood from the same horizon. Dates on modern soil A horizons from the same locations yield ages between 50 and 300 years. Based on Nelson's conclusions, Machette and others (1987) suggest between 100 to 200 years should be subtracted before calendar correcting bulk soil organic radiocarbon dates to allow for the mean residence time of carbon in the soil. One hundred years is subtracted for a relatively weak A horizon (less than 10 cm [0.39 in] thick), while a 200-year correction is used for cumulic A horizons greater than 10 cm (0.39 in) thick.

To provide continuity in the comparison of soil A horizon radiocarbon dates along the WFZ, the correction factor suggested by Nelson was applied to soil A horizons dated in this study. It must be noted that the rates of organic carbon accumulation have not been studied on the southern portions of the WFZ. Thus, the 100 to 200-year correction is an approximation of the mean residence time for organic carbon found in soils on the Weber segment.

Once the 100 to 200-year mean residence time has been subtracted from the laboratory reported age, the age is converted to calendar years using the bidecadial calibrated data set of Stuiver and Reimer (1986) and a laboratory calibration error of two. Carbonized wood radiocarbon dates are also converted to calendar years and a factor of 2 laboratory error is applied. All dates are then rounded to the nearest 100 years. All radiocarbon dates are then reported at the one sigma confidence level in calendar years before present. Finally, unless otherwise noted, all radiocarbon dates reported by other authors will be corrected as detailed above. Appendix 2 provides a detailed account of the laboratory reported age and the corrected ages for all radiocarbon dates reported in this work.

PALEOSEISMIC METHODS AND TRENCH EXCAVATION ON NEPHI AND LEVAN SEGMENTS

The methods used in excavating the trenches on the Nephi and Levan segments came primarily from experience gathered while helping investigators trench other segments of the fault. A reference for excavating trenches is provided by Hatheway and Leighton (1979) who detail the methods of site selection and trench excavation for engineering and seismic-hazard studies.

Both trenches were excavated with a Cat 125 backhoe fitted with a 1 m (3.2 ft) bucket. Excavation started on the upthrown side of the fault where the trench was dug deep enough to provide a recognizable sequence of stratigraphy (about 3 m [9.6 ft]) which could be traced to the downthrown block. Excavation continued down the scarp until the main fault zone was reached, at which point the backhoe dug as deep as possible. If graben formation was suspected, the trenching was continued far enough down fan to uncover antithetic faults. No graben formation was suspected or found at the Red Canyon or Skinner Peaks trench sites. Both trenches exceeded 5 m (16.4 ft) in depth and for safety reasons were benched approximately 1.5 to 2 m (4.9-6.6 ft) on the downthrown block. After excavation was completed, the trenches were stabilized using 1.5 m (4.9 ft) hydraulic shores. Shoring was placed on 2 m (6.6 ft) centers, unless an area was unstable, or if the shore blocked a key tectonic deposit. Once the trench was shored, the perimeter was fenced to keep cattle and people away from the trench.

The walls of the exposure were cleaned with trowels and hand hoes to expose the stratigraphy. Horizontal level lines and vertical plumb lines were strung to provide an X-Y grid system on the trench wall to be logged. Numbered flagging was placed at each meter increment along the level lines with half-meter increments marked with tape.

At Nephi and Levan, stratigraphic relations were traced from the end of the trench on the upthrown and downthrown blocks toward the fault zone. Colored flagging was used to mark key stratigraphic horizons, including buried soils, debris and mudflows, alluvial and fluvial deposits, and tectonic colluvium (colluvial wedges). Stratigraphic relations were logged on graph paper at a scale of 1 inch (2.5 cm) = 1 m (3.2 ft). During the trench logging procedure, any available charcoal material was collected for later radiocarbon dating. Once the buried soil/colluvial-wedge stratigraphy was established, the buried soil A horizons were sampled for both TL and bulk soil organic radiocarbon analysis. The TL and radiocarbon sampling strategy employed at Skinner Peaks and Red Canyon is illustrated in figure 5. McCalpin (1987) provides a summary of an effective sampling strategy for determining the timing of individual paleoseismic events in an extensional terrain.

Total NVTD across faults exposed in the trenches was determined by measuring the offset along key stratigraphic units, then subtracting any back-tilting or graben formation (Machette, 1984 and McCalpin, 1987). Determining the NVTD per event is more difficult unless multiple, pre-fault surfaces can be recognized. One method is to divide the cumulative NVTD by the number of events recognized at the site, which results in an average displacement per event. The analysis of colluvial stratigraphy adjacent to the fault scarp provides another method of determining displacement per event. The thickness of scarp-derived colluvium provides a minimum value of displacement (Swan and others, 1980). If there has been significant back-tilting or graben formation, then displacement per event is generally greater than NVTD. If no back-tilting of units is observed, then colluvial-wedge thickness is less than the

NVTD (McCalpin, 1987). A factor of 1.5 times wedge thickness is used to estimate the NVTD for the two oldest events at Red Canyon. Because the colluvial wedge produced by the MRE at Red Canyon may not be in equilibrium with the fault scarp, the wedge thickness is considered a minimum estimate of NVTD. At Skinner Peaks, a single-event fault scarp is exposed with some post-seismic settling. The colluvial-wedge thickness is also a minimum estimate of NVTD.

PALEOSEISMIC HISTORY OF THE LEVAN SEGMENT

INTRODUCTION AND PREVIOUS WORK

The Levan segment (figure 6) is approximately 43 km (26.9 mi) in length with evidence of Holocene faulting from the mouth of Hartleys Canyon (3.8 km [2.4 mi] northeast of Levan) to as far south as Botham Road (15 km [9.4 mi] south of Levan). Machette and others (1987) find evidence for late Pleistocene faulting for another 3 km (1.9 mi) south of Botham Road. The southern end of the segment is located 0.5 km (0.3 mi) east of where Utah Highway 28 crosses the Juab-Sanpete County line (figure 6).

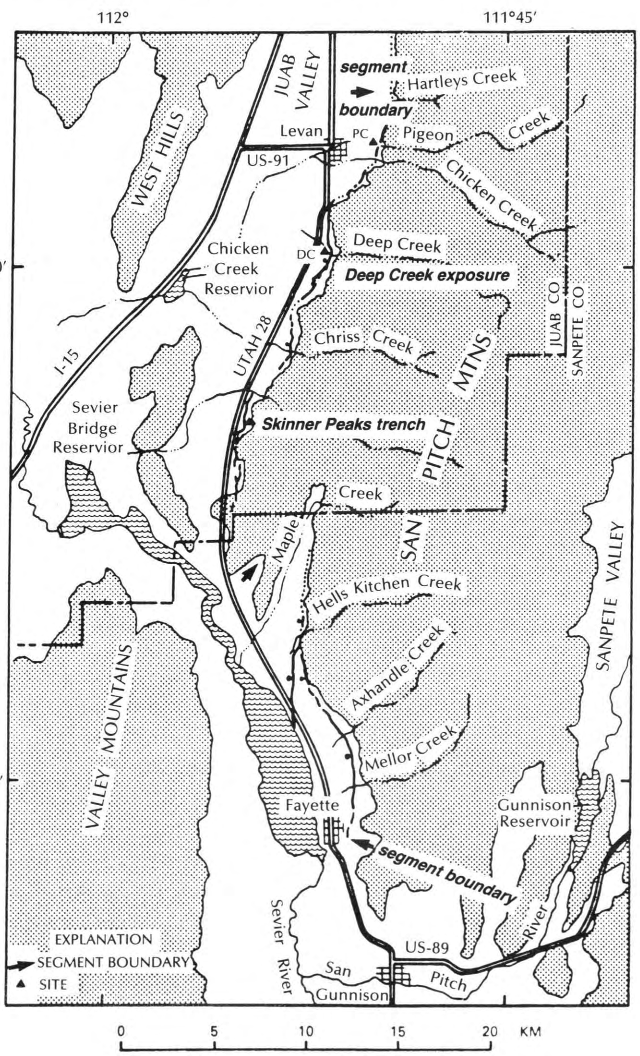


Figure 6. Map of the Levan segment of the Wasatch fault zone. The Deep Creek (DC), Pigeon Creek (PC), and Skinner Peaks trench locations are shown. Modified from Machette and others (1987).

The majority of fault scarps along the Levan segment are approximately 3 m (9.6 ft) high, suggesting only one fault event on this segment since early in the Holocene (Cluff and others, 1970; Schwartz and Coppersmith, 1984; Machette and others, 1987).

No previous trenching had taken place on the Levan segment of the WFZ. However, a stream cut near Deep Creek provided a natural exposure for the analysis of Schwartz and Coppersmith (1984) and Machette (unpublished data, 1985). The Deep Creek natural exposure is located 8 km (5 mi) south of Levan and 0.5 km (0.3 mi) east of State Highway 28 (figure 6). Deep Creek is a south-facing exposure where the WFZ offsets debris-flow and alluvial-fan deposits (figure 7, plate 1).

The Deep Creek exposure was studied by Schwartz and Coppersmith (1984) who recognized a fault scarp 2.7 m (8.9 ft) high and a single colluvial wedge indicating a single rupture event. Charcoal from within a debris flow on the upthrown block places a maximum limit on the event at 7300 ± 1000 yrs B.P. (Schwartz and Coppersmith, 1984). However, no record remains of exactly where in the stratigraphic section the charcoal was collected. Schwartz (personal communication, 1988) thought the sample came from very low (2-3 m [6.6-9.8 ft] above the base of the exposure) in the stratigraphic package and thus provided a poorly constrained maximum age estimate for the single event exposed at Deep Creek (plate 1). Work by Machette (unpublished data, 1985) documents 2.3 m (7.5 ft) of displacement across the main fault with 0.55 m (1.8 ft) of displacement on an antithetic fault (50 m [164 ft] to the west) resulting in 1.75 m (5.7 ft) of NVTD. Machette also agrees with the single-event interpretation of Schwartz and Coppersmith (1984).

At Pigeon Creek, 2 km (1.3 mi) to the north and due east of Levan, Schwartz and Coppersmith (1984) report a radiocarbon age of 1600 + 500/-300 yrs B.P. for alluvial-fan deposits faulted during a single-event earthquake. The 1600 year age provides another, and somewhat closer, maximum estimate for the MRE on the Levan segment.

DEEP CREEK NATURAL EXPOSURE

The Deep Creek natural exposure records only one earthquake event, which displaced a thick sequence of Holocene-age debris-flow deposits. To better constrain the age of this event and to possibly uncover an older event, the single-event colluvial wedge was dated at Deep Creek and a trench was excavated farther south near the Skinner Peaks.

The stratigraphic section at Deep Creek is composed of a thick sequence of debris flows combined with thin, interbedded alluvial deposits, all displaced by a single fault event (figures 7 and 8). This ground-rupturing earthquake event produced a 2.4 m (7.9 ft) west-facing scarp at the main fault, and a 0.5 m (1.6 ft) east-facing antithetic scarp roughly 50 m (164 ft) to the west (Schwartz and Coppersmith, 1984; Machette, unpublished data, 1985). The NVTD for this single event is calculated at 1.8 m (5.9 ft) (plate 1).

Movement on the main fault produced an unstable, upslope scarp. Soon after rupture (probably minutes to days), a block of material (plate 1, unit 4) spalled off the upthrown block and was deposited directly on top of the soil formed on the pre-fault fan surface (unit 3A, plate 1). The void formed between the proximal colluvium and the main fault zone was filled with additional material raveled off the fault free face (plate 1, unit 2). The coarse, proximal colluvial deposits were subsequently covered by a thin, fine-sand colluvial wedge (plate 1, unit 1).

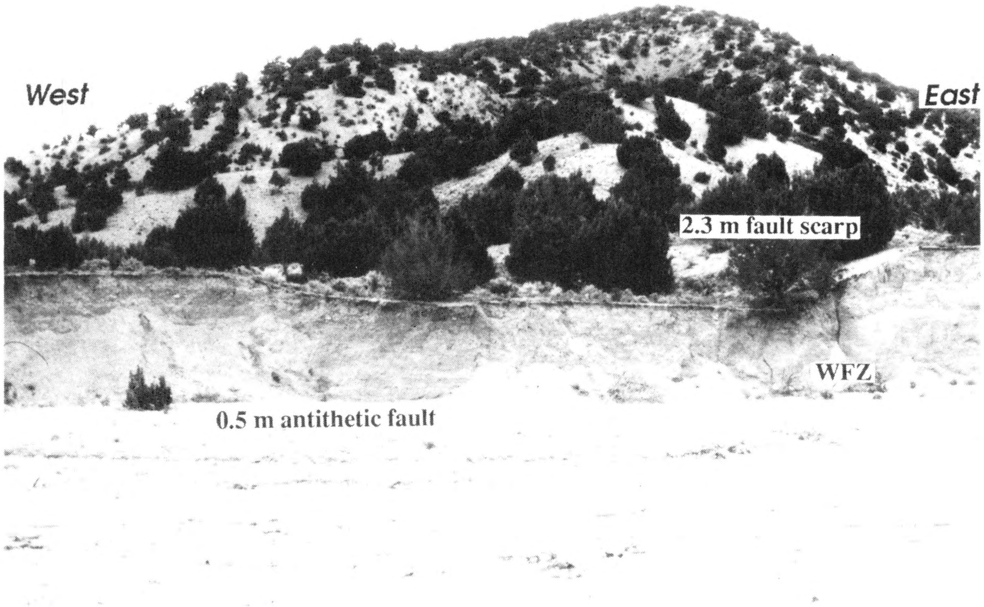


Figure 7. *Photograph of the Deep Creek natural exposure on the Levan segment of the WFZ. The WFZ is expressed as a fault scarp 2.4 m (7.9 ft) high with the main strand of the fault dipping steeply from east to west. Note the 0.5 m (1.6 ft) of graben formation west of the main fault zone.*

Sample ITL-50 was taken from the upper few centimeters of the buried soil A horizon which formed on the pre-fault fan surface. Because the block of unit 4 on the downthrown block (between meter marks 5 and 7) was deposited soon after fault rupture, sample ITL-50 provides a close maximum for the timing of the earthquake event. The TL age estimate of the buried soil is 1000 ± 100 years and is an average of four replicate age determinations (table 1). Due to the stratigraphic relations sample ITL-50 is considered a very close maximum for the single fault event at Deep Creek.

Schwartz and Coppersmith's (1984) radiocarbon date of 7300 ± 1000 yrs B.P. provides a very broad maximum for the single earthquake event as well as a broad minimum for any unexposed older events at the Deep Creek site. Recent work by Machette and others (1987) and Schwartz and Coppersmith (1984) suggests that along its length, the Levan segment shows evidence for only one surface rupture during the Holocene. Three age estimates are available which provide a maximum constraint on this event: radiocarbon ages of 7300 ± 1000 from Deep Creek and 1600 +500/-300 yrs B.P. from Pigeon Creek provide a maximum age on faulting; a TL age estimate of 1000 ± 100 years probably provides the closest maximum on faulting. Therefore, in agreement with Schwartz and Coppersmith (1984) and Machette (unpublished data, 1985), it is suggested that only one surface-rupture event occurred within the last 7300 years, but that event occurred very close to 1000±100 yrs B.P. The single event at Deep Creek was responsible for 1.8 m (5.9 ft) of NVTD as measured from the trench log (plate 1) and is in agreement with Machette's unpublished estimate of 1.75 m (5.7 ft).

SKINNER PEAKS TRENCH

The Skinner Peaks trench was excavated 1.5 km (0.9 mi) northwest of Skinner Peaks and about 200 m (660 ft) east of Utah State Highway 26 (figure 6). The trench was cut across a fault scarp 3.3 m (10.8 ft) high on Holocene-age alluvial-fan sediments. The height of the fault scarp decreases to the south (15 m [49.2 ft] along fault strike) to 1.5 m (4.9 ft) where the fault intersects an active drainage channel and is covered by alluvial-fan sediments (figure 8). The scarp reappears 35 m (115 ft) to the east where movement is recorded in a diffuse scarp 1.5 m (4.9 ft) high. The area encompassing the eastward step of the fault shows numerous scarplets 10 to 20 cm (4-8 in) in height.

Trenching at Skinner Peaks began on the upthrown block of the fault where the backhoe cut through approximately 2 m (6.6 ft) of mudflow and alluvial-fan deposits before encountering a planar bedrock contact (plate 2). The bedrock material (unit 13, plate 2), probably of the Green River Formation, is composed of a fine- to medium-grained, light green, quartz sandstone with 5-10 percent chert pebbles. The unit is cut by numerous calcium carbonate-filled fractures, which in places extend into the overlying alluvium. Both the mudflow and alluvial deposits, and the bedrock unit are truncated by the main, west-dipping fault (fault F1, plate 2). On the downthrown block, a thick sequence of mudflow and alluvial-fan deposits are exposed (plate 2). Bedrock was not encountered on the downthrown block. A large crack filled with tectonic colluvium (unit 2-2, plate 2) and a single colluvial wedge (unit 2-1, plate 2) are mapped as crosscutting and overlying the uppermost mudflow deposit (unit 3, plate 2).

The fine-grained composition of the mudflow and alluvial layers made differentiation between the units difficult. However, numerous charcoal and organic-rich burn layers, possibly representing paleo-surface horizons, were used to correlate stratigraphic units on the downthrown block (plate 2). Burn layers on the upthrown and downthrown block were sampled for radiocarbon and TL analysis (samples ITL-64 and ITL-65, respectively).

A major problem in interpreting the Skinner Peaks stratigraphy is resolving the greater thickness of depositional units on the downthrown versus the upthrown block of the fault (i.e., 2 m [6.6 ft] of stratigraphy on the upthrown block above the bedrock contact versus a minimum of 4.5 m [14.8 ft] on the downthrown block, plate 2). This suggests that either material was stripped from the upthrown block or it was never deposited at all. It is also problematic that none of the stratigraphy mapped on the upthrown block can be confidently correlated to units on the downthrown block. This excess stratigraphy on the downthrown block suggests that more than one event is recorded at the Skinner Peaks trench.

The MRE event at Skinner Peaks is recorded by a well-preserved colluvial wedge indicating a single discrete ground-rupture event (unit 2-1, plate 2). However, a single rupture event does not explain the excess thickness of stratigraphy. One possibility is that the Skinner Peaks trench only records one event in a 3 m (9.8 ft) scarp. This would require that material was stripped off the upthrown block of the fault after the MRE. A second interpretation argues for 2 fault events, but with the newly formed fault scarp being covered by a mudflow. The lack of correlative units from the upthrown to the downthrown block contradicts this interpretation. The excess stratigraphy on the downthrown block may be a result of gradual downwarping of the local stratigraphy or long-term creep on the fault. Downwarping could be caused by an eastward flexure of the stratigraphy about a hinge within the basin (i.e., west of the fault zone). However, there is no evidence that back-tilting of the stratigraphy has occurred (backtilting < 3 degrees, plate 2) and downwarping is probably not responsible for the displacement.

It is also possible that the MRE was a co-seismic rupture, but the older displacement was due to aseismic fault creep of millimeters or less to tens of millimeters. A first-order leveling line survey to detect fault creep and to monitor crustal rebound around the Great Salt Lake has been proposed by Smith and Cohen (written communication from Cohen, 1988) but has yet to be accomplished. Savage and others (1985) implemented a triangulation network across the WFZ near Ogden on the Weber segment. Their study measured a slight east to west component of extension and a westward tilt between the years 1979-1983. However, the trilateration network requires more time to separate the tectonic signal from measurement noise. Because of the small displacements involved, a vertical creep event would be virtually impossible to recognize in a stratigraphic sequence; therefore, it is suggested that vertical creep events are not responsible for the thick and continuous stratigraphy found on the downthrown block at Skinner Peaks.

The preferred interpretation is that there are two events recorded in the Skinner Peaks trench. The MRE is recorded by the deposition of the colluvial wedge, whereas the older event is inferred from the thick stratigraphic sequence on the downthrown block. A drainage system to the south of the trench site (figure 8) was the probable source for the alluvial and mudflow deposits found on the downthrown block (units 9 through 3). Material derived from this southern drainage moved northward, probably destroying any evidence of early, colluvial-wedge stratigraphy, and was deposited parallel to the fault scarp. Conversely, the units found on the upthrown block originated from a small drainage immediately behind the trench (figure 8). Therefore, the lack of correlative units is due to different sources for the stratigraphy on the upthrown versus the downthrown blocks of the fault.

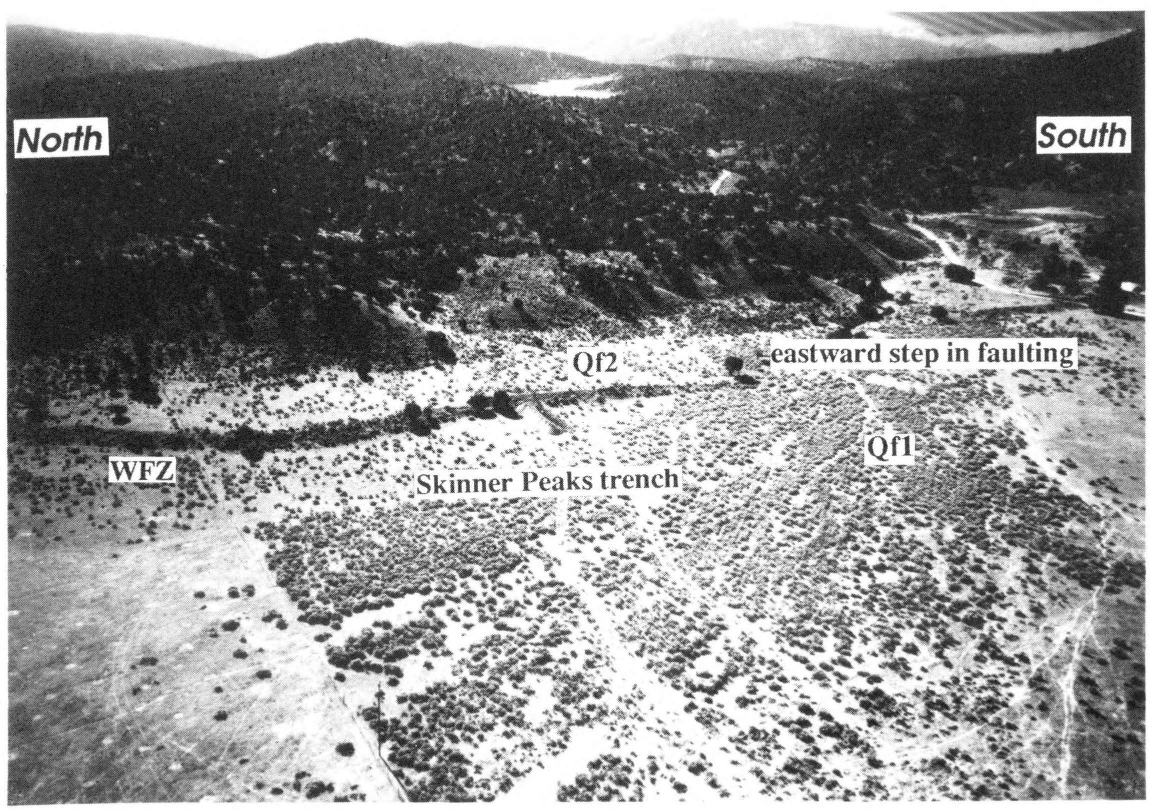


Figure 8. *Aerial photograph (looking east) of the Skinner Peaks trench site. To the north the fault scarp is 2.8-3.0 m (9.2-9.8 ft) high and decreases to 1-1.5 m (3.2-4.9 ft) to the south where the fault is covered by alluvium (Qt_1). Deformation steps to the east where a 1.5 m (4.9 ft) scarp is observed flanking the mountain front. The area within the step shows numerous small scarplets. Stratigraphic units, detailed on plate 2, from the downthrown block are the vertical expression of the Qf_1 fan, while stratigraphic units on the upthrown block come from a source directly behind the trench (Qf_2).*

Thermoluminescence (ITL-64, table 1) and radiocarbon (Beta-24200, table 2) samples were taken from a burn layer on the upthrown block of the fault (unit 12, plate 2). This layer represents an in situ burn, probably from a brush fire. The TL signal of this incipient A horizon was reset by sunlight exposure as well as by heating during the burn. An age for this layer provides a maximum estimate for the MRE at Skinner Peaks (the event which produced the colluvial wedge and fault scarp, unit 2-1, plate 2). The TL method provides an age estimate of 2000 ± 300 years (ITL-64) for the burn layer. Charcoal from the same burn layer is radiocarbon dated at 1700 ± 200 yrs B.P. (Beta-24200). Both samples place a maximum constraint on the MRE. How close this maximum is to the actual time of faulting depends on the time needed to deposit the 0.5 m (1.6 ft) of overlying sediment on the upthrown block and the time between fan stabilization and fault movement. If a range of 300-800 years is assumed for deposition of the overlying stratigraphy and fan stabilization (based on the weakly developed modern A horizon) then the MRE probably occurred between 1500 and 1000 years ago. Given the constraining maximum of 1000 years at Deep Creek, the MRE at Skinner Peaks probably occurred around 1000 yrs B.P.

A large piece of wood was collected from a strath terrace cut into the fault scarp, but not offset by the most recent movement. A radiocarbon date on this wood should provided a minimum limiting age on the MRE. However, this sample yields a radiocarbon age of 69±35 years (Beta-23309, table 2) and provides no additional constraints on the latest faulting event. Historical records indicate that no ground-rupture events have occurred on the WFZ since Utah was settled in 1847 (Machette and others, 1987). This places a broad minimum limiting age on the MRE at 144 yrs B.P.

Thermoluminescence and radiocarbon samples were taken from an incipient soil A horizon which contained flecks of charcoal (a probable surface burn) from a depth of approximately 2 m (6.6 ft) below the surface on the downthrown block of the fault (unit 6, plate 2). Disseminated charcoal from this horizon was concentrated for radiocarbon dating. The burn layer yields a TL age estimate of 3100 ± 300 years (ITL-65, table 1). The corresponding radiocarbon date is 3900 ± 300 yrs B.P. (Beta-24201, table 2). The detrital nature of the charcoal and the possible mean residence time of the organic matter combine to make the ^{14}C estimate of the burn layer older than the TL age estimate. The burn layer is located 1 m (3.3 ft) below the bottom of the colluvial wedge generated by the MRE; therefore, both dates provide a minimum age for the older fault event.

Table 1

Equivalent dose, TL age estimates and corrected radiocarbon dates for samples from the Deep Creek natural exposure and the Skinner Peaks trench, Levan segment, Wasatch fault zone, Utah.

Sample	Location	Paleodose Method	Sunlight[1] Exposure (hrs)	Paleodose[2] Range (C^0)	Paleodose (grays)	Reported TL age (yrs)	Corrected radiocarbon age (yrs B.P.)
ITL-50	Deep Creek	Total Bleach	8 (UV)[3]	290-330	4.16± 0.16	1000 ± 100	7300 ± 1000
		Total Bleach	12	290-330	3.61± 0.21		(Schwartz and
		Total Bleach	16	290-330	4.61± 0.71		Coppersmith,1984)
		Regeneration	16	280-320	4.05± 0.11		
ITL-64	Skinner Peaks	Total Bleach	16	280-360	18.61± 1.41	2000 ± 300	1700 ± 200
		Partial Bleach	1	280-360	7.81± 1.27		Beta-24200
		Partial Bleach	3	280-360	25.67± 4.54		
ITL-65	Skinner Peaks	Total Bleach	16	270-340	24.26± 1.70	3100 ± 300	3900 ± 300
		Partial Bleach	1	270-330	19.32± 0.84		Beta-24201
		Partial Bleach	3	270-340	27.37± 2.56		

1 Hours of sunlight exposure used to define the residual TL level.
2 The temperature range over the stable portion of the paleodose plot. Paleodose is averaged over this region then used to calculate TL age.
3 UV is ultraviolet light from a 275 watt General Electric UV lamp placed 40 cm from the sample.

Table 2

Laboratory-reported and calendar-corrected radiocarbon dates for samples from Deep Creek, Pigeon Creek (Schwartz and Coppersmith, 1984), and Skinner Peaks trench site, Levan segment, Wasatch fault zone, Utah.

Lab Sample Number	Material Sampled	Lab Reported Radiocarbon age (years)	MRTC[1] (years)	Calibrated[2] calendar age (yrs B.P.)	Location
Beta-24200	Charcoal	1850 ± 70	-----	1700 ± 200	Skinner Peaks
Beta-24201	Charcoal Organics	3720 ± 90	100	3900 ± 300	Skinner Peaks
Beta-233-9	Wood	69 ± 35	-----	not converted	Skinner Peaks
Schwartz and Coppersmith (1984)	Charcoal	1750 ±350	-----	1600 + 500/-400	Pigeon Creek
Schwartz and Coppersmith (1984)	Charcoal	7300 ± 1000	-----	not converted	Deep Creek

1 Mean residence time correction for organic material in soil A horizons
2 Conventional radiocarbon ages converted to calendar years (Stuiver and Reimer, 1986)
All errors are at 1 sigma

The NVTD for the MRE is estimated from the amount of offset of the paleoground surfaces. Projecting from the burn on the upthrown block to the base of the colluvial-wedge package provides a minimum NVTD of 2.0 ± 0.2 m (6.6 ± 0.6 ft). Projecting from the modern fan surface yields a maximum NVTD of 2.8 ± 0.2 m (9.2 ± 0.6 ft) for the MRE. Slight backtilting ($<$ 3 degrees) of the stratigraphic units near the main fault zone was observed. Slight movement occurred on steeply east-dipping faults (faults F3, F4, F5, plate 2) producing 0.5-0.7 m (1.6-2.3 ft) of antithetic displacement. This displacement is attributed to post-seismic settling and was not included in the measurements of NVTD.

The amount of displacement for the older event is difficult to determine. At the trench exposure, the fault scarp is 2.8 m (9.2 ft) high and a minimum of 2.0 m (6.6 ft) of displacement is attributed to the MRE. This leaves the older event responsible for a minimum of 0.8 m (2.6 ft) of displacement. Schwartz and Coppersmith (1984) hypothesize that past large-magnitude earthquakes along the same fault segment tend to produce similar-sized ground ruptures. It may be that the 0.8 m (2.6 ft) of displacement calculated for the older event was associated with a larger (~ 2 m; 6.6 ft) rupture with displacements equal to the MRE. The missing scarp height may be due to aggradation of material on the downthrown block or stripping of material from the upthrown block.

Thermoluminescence sample ITL 64 and radiocarbon sample Beta-24200 (table 1) ages agree at the one sigma level. Both age estimates place a maximum constraint on the MRE. Considering the time needed to deposit the 0.5 m (1.6 ft) of overlying stratigraphy on the upthrown block and the close maximum age of 1000 years for the earthquake event at Deep Creek, the age for the MRE at Skinner Peaks is probably closer to 1000 yrs B.P. Faulted alluvium from Pigeon Creek, dated at 1600 +500/-300 yrs B.P., also agrees with Skinner Peaks TL and radiocarbon dates at the one sigma level.

The minimum ages estimates for the second event of 3100 ± 300 (ITL-65) and 3900 ± 300 yrs B.P. (Beta-24201) agree at the two sigma level. Only 100 years (table 2) was subtracted from the radiocarbon age to account for the mean residence time of organic carbon in sample Beta-24201 and there may be an inherited age signal in the detrital carbon, possibly making the age hundreds of years younger. Both minimum dates are in agreement with a single event in 7300 years at Deep Creek. The amount of NVTD for the oldest event is at least 0.8 m (2.6 ft), but may be closer to 2.0 m (6.6 ft). The NVTD for the MRE is estimated at 2.0 m (6.6 ft).

PALEOSEISMIC HISTORY OF THE NEPHI SEGMENT

INTRODUCTION AND PREVIOUS WORK

The Nephi segment consists of two strands (figure 9), one that bounds the west side of the Wasatch Range in the northern Juab Valley, and a second that flanks the west side of the Dry Mountains, east of Santaquin Canyon (Machette and others, 1987). The segment is approximately 50 km (31 mi) long and is one of two segments proposed by Schwartz and Coppersmith (1984) which has not been modified by Machette and others (1987). The Nephi segment was mapped by Cluff and others (1970) and again in detail by Machette (1984) and both studies agree that the segment displays Holocene-age ruptures along its entire length. The southern end of the Nephi segment and the northern end of the Levan segment are separated by a 15 km (9.4 mi) gap in Holocene faulting. The last ground rupture on this gap may well be late Pleistocene or older in age (Machette and others, 1989).

Scarp morphology data, including fault-scarp height and scarp slope angle, suggest very recent movement (as young as 1000 yrs B.P.) along the main strand of the segment (Machette, 1984). Machette (1984) found evidence for at least 2 surface-faulting events, totalling 5.2-6.0 m (17.1-19.7 ft) of offset, at a natural exposure near Willow Creek (figure 9). The degree of soil development and fault-scarp morphology indicate a mid-Holocene age for the faulted surface (Machette, 1984). A few kilometers south, Machette (1984) infers a late Quaternary slip rate of 0.10-0.14 mm/yr (0.0004-0.0006 in/yr) at Gardner Creek based on 30 ± 5 m (98.4 ± 16.4 ft) displacement of a 250,000-year-old alluvial fan. He concludes that the late Quaternary slip rate is only 15 percent of the mid-Holocene slip rate (0.78 mm/yr.; 0.003 in/yr) for the same area.

Schwartz and others (1983) excavated 3 trenches at North Creek on the central portion of the Nephi segment (figure 9). At the North Creek site, the WFZ displaces alluvial-fan material containing charcoal radiocarbon dated at 5300 +600/-700 yrs B.P. (Bucknam, 1978; cited by Schwartz and Coppersmith, 1984, table 3). Schwartz and Coppersmith (1984) conclude that three fault events were responsible for 7.0 ± 0.5 m (23.0 ft ± 1.6 ft) of offset on this mid-Holocene fan surface. The most recent and penultimate events are represented by scarp-derived colluvium, while the oldest event is inferred from a tectonic strath terrace cut into the North Creek fan surface on the upthrown block of the fault.

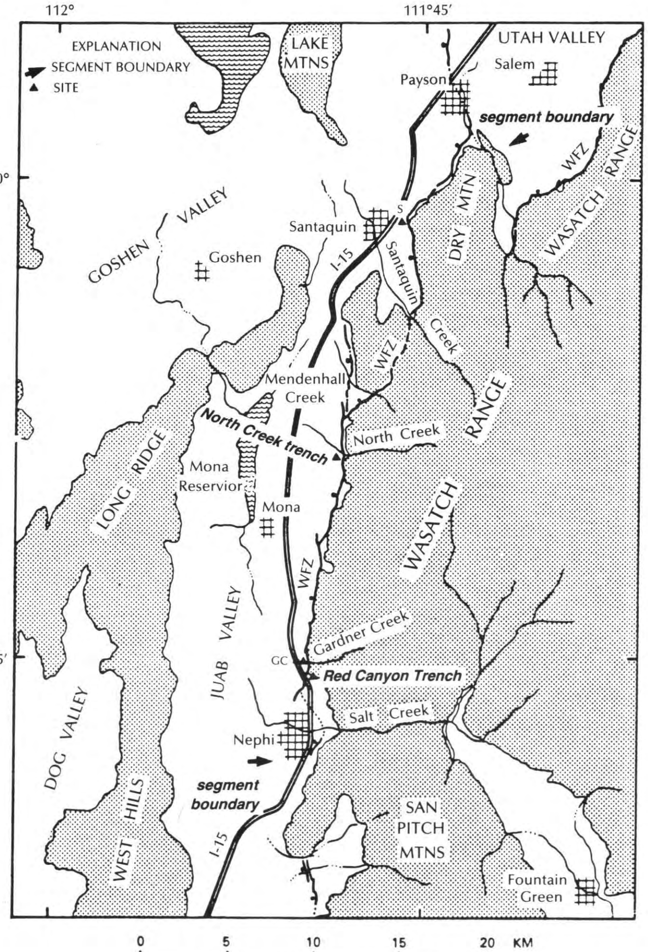


***Figure 9.** Map of the Nephi segment of the Wasatch fault zone. The North Creek site of Schwartz and Coppersmith (1984) is in the middle of the fault segment, whereas the Red Canyon trench is near the southern segment boundary. Modified from Machette and others (1987).*

A maximum age for the MRE (event A of Schwartz and Coppersmith, 1984) is constrained by a radiocarbon age on charcoal of 1000 ± 100 yrs B.P. (WC-12-80-6, table 3) from a soil buried by colluvium deposited after the MRE. An additional radiocarbon date of 1300 ± 100 yrs B.P. (WC-12-80-5) comes from organic material within a debris flow below the colluvium in an adjacent trench. Both radiocarbon dates suggest a maximum age estimate for the MRE between 1000-1300 yrs B.P. A minimum age for the MRE is placed at 300-500 years ago based on the lack of the migration of a knickpoint in the channel above the scarp, and a generally continuous fault scarp (15 km long; 9.4 mi) which lacks vegetation (Schwartz and Coppersmith, 1984). Machette's (1984) fault-scarp morphology data suggest an age closer to 1000 years for the MRE. Approximately 2.0-2.2 m (6.6-7.2 ft) of displacement is estimated for event A.

Conventional radiocarbon dates of 4000 ± 200 (WC-12-80-7) and 1400 + 200/-100 yrs B.P. (WC-12-80-7, table 3), from a buried soil developed on top of the second colluvial wedge, provide a minimum estimate for the middle event (event B). Hanson and Schwartz (1982) report accelerator mass spectrometry radiocarbon dates on soil-organic material of 4400 + 700/-800 and 1500 +800/-600 yrs B.P. (both also WC-80-12-7), which show a similar variation in age. Detrital charcoal from the same soil yields an accelerator radiocarbon age of 1300 ± 400 yrs B.P. (WC-12-80-9). Hanson and Schwartz (1982) argue that the younger ages represent young carbon material incorporated into the soil prior to burial by colluvium, and as such, prefer the older dates as a minimum constraint for event B. The older 3-4 ka dates are reported in Schwartz and Coppersmith (1984) as a minimum constraining age for event B with no mention of the younger dates. Schwartz and Coppersmith (1984) estimate the displacement for event B as between 2.0-2.5 m (6.6-8.2 ft).

It may also be argued that the younger radiocarbon dates mentioned above provide a better minimum constraint on event B because: 1) the older age may represent older carbon transported downslope during the period indicated by the formation of the soil on event B colluvium; 2) out of 5 radiocarbon dates, 3 indicate a young age for the surface; and 3) the organic status of the carbonized wood (sample WC-12-80-9) is better defined than that for the soil-organic material. If the older of the WC-80-12-7 dates is ignored, then the difference in age between the 1500 year soil-organic and the 1300 year charcoal radiocarbon dates suggests that the mean residence time for soil-organic carbon is approximately 200 years. This mean residence time for carbon agrees with data presented from Nelson (1988) from the northern WFZ. The three younger radiocarbon dates (1500, 1300, and 1400 yrs B.P.), combined with minimum age constraints for the middle event found at Red Canyon, suggest that the younger dates may better approximate the age of the buried soil, and provide a better minimum constraint on event B at North Creek.

No evidence for event C, the oldest event, is found in the colluvial stratigraphy at North Creek. Rather, the event was inferred from a tectonic strath terrace inset into the North Creek fan on the upthrown block of the fault (Schwartz and Coppersmith, 1984). Bucknam's (1978) corrected radiocarbon date of 5300 +600/-700 yrs B.P. from within the North Creek fan provides a maximum limiting age for event C. A minimum age for this event is provided by the 1300 year (WC-12-80-9) and 1500 year (WC-12-80-9) radiocarbon dates. The amount of displacement for event C is approximately 2.6 m (8.5 ft) (Schwartz and Coppersmith, 1984).

RED CANYON TRENCH

A trench was excavated near the southern terminus of the Nephi segment in an attempt to provide independent corroboration of the 3 fault events within the past 5 thousand years on the Nephi segment as determined by Schwartz and Coppersmith (1984), and to compare the number and magnitude of rupture events at a segment boundary (Red Canyon) versus middle segment values (North Creek).

The Red Canyon trench site is located near the southern terminus of the Nephi segment, just east of Highway I-15 about 3.5 km (2.2 mi) north of the town of Nephi (figure 9). The trench was excavated approximately 5 km (3.1 mi) north of the Nephi segment boundary where a fault scarp 5.5 m (18.0 ft) high crosses the distal portion of the Red Canyon alluvial fan (figure 10). Machette (oral communication, 1988) estimates the age of the Red Canyon alluvial-fan surface at latest Pleistocene (10-15 thousand years) based on fan morphology and soil profile development.

To the south (20-40 m; 66-130 ft), the scarp rapidly decreases in height from 5.5 to 3.4 m (18.0-11.2 ft). Farther south, the fault scarp is destroyed by construction of Interstate I-15, and eventu-

Table 3

Laboratory-reported and calendar-corrected radiocarbon dates for samples from North Creek, Nephi segment, Wasatch fault zone, Utah. Modified from Hanson and Schwartz, 1982.

Field Number	Material Sampled	Lab Reported Radiocarbon age	MRTC[1] (years)	Calibrated[2] calendar age (yrs B.P.)
Bucknam (1978)	Charcoal	4580± 250	-----	5300 +600/-700
WC-12-80-7[(4)]	A horizon	3640±75	100	4000 ± 200
	A horizon	1650± 50	100	1400 +200/-100
WC-12-80-7	A horizon[(3)]	3894 +288/-278	100	4400 +700/-800
	A horizon[(3)]	1645 +270/-262	100	1500 +800/-600
WC-12-80-9	Charcoal[(3)]	1389 +181/-177	-----	1300 ± 400
WC-12-80-5	Charcoal	1350± 70	-----	1300 ± 100
WC-12-80-6	Charcoal	1110± 60	-----	1000 ± 100

1 Mean residence time correction for organic material in soil A horizons
2 Conventional radiocarbon ages converted to calendar years (Stuiver and Reimer, 1986). All errors are at 1 sigma
3 Samples dated by accelerator mass spectrometry.
4 All WC dates from Hanson and Schwartz (1984)

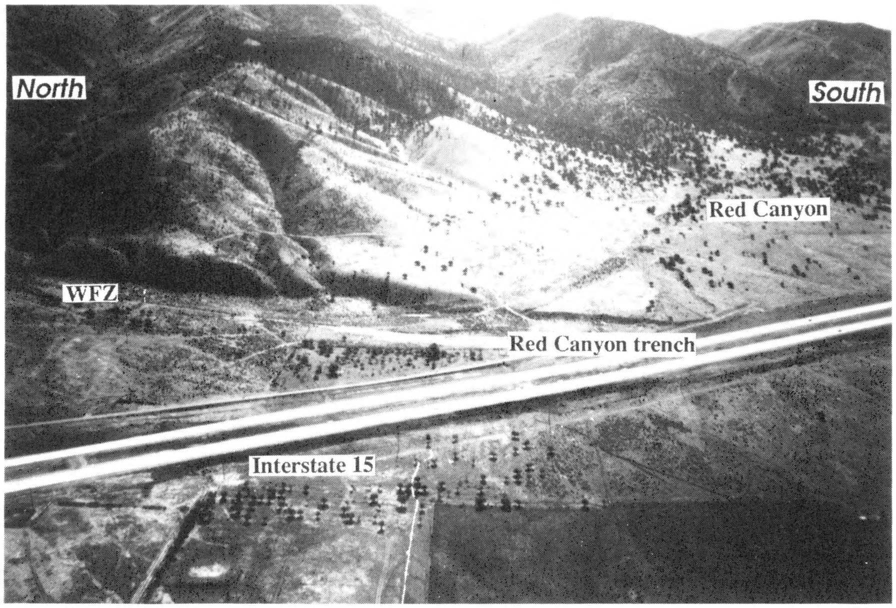


Figure 10. *Aerial photograph of the Red Canyon trench excavated across the Red Canyon alluvial-fan surface, just north of Nephi, Utah, at the southern boundary of the Nephi segment. Repeated rupture on the fault has produced 25-30 m (82-93 ft) of fault scarps (to the north). The fault dies out into the valley alluvium 1 km (0.6 mi) to the south of the trench site.*

ally dies out in valley-fill sediments (figure 10). To the north of the trench site, but still on the Red Canyon fan, the fault scarp increases in height from 5.5 to 6.3 m (18.0 -20.7 ft). Farther to the north, near Gardner Creek, where the fault displaces late Pleistocene-age sediments, the scarp is as much as 30 m (98.4 ft) high (figure 10).

The Red Canyon trench was excavated into interbedded, distal alluvial-fan sediments composed primarily of course-grained, alluvial-channel deposits and locally derived silty mudflows and colluvium. Large boulders (often 2 m [6.6 ft] in diameter) found within the alluvial units attest to the transport power of the streams which formed the Red Canyon alluvial fan. The sediment in the alluvial fan was provided by different sources as evidenced by two distinct sediment colors in the trench stratigraphy. Deposits derived from Red Canyon are predominantly reddish to brown, poorly sorted, alluvial and colluvial deposits composed of red sandstone pebbles, cobbles, and boulders (plate 3, units 10 and 17). These reddish-brown deposits are interbedded with locally derived grey to pale brown, silty mudflows and alluvial and colluvial deposits composed of limestone pebbles and cobbles (plate 3, units 9 and 12). Stacked red and tan units provided excellent marker beds, which were used to trace the stratigraphy across the complex fault zone (plate 3).

Three distinct stacked colluvial-wedge/buried-soil sequences were exposed in the Red Canyon trench indicating at least 3 movements on the fault (colluvial units 2, 3, and 4, plate 3). Deformation is not limited to a single fault, but is spread out over a 5 m (16.4 ft) zone with the majority of movement restricted to faults F1 and F4 (plate 3). Radiocarbon datable material within the Red Canyon trench was limited to soil-organic matter. In this location, the soil on top of the youngest colluvial wedge was poorly developed; therefore, no TL or radiocarbon samples were taken and thus there is no minimum dated constraint on the MRE. Further, no datable material was found in the stratigraphic section on the upthrown block to provide a maximum limiting age on the oldest event.

A maximum limiting age for the MRE is provided by a TL age estimate and a radiocarbon date from the soil buried by colluvium shed following the MRE (unit 3S, plate 3). The TL technique yields age estimates of 1300 ± 500 (ITL 88) and 1500 ± 400 yrs B.P. (ITL 67, table 4). The radiocarbon sample dates at 2900 +300/-200 yrs B.P. (Beta-25402, table 5). Radiocarbon sample (Beta-25402) was taken from a thin, buried soil A horizon (unit 3S) juxtaposed directly against the main, east-bounding fault (fault F1, plate 3). This sample was very low in concentrated organics (0.2 percent) and may have been slightly contaminated by older carbon during the MRE. Because of the low carbon content, Beta 23402 is considered an unreliable indicator of sample age. Paleodose estimates for sample ITL-88 are consistent over a wide range of sunlight bleach exposure (table 4) and its age is considered a reliable estimate for the soil. Paleodose estimates for sample ITL-67 show more scatter, but both TL dates (ITL-88, ITL-67) overlap at the one sigma level. Based on the TL dates, and the low carbon content of sample Beta-25402, a maximum age of approximately 1400 yrs B.P. is suggested for the MRE (event 1).

Samples for TL (ITL-66) and radiocarbon dating (Beta-24186, table 5) were taken from a soil A horizon (unit 4S, plate 3) buried by colluvium shed after the middle event (unit 3, plate 3), and should provide a maximum age for the penultimate event. Both samples were excavated from below a laterally continuous stone line which marked the top of the lowest colluvial wedge (plate 3). The age of the radiocarbon sample (Beta-25186) is 1300 + 200/ -300 yrs B.P.; the TL age estimate is 1700 ± 200 yrs B.P. (ITL-66). These samples came from a separate, distinct colluvial wedge below units 3S and 3. Therefore, the age estimates from ITL-66 and Beta-24186 should date older than ITL-88 and ITL-67. This agreement between two sets of radiocarbon and TL dates separated by a distinct colluvial wedge poses a problem in interpreting the timing of events 2 and 3.

One explanation for the discrepancy (one which was not recognized in the field) between samples Beta 25185, Beta 25184, and the ITL-66/Beta 25186 pair is that a burrowing animal may have excavated down through units 3S and 3 colluvium into the unit 4S soil (plate 3). Then, the burrow was back filled, either prior to or during the deposition of the overlying, scarp-derived colluvial unit 3. Therefore, the material sampled from this surface may be con-

Table 4

Equivalent dose, TL age estimates, and corrected radiocarbon dates for samples from the Red Canyon trench, Nephi segment, Wasatch fault zone, Utah.

Sample	Location	Paleodose Method	Sunlight[1] Exposure (hrs)	Paleodose[2] Range (Co)	Paleodose (grays)	Reported TL age (yrs)	Corrected radiocarbon age (yrs B.P.)
ITL-48	Red Canyon	Total Bleach	8(UV)[3]	280-340	55.68±2.4	14600± 1200	3600 ± 400
		Total Bleach	8	280-340	52.15± 1.55		(Beta-25185)
		Total Bleach	16	280-340	58.82± 1.27		
		Partial Bleach	2	280-340	53.75± 3.04		
ITL-66	Red Canyon	Total Bleach	16	270-340	8.10± 0.93	1700± 200	1300 +200/-300
		Total Bleach	8	270-340	6.07± 0.45		(Beta-25186)
		Partial Bleach	1	270-340	4.35± 0.50		
		Partial Bleach	2	270-340	5.61± 0.74		
ITL-67	Red Canyon	Total Bleach	16	270-350	3.31± 1.80	1500± 400	
		Partial Bleach	2	270-350	6.38± 2.40		
ITL-88	Red Canyon	Total Bleach	16	280-340	4.95± 17.0	1300± 500	2900 +300/-200
		Total Bleach	8	280-340	4.56± 1.34		(Beta-25402)
		Partial Bleach	2	280-340	4.31± 2.40		
		Partial Bleach	1	280-340	4.55± 2.87		
ITL-90	Red Canyon	Total Bleach	16	270-360	19.3± 1.00	7000± 800	3900 +500/-400
		Total Bleach	8	270-360	19.52± 2.11		(Beta-25184)
		Partial Bleach	2	270-360	17.15± 2.00		
		Partial Bleach	1	270-360	17.63± 3.89		

[1] Hours of sunlight exposure used to define the residual TL level.

[2] The temperature range over the stable portion of the paleodose plot. Paleodose is averaged over this region then used to calculate TL age.

[3] UV is ultra violet light from a 275 watt General Electric UV lamp placed 40 cm from sample.

Table 5

Laboratory-reported and calendar-corrected radiocarbon dates for samples from Red Canyon, Nephi segment, Wasatch fault zone, Utah.

Lab Sample Number	Field Number	Material Sampled	Lab Reported Radiocarbon age	MRTC[1] (years)	Calibrated[2] calendar age (yrs B.P.)
Beta-25185	JRC-16	A horizon	3550± 150	200	3600 ± 400
Beta-24186	JRC-17	A horizon	1380± 120	100	1300 +200/-300
Beta-25402	JRC-14	A horizon	2900± 90	100	2900 +300/-200
Beta-25184	JRC-15	A horizon	3690± 170	100	3900 +500/-400

1 Mean residence time correction for organic material in soil A horizons
2 Conventional radiocarbon ages converted to calendar years (Stuiver and Reimer, 1986)
All errors are at 1 sigma

taminated by, or composed of, well-zeroed material from the unit 3S soil. Although burrows are not uncommon, the preferred explanation is that an unrecognized fault splays off fault F4 to create a graben structure, which drops unit 3 to the same stratigraphic level as unit 4 in the vicinity of the sample area.

Two other samples, TL sample ITL-90 and radiocarbon sample Beta-25184, from the unit 4S buried soil help resolve this discrepancy and provide a maximum constraint on the penultimate event. Both samples come from a soil developed on the lowest colluvial wedge (unit 4S, plate 3), which was buried by colluvium shed after event 2 (unit 3, plate 3). Samples ITL-90 and Beta-25184 were correlated to the same stratigraphic position as samples ITL-66 and Beta-24186. Thermoluminescence sample ITL-90 yields an age estimate of 7000 ± 800 yrs B.P., while the radiocarbon sample dates at 3900 +500/-400 yrs B.P. (Beta-25184, table 5).

The paleodose data for ITL-90, consistent over a wide range of total and partial bleach times (table 4), suggest that the sample was well sunlight-bleached prior to burial. Sample ITL-90 was excavated from a thin, laterally discontinuous soil interpreted as being correlative with soil unit 4S (plate 3). The 3900 +500/-400 yrs B.P. radiocarbon age (Beta-25184) suggests that sample ITL-90 may have been contaminated by well-zeroed, but older material sheared into the sample area during events 1 and 2. Therefore, ITL-90 is considered an overestimate, while Beta-25184 provides a closer maximum age for event 2. A further constraint on the deposition of unit 4 comes from sample Beta 25185 (plate 3), taken from within organic-rich, proximal colluvium at the base of the third colluvial wedge (unit 4, plate 3), which yields a radiocarbon age of 3600 ± 400 yrs B.P.

A late Pleistocene age for the fan surface (unit 6) on the upthrown block of the fault (Machette, personal communication, 1988) provides a broad maximum age for the oldest ground-rupture event. The overlap of radiocarbon samples Beta 25185 and Beta 25184 at the one sigma level suggests little time elapsed between fault rupture, deposition of colluvial unit 4, and stabilization of soil 4s. A maximum limiting age for event 3 is probably closer to the oldest date for the colluvium (Beta 25184, 3900 ± 500 yrs B.P. or between 4 and 4.5 thousand years).

The trench stratigraphy at Red Canyon indicates three major, surface-faulting events occurred in the last 4500 years. The majority of movement occurred on two west-dipping normal faults (F1 and F4, plate 3), with minor amounts of displacement on two east-dipping reverse faults (F5 and F6) and one near-vertical fault (F3). The 2 m-wide (6.6 ft) area between faults F1 and F4 is a complex zone of shearing and block rotation. Crosscutting stratigraphic relations and the lack of a thick colluvial wedge (unit 4) near fault F1 indicate that the majority of displacement occurred along the F4 fault during event 3. The thick accumulation of colluvium (unit 4) west of fault F4, and minor displacement on reverse faults F5 and F6, suggest that the majority of deformation during event 3 was restricted to a 3 m-wide (9.8 ft) zone west of fault F4. Faults F1, F5, and F6 could not be traced up through the overlying colluvium, indicating the absence of movement during the younger events (events 1 and 2). A large crack formed adjacent to the F1 fault during event 3. This crack quickly filled with colluvial material (unit 5, plate 3) which spalled off the newly formed fault scarp. The crack fill was in turn covered by a thin colluvial wedge (unit 4) on which soil unit 4S formed.

Based on the thickness of colluvium adjacent to faults F1 and F4, and the measurable offset at faults F4 and F5, the NVTD during event 3 is estimated at 1.7 ± 0.3 m (5.6 ± 1.0 ft). Displacement during event 2 occurred predominantly on fault F1, resulting in the deposition of colluvial unit 3. Soil 3S formed on unit 3 during the interval of fault inactivity. Based on the thickness of colluvium, the NVTD for event 2 is estimated at 1.5 ± 0.2 m (4.9 ± 0.7 ft). During the MRE, deformation was again restricted to the F1 fault. A large crack formed adjacent to the F1 fault during coseismic deformation. An intact sliver of unit 3 and soil 3S was dropped into the crack then quickly covered by a block of unit 9 which spalled off the unstable scarp free face. Proximal and distal colluvium (unit 2) then buried the soil unit 3S. Based on colluvial-wedge thickness, the displacement during the MRE is estimated at 1.4 ± 0.3 m (4.6 ± 1.0 ft). The total NVTD as measured from the offset of unit 7 is 5.4 ± 0.3 m (17.7 ± 1.0 ft). The cumulative displacement estimated from colluvial-wedge thickness is 4.6 ± 0.8 m (15.1 ± 2.6 ft), which agrees with the total NVTD of 5.4 ± 0.3 m (17.7 ± 1.0 ft). These data are in general agreement with the minimum displacement of 5.2-6.0 m (17.1-19.7 ft) found at Willow Creek, approximately 6 km (3.8 mi) to the north (Machette, 1984).

The middle event is constrained by a maximum date of 3900 yrs B.P. and a minimum date of approximately 1300 yrs B.P. Given that event 2 is constrained by a bulk soil-organic radiocarbon date, it is probably slightly younger than the maximum, or between 3000-3500 yrs B.P. If so, the interval between events 2 and 3 is a maximum of 2200 years and a minimum of 1700 years. The MRE may be as young as 144 years or as old as 1500 years. The time interval between events 1 and 2 is a maximum of 3350 years and a minimum of 1500 years.

The timing of the oldest and the youngest events at North Creek agrees well with data from Red Canyon. However, there is a disagreement as to the minimum age for the penultimate event. At North Creek, Schwartz and Coppersmith (1984) place a minimum age on the MRE (event A) of 300-500 years ago with a maximum limiting age provided by the 1032 +139/-101 (WC-12-80-6) and 1287 + 95/-127 yrs B.P. (WC-12-80-5) radiocarbon dates. Based on height/slope-angle relations of the fault scarp, and the lack of a fault free face, Machette (1984) suggests an MRE closer to 1000 years. The NVTD for the NRE is 2.0-2.2 m (6.6-7.2 ft). Schwartz and Coppersmith (1984) argue for a minimum age of nearly 4000 years for the penultimate event at North Creek. However, additional data present in Hanson and Schwartz (1982) indicate the minimum age could be closer to 1600 years. Schwartz and Coppersmith (1984) suggest a maximum age for event C at North Creek of 5300 years. Therefore, the oldest event occurred between 4000 and 5300 years ago.

The Red Canyon data suggest a minimum age of faulting between 1300 and 1700 yrs B.P., based on TL dates from soil formed on the middle colluvial wedge. The minimum limiting dates for event B of approximately 1600 yrs B.P. (Hanson and Schwartz, 1982) are in better agreement with minimum dates for event 2 at Red Canyon. Schwartz (personal communication, 1988; also Hanson and Schwartz, 1982) argues that the younger dates represent young carbon incorporated into the soil surface prior to burial by the colluvium from the MRE. This is a valid argument if both accelerator charcoal dates indicate young ages while the concentrated organic samples provide an older age. It may be argued that the older radiocarbon ages preferred by Schwartz and Coppersmith (1984) represent older carbon transported downslope during the period indicated by the formation of the soil on event B colluvium. The 3 approximately 1400 yrs B.P. radiocarbon dates of Hanson and Schwartz (1984), and the two TL (ITL-88, ITL-67) and possibly the TL/radiocarbon pair (ITL-66, Beta-25186) at Red Canyon, suggest a maximum age for the MRE (and a minimum for the penultimate event) of closer to 1300 yrs B.P. The Red Canyon data do suggest an age of between 3000 and 3500 years for the second event which is in approximate agreement with the 3600 years for event B at North Creek.

An alternative interpretation is that event 3 colluvium (unit 4, plate 3) at Red Canyon correlates with event B colluvium at North Creek. However, this interpretation could not explain the presence of event 2 colluvium (unit 3, plate 3) at Red Canyon.

The oldest event at Red Canyon occurred between 4000 years ago and sometime in the late Pleistocene, but probably closer to 4500 years ago. This age estimate for the oldest event is in general agreement with the maximum age constraint of 5300 yrs B.P. from event C at North Creek. The amount of NVTD is consistently lower at Red Canyon (1.3-1.7 m; 4.3-4.5 ft) than at North Creek (2.0-2.6 m; 6.6-8.5 ft). The smaller displacement values at Red Canyon are in keeping with the location of the trench near the segment boundary, where non-thoroughgoing ruptures would cause a slip deficit.

A broad, late Pleistocene age based on soil development on unit 6A has been used to provide a poorly constrained maximum on fault event 3. If a minimum age for event 3 is taken as between 4000 and 4500 years, then the Nephi segment of the fault was inactive between 15,000 and 4500 years ago. There is no indication of faulting down though unit 20 which indicates the fault was inactive for the additional time interval represented by the 5 m (16.4 ft) thickness of stratigraphy (maybe 10 thousand years ±). One possibility is that the age estimate of Machette (personal communication, 1988) for the fan surface is younger, say 6 to 7 thousand years. However, a comparison of the degree of soil development, calcium-carbonate content, thickness of the soil A horizon, and surface morphology between the North Creek (maximum age 5300 yrs B.P.) and the Red Canyon fans, suggests that Red Canyon is indeed the older fan surface.

Machette (1984) and Machette and others (1987) suggest a correlation between the catastrophic draining of Lake Bonneville, approximately 15 thousand years ago, and an increase in Holocene slip rates. They correlate times of high Bonneville lake levels with periods of low fault slip rates and times of low lake stands with increased slip rates. If their suggestion is correct, higher slip rates should have occurred on the Nephi segment starting soon after the draining of Lake Bonneville (approximately 15 thousand years ago. Increased slip rates at 15 thousand years should show as discreet slip events between 15 thousand years and the present and should be seen as colluvial wedges in the stratigraphic section at Red Canyon. However, the lake embayment that extended into the Nephi area was small. Consequently, the draining of Lake Bonneville may not have provided enough crustal unloading to initiate an increase in slip on the Nephi segment. A closer constraint on the age of the fan surface at Red Canyon must be determined before any further conclusion can be drawn.

The data from Red Canyon indicate three Holocene-aged, ground-rupture events. The MRE probably occurred between 1000-1200 years ago with an estimated 1.4 ± 0.3 m (4.6 ± 1.0 ft) of NVTD. The penultimate event (event 2) occurred close to 3000-3500 years ago, and was responsible for 1.5 ± 0.2 m (4.9 ± 0.7 ft) of NVTD. The oldest event exposed in the trench (event 3) occurred after 4000-4500 years ago, but well before the late Pleistocene. If continuity of faulting is assumed, and the maximum age for the oldest event at North Creek is valid, then the oldest event at Red Canyon may be closer to 4500 years ago. Net tectonic displacement for the third event is estimated at 1.7 ± 0.3 m (5.6 ± 1.0 ft). The net vertical offset estimated for each event agrees well with the 5.4 ± 0.2 m (17.7 ± 0.7 ft) of total displacement measured from offset stratigraphic marker beds.

The Red Canyon data agree with the number of events and the timing of the most recent and oldest events at North Creek. However, work at Red Canyon suggests a minimum age of 1200 to 1700 years for the middle event versus 3600 years suggested by Schwartz. However, both data sets suggest the most probable timing for the event was around 3500 yrs B.P.

CONCLUSIONS AND RECOMMENDATIONS

THERMOLUMINESCENCE DATING OF PALEOSEISMIC EVENTS

The TL technique is a relatively new and experimental method for determining age estimates for geologic deposits between 500 and 250,000 years old. In this study, the TL method was used to constrain past faulting events on two segments of the WFZ by dating soils buried by fault-generated colluvium. Two TL samples from the Red Canyon trench show a variation from the radiocarbon dates. Sample ITL-90 was taken from a thin, laterally discontinuous soil correlated to unit 4S. Thermoluminescence data suggest a soil well bleached prior to burial by event 2 colluvium, but the age estimate of 7000 ± 800 years seems anomalously high compared to the radiocarbon dates of 3600 ± 400 (Beta-25185) and 3900 +500/-400 yrs B.P. (Beta-25184). The overestimate of TL age may be the result of older, well-zeroed material being sheared into the sample area during event 2. It is also possible that the dose rate sample was biased such that an underestimate of dose rate caused an apparent older TL age. An age closer to 3900 years minimum for event 3 is preferred, based on the two radiocarbon dates.

Thermoluminescence sample ITL-88 (1300 ± 500 yrs B.P.) and radiocarbon sample Beta-25402 (2900 +300/-200 yrs B.P.) are another sample pair not in agreement. The radiocarbon sample was very low in concentrated organics (0.2 percent) and does not provide a reliable age estimate for the surface. Sample ITL-67 provides a better estimate for the minimum age of event 2 and the maximum age for event 3 with a TL age estimate of 1500 ± 400 yrs B.P.

Samples from the Levan segment agree well with the established radiocarbon chronology. Sample ITL-64, which provides a maximum constraint on the MRE event at Skinner Peaks, is dated at 2000 ± 300 yrs B.P. with a corresponding radiocarbon date of 1700 ± 200 yrs B.P. (Beta 24200). ITL-65 yields a TL age estimate of 3100 ± 300 years which is slightly younger than the associated radiocarbon date of 3900 ± 200 years (Beta-24201). The older radiocarbon age is probably the result of dating a mixture of charcoal and bulk organic material.

Figure 11 shows a plot of TL age versus calendar-corrected radiocarbon dates for all TL samples dated on the WFZ at the present time (Jackson, 1988, Forman and others, 1989). This figure displays a reasonable correlation between radiocarbon and TL age estimates at the one sigma level. Samples contaminated by fault-derived material show a TL age estimate which is greater by a factor of two over the radiocarbon date. This figure indicates that buried soils from the WFZ are generally well light-bleached (or the bleach time can be modeled using the partial bleach method) prior to burial, and that the TL method provides good age estimates for the time of burial of the soils with respect to an independent radiocarbon chronology. It is demonstrated that the TL method, when properly applied, can yield accurate maximum and minimum age constraints on paleoseismic events in an extensional terrain.

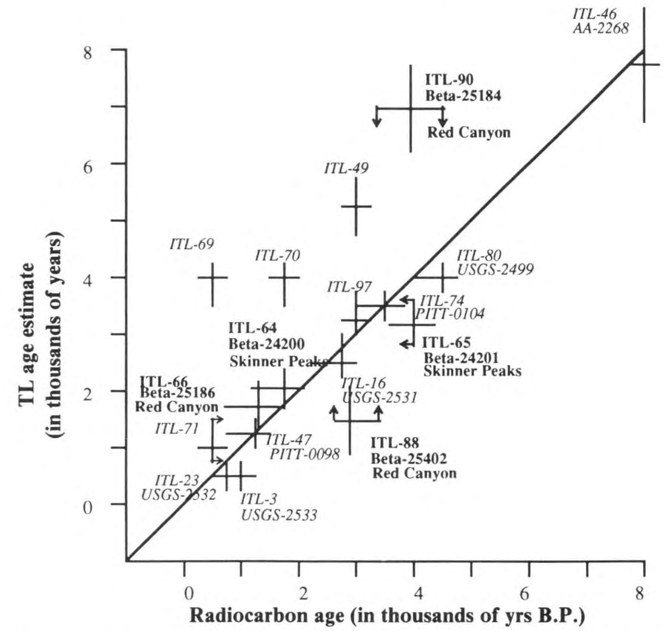


Figure 11. *Plot of TL age versus calendar-corrected radiocarbon ages. The samples provide maximum and minimum limiting dates for paleoseismic events on the Weber segment (Forman and Maat, unpublished data), American Fork subsegment (Forman and others, 1989), Spanish Fork subsegment (Jackson, 1988), and Nephi and Levan segments of the Wasatch fault zone. Correlations between TL and radiocarbon dates suggest that the TL method may be used to date paleoseismic events. Arrows indicate the suggested direction of movement of the date pair due to problems either with the TL or radiocarbon samples. For instance, TL sample ITL-90 is thought to be contaminated by unzeroed material, so the sample provides an overestimate of the buried soil age with respect to the radiocarbon date. Error bars are one sigma. Modified from Forman and others (1989).*

SUMMARY PALEOSEISMIC HISTORY OF THE LEVAN AND NEPHI SEGMENTS

This study provided two additional minimum constraints on the age of the MRE on the Levan segment. Thermoluminescence sample ITL-50 from Deep Creek was taken from a soil buried by a block of colluvium shed during the last ground-rupture event. This sample yields a TL age estimate of 1000 ± 100 yrs B.P. and provides a close approximation for the timing of this event. The NVTD is 1.8 m (5.9 ft) which is in agreement with the amount of offset determined by Machette (unpublished data, 1985) and by Schwartz and Coppersmith (1984).

At the Skinner Peaks trench site, the MRE is manifest as a west-facing scarp 3 m (9.8 ft) high. An older event, not displayed in the colluvial stratigraphy, is inferred from a thicker sequence of stratigraphy on the downthrown, versus the upthrown, block of the fault. A maximum age for the MRE is provided by a TL age estimate of 2000 ± 300 years (ITL-64) and a radiocarbon age of 1700 ± 200 yrs B.P. The actual age of the event is probably a few hundred to a thousand years younger than this maximum estimate. A minimum age for the older inferred event is given by a TL age estimate of 3100 ± 300 yrs B.P. (ITL-65) and a radiocarbon date of 3900 ± 300 yr B.P. (Beta-24201). Both dates imply that the older event must have occurred earlier than 3000 to 4000 yrs B.P. Based on the 7300 ± 1000 yr B.P. radiocarbon date from the upthrown block of the fault at Deep Creek (Schwartz and Coppersmith, 1984), the older event at Skinner Peaks may have occurred prior to 7300 yrs B.P. The NVTD for the MRE is estimated at 2.0 ± 0.2 m (6.6 ± 0.7 ft). There is a minimum of 0.8 m (2.6 ft) of measurable displacement associated with the older inferred event. The minimum and maximum ages found at Skinner Peaks agree with those of Deep Creek, suggesting that the MRE occurred on the Levan segment approximately 1000 years ago.

Past work by Schwartz and Coppersmith (1984) demonstrates three surface-faulting events on the Nephi segment during the past 5000 years. They estimate the MRE to be as young as 300 to 500 years old, with the middle event constrained to a minimum of 3600 years old, and the oldest event occurring before 5300 years ago. The amount of NVTD was estimated at 2 to 2.6 m (6.6-3.5 ft) per event.

Using a combination of TL and radiocarbon dates, the MRE at Red Canyon was dated at 1200 years ago with an estimated offset of 1.4 ± 0.3 m (4.6 ± 1.0 ft). The penultimate event occurred between 3000 to 3500 years ago with 1.5 ± 0.2 m (4.9 ± 0.7 ft) of displacement. The oldest event is constrained to between 4000-4500 years ago with 1.7 ± 0.3 m (5.6 ± 1.0 ft) of offset. The NVTD, as measured from offset stratigraphic layers, is 5.4 ±0.3 m (17.7 ± 1.0 ft) and agrees with 4.6 ± 0.8 m (15.1 ± 2.6 ft) of displacement calculated from the thickness of the colluvial wedges.

The values of NVTD for Red Canyon, Willow Creek (Machette, 1984), and for North Creek (Schwartz and Coppersmith, 1984) were compared to determine the slip distribution for the southern portion of the Nephi segment. Slip values decrease steadily from 7.0 m (23.0 ft) at North Creek to 5.4 m (17.7 ft) at Red Canyon. The gap in late Holocene faulting between the southern Nephi and the northern Levan segments indicates zero slip at the segment boundary. Slip rapidly decreases from the Red Canyon trench to the segment boundary.

Figure 12 shows that the 6 m (19.7 ft) of displacement estimated by Machette (1984) for Willow Creek (2 or possibly 3 events) falls slightly below an elliptical distribution (Eshelby, 1957). Estimates of displacement for Red Canyon fall on the elliptical distribution, suggesting a systematic decrease in slip rates along the Nephi segment.

NEPHI AND LEVAN SEGMENTS IN THE OVERALL CONTEXT OF THE WASATCH FAULT ZONE

Over 50 logged trench and natural exposure sites make the WFZ one of the most intensely studied fault system in the western United States. The fault zone is composed of a number of discrete rupture segments, each of which tend to produce a narrow range of surface displacement associated with a characteristic magnitude earthquake (Schwartz and Coppersmith, 1984). The current consensus suggests a total of 5 to 6 central segments, all showing multiple offsets within the past 6000 years, and five distal segments to the north and south (figure 13). All the central segments except the Brigham City and Salt Lake City segments show a rupture at or younger than 1000 years ago. Fedotov (1968) proposed that regional shear stress accumulates on a fault zone and that, after a critical stress level is reached, the fault ruptures and releases the stored energy. Stress again accumulates until a critical stress value is reached causing further rupture. If the yield stress was reached on six of the WFZ segments 1000 years ago, then the fault may be in a period of stress accumulation and further ground-rupture may not occur for the next hundred to thousands of years. However, as noted by Wallace (1983), fault zones in the western United States may experience periods of accelerated slip punctuated by times of fault quiescence when deformation is transferred to adjacent fault zones. The consistent rupture occurring near 1000 years ago may be an indicator that the WFZ, or at least six segments, are in a period of high slip which will manifest itself as large-magnitude earthquake events in the near future (hundreds of years). Compilations by Machette and others (1989) indicate that an earthquake has ruptured the central segments of the WFZ on an average recurrence interval of 2050 years. For the past 6000 years, a ground-rupture event has struck the central segments on an average of once every 400 years. Machette and others (1989) further conclude that between 400 and 1500 years ago faulting occurred at an accelerated rate of one event every 220 years. However, as figure 13 indicates, surface-faulting earhtquakes are irregularly distributed in both time and space.

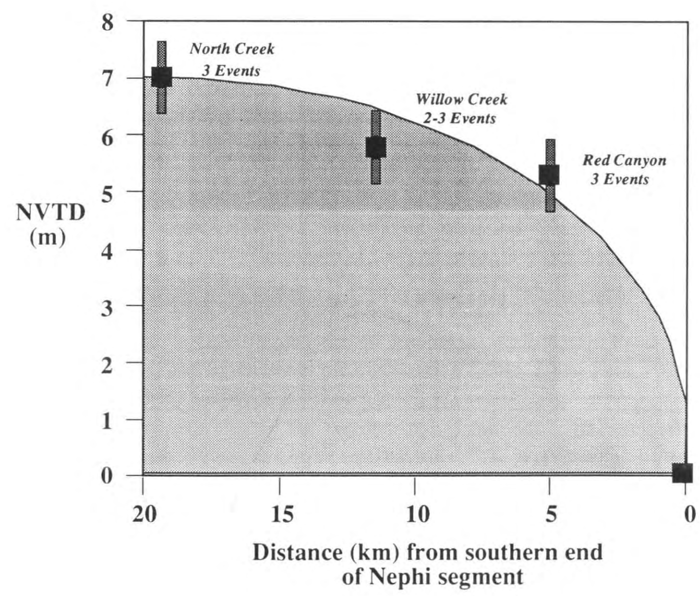


Figure 12. *Slip distribution for the southern Nephi segment based on NVTD at North Creek (Schwartz and Coppersmith, 1984), Willow Creek (Machette, 1984), and Red Canyon. The ~15 km (9.6 mi) gap in Holocene-age faulting between the southern Nephi and northern Levan segments suggests zero slip at the segment boundary.*

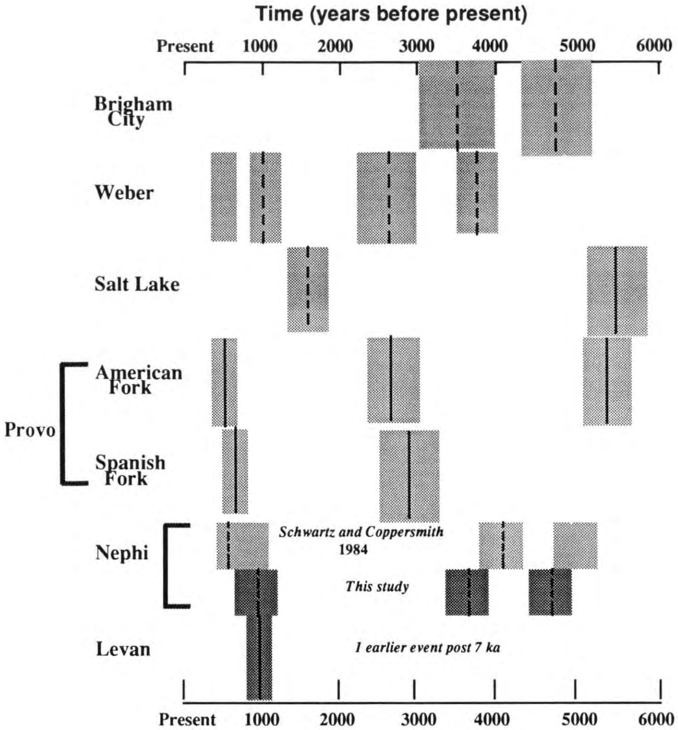


Figure 13. *Holocene paleoseismic history of the central eight segments of the Wasatch fault zone as modified from Machette and others (1989). On the Nephi segment, this study suggests a slightly older range of ages for event 1 and slightly younger range of ages for events 2 and 3. A flurry of faulting activity is suggested for 7 of the 8 segments between 500 and 1500 years ago.*

ACKNOWLEDGMENTS

This study was supported by contract #14-8-0001-G1096 from the U.S. Geological Survey, National Earthquake Hazard Reduction Program to Dr. Steve Forman, INSTAAR, University of Colorado. Other support was made possible through a University of Colorado Excellence in Research grant and a Sigma Xi grant in aid of research. Trench excavations, one radiocarbon date, some field expenses, and manuscript preparation fees were paid for by the Utah Geological Survey.

I am indebted to Jim McCalpin for his help in selecting locations for trench excavations and help in logging the stratigraphy at Skinner Peaks. Michael Machette helped log the stratigraphy at Red Canyon as well as offered valuable suggestions for trench locations and encouragement throughout the project. I would like to thank William Lund of the Utah Geological Survey for his financial and moral support during the summer of 1987. I extend my sincerest gratitude to Dave Schwartz who provided critical insights and alternative interpretations of the tectonics of both the Levan and Nephi segments. Jim Ruzika offered his strong back, good humor, and use of his airplane during the 1987 field season. I thank Dr. Steve Forman for unlimited access to the Thermoluminescence Dating Laboratory at INSTAAR and to Dr. Randolph Ware, UNAVCO for his financial support.

REFERENCES

Aitken, M.J., 1974, Physics and archeology (2nd ed.): Oxford University Press, London, 291 p.

Aitken, M.J., 1985, Thermoluminescence dating: Academic Press, London, 359 p.

Bucknam, R.C., 1978, Northwestern Utah seismic studies: U.S. Geological Survey Summaries of Technical Reports, v. 7, p. 64.

Cluff, L.S., Brogan, G.E., and Glass, C.E., 1970, Wasatch fault, northern portion — Earthquake fault investigation and evaluation, prepared for the Utah Geological and Mineral Survey: Woodward Clyde and Associates, Oakland California, 27 p., 21 maps, scale 1:24,000.

Crone, A.J., and Machette, M.N., 1984, Surface faulting accompanying the Borah Peak earthquake, central Idaho: Geology, v. 12, p. 664-667.

Currey, D.R., and Oviatt, G.C., 1985, Durations, average rates, and probable causes of Lake Bonneville expansions, still-stands, and contractions during the last deep-lake cycle, 32,000 to 10,000 years ago, *in* Kay, P.A., and Diaz, N.F., editors, Problems and Prospects for Predicting Great Salt Lake Levels — Proceedings of a NOAA Conference held March 26-29, 1985: Center for Public Affairs and Administration, University of Utah, Salt Lake City, UT, p. 9-24.

Debenham, N.C., and Walton, A.J., 1983, TL properties of some windblown sediments: PACT (Journal of the European Study Group of Physical, Chemical and Mathematical Techniques Applied to Archaeology), v. 9, p. 531-538.

Fedotov, S.A., 1968, The seismic cycle, quantitative seismic zoning, and long-term seismic forecasting, *in* Medvedev, S., editor, Seismic Zoning of the USSR: Izdatelstvo "Nauka," Moscow.

Forman, S.L., Jackson, M.E., and Maat, Paula, 1988, The potential of using thermoluminescence to date buried soils developed on colluvial and fluvial sediments from Utah and Colorado, U.S.A.: Preliminary results: Quaternary Science Reviews, v. 7, p. 287-293.

Forman, S.L., Jackson, M.E., and McCalpin, James, 1986, Thermoluminescence studies on colluvial and alluvial sediments from Utah and Colorado: Preliminary results: Geological Society of America, Abstracts and Programs, v. 19, no. 5, p. 254.

Forman, S.L., Machette, M.N., Jackson, M.E., and Maat, Paula, 1989, An evaluation of thermoluminescence dating of paleoearthquakes on the American Fork segment, Wasatch fault zone, Utah: Journal of Geophysical Research, v. 94, B2, p. 1622-1630.

Forman, S.L., Wintle, A.G., Thorleifson, L.H., and Wyatt, P.H., 1987, Thermoluminescence properties and age estimates for Quaternary raised marine sediments, Hudson Bay lowland, Canada: Canadian Journal of Earth Sciences, v. 24, p. 2405-2411.

Giffen, Charles, Kaufman, Aaron, and Broecker, Wallace, 1963, Delayed coincidence counter for the assay of actinon and thoron: Journal of Geophysical Research, v. 68, p. 1749-1757.

Hanson, K.L., and Schwartz, D.P., editors, 1982, Guidebook to late Pleistocene and Holocene faulting along the Wasatch Front and vicinity — Little Cottonwood Canyon to Scipio, Utah: prepared by Woodward-Clyde Consultants, San Francisco, California for the AGU Chapman Conference on Fault Behavior and the Earthquake Generation Process, Snowbird, Utah, variously paginated.

Hatheway, A.W., and Leighton, F.B., 1979, Trenching as an exploratory method: Geological Society of America Reviews in Engineering Geology, v. IV, p. 169-195.

Hintze, L.F., 1980, Geologic map of Utah: Utah Geological and Mineral Survey, scale 1:500,000.

Huntley, D.J., Berger, G.W., Divigalpitiya, W.M.R., and Brown, T.A., 1983, Thermoluminescence dating of sediment: PACT (Journal of the European Study Group of Physical, Chemical and Mathematical Techniques Applied to Archaeology), v. 9, p. 607-618.

Huntley, D.J., and Wintle, A.G., 1981, The use of alpha scintillation counting for measuring Th-230 and Pa-231 contents of ocean sediments: Canadian Journal of Earth Sciences, v. 18, p. 419-432.

Jackson, M.E., 1988, Thermoluminescence dating of Holocene paleoseismic events on the Levan and Nephi segments of the Wasatch fault zone, Utah: Unpublished Ms thesis, University of Colorado, Boulder, CO, p. 121.

Keaton, J.R., Currey, D.R., and Olig, S.J., 1987, Paleoseismicity and earthquake hazards evaluation of the West Valley fault zone, Salt Lake City urban area, Utah: Report to the U.S. Geological Survey for contract no. 14-08-0001-22048, 55 p. and 33 p. appendix.

Lund, W.R., Black, B.D., and Schwartz, D.P., 1990, Late Holocene displacement on the Provo segment of the Wasatch fault zone at Rock Canyon, Utah County, Utah: Geological Society of America Abstracts with Programs, v. 22, no. 6, p. 37.

Lund, W.R., and Schwartz, D.P., 1987, Fault behavior and earthquake recurrence at the Dry Creek site, Salt Lake segment, Wasatch fault zone, Utah: Geological Society of America Abstracts with Programs, v. 19, no. 5, p. 317.

Lund, W.R., Schwartz, D.P., Budding, K.E., and Mulvey, W.E., 1989, Fault behavior and earthquake recurrence on the Wasatch fault zone (WFZ) at Mapleton, Utah: Geological Society of America Abstracts with Programs, v. 21, no. 5, p. 109.

Machette, M.N., 1984, Preliminary investigations of late Quaternary slip rates along the southern part of the Wasatch fault zone, central Utah, *in* Hayes, W.W., and Gori, T.L., editors, Proceedings of Conference XXVI, A Workshop "Evaluation of Regional and Urban Earthquake Hazards and Risk in Utah: U.S. Geological Survey Open-File Report 84-763, p. 391-406.

——1987, Recent studies of the late Quaternary history of the Wasatch fault zone — A review: Geological Society of America Abstracts with Programs, v. 19, no. 5, p. 317.

Machette, M.N., and Lund, W.R., 1987, Late Quaternary history of the American Fork segment of the Wasatch fault zone, Utah: Geological Society of America Abstracts with Programs, v. 19, no. 5, p. 317.

Machette, M.N., Personius, S.F., and Nelson, S.T., 1987, Quaternary geology along the Wasatch fault zone — Segmentation, recent investigations, and preliminary conclusions, *in* Gori, P.L., and Hays, W.W., editors, Assessing Regional Earthquake Hazards and Risk Along the Wasatch Front, Utah: U.S. Geological Survey Open-File Report 87-585, v. I, p. A-1-72.

Machette, M.N., Personius, S.F., Nelson, A.R., Schwartz, D.P., and Lund, W.R., 1989, Segmentation models and Holocene movement history of the Wasatch fault zone, Utah, *in* Schwartz, D.P., and Sibson, R.H., editors, Fault Segmentation and Controls of Rupture Initiation and Termination: U.S. Geological Survey Open-File Report 89-315, p. 229.

Machette, M.N., Personius, S.F., Scott, W.E., and Nelson, A.R., 1986, Quaternary geology along the Wasatch Front: Evidence for 10 fault segments and large-scale changes in slip rate along the Wasatch fault zone: U.S. Geological Survey Administrative Report, prepared for 1986 Earthquake Hazards Conference, Salt Lake City, Utah, 7 p.

Madson, D.B., and Currey, D.R., 1979, Late Quaternary glacial and vegetation changes, Little Cottonwood Canyon area, Wasatch Mountains, Utah: Quaternary Research, v. 12, no. 2, p. 245-270.

McCalpin, J.P., 1986, Thermoluminescence (TL) dating in seismic hazard evaluations — An example from the Bonneville basin, Utah: Proceedings of the 22nd Symposium on Engineering Geology and Soils Engineering, Boise, Idaho, p. 156-176.

——1987, Geologic criteria for recognition of individual paleoseismic events in extensional environments, *in* Crone, A.J., and Omdahl, E.M., editors, Proceedings of Conference XXXIX, Directions in Paleoseismology: U.S. Geological Survey Open-File Report 87-672, p. 102-114.

Naeser, C.W., Bryant, Bruce, Crittenden, M.D., Jr., and Sorenson, M.L., 1983, Fission-track ages of apatite in the Wasatch Mountains, Utah: An uplift study: Geological Society of America Memoir 157, p. 29-36.

Nelson, A.R., Klauk, R.H., Lowe, Michael, and Garr, J.D., 1987, Holocene history of displacement on the Weber segment of the Wasatch fault zone at Ogden, northern Utah: Geological Society of America Abstracts with Programs, v. 19, no. 5, p. 322.

Ostenaa, D.A., 1990, Late Holocene displacement history, Water Canyon site, Wasatch fault, Utah: Geological Society of America Abstracts with Programs, v. 22, no. 6, p. 42.

Oviatt, C.G., McCoy, W.D., and Reider, R.G., 1987, Evidence for a shallow early or middle Wisconsin lake in the Bonneville basin: Quaternary Research, v. 27, p. 248-262.

Parry, W.T., and Bruhn, R.L., 1987, Fluid inclusion evidence for minimum 11 km vertical offset on the Wasatch fault, Utah: Geology, v. 15, p. 67-50.

Personius, S.F., 1988, Preliminary surficial geologic map of the Brigham City segment and adjacent parts of the Weber and Collinston segments, Wasatch fault zone, Box Elder and Weber Counties, Utah: U.S. Geological Survey Miscellaneous Field Studies Map MF-2042, scale 1:50,000.

Personius, S.F., and Gill, H.E., 1987, Holocene displacement on the Brigham City segment of the Wasatch fault zone near Brigham City, Utah: Geological Society of America Abstracts with Programs, v. 19, no. 5, p. 326.

Personius, S.F., and Scott, W.E., 1990, Preliminary surficial geologic map of the Salt Lake City segment and parts of adjacent segments of the Wasatch fault zone, Davis, Salt Lake, and Utah Counties, Utah: U.S. Geological Survey Miscellaneous Field Studies Map MF-2114, scale 1:50,000.

Savage, J.C., Lisowski, Michael, and Prescott, W.H., 1985, Strain accumulation in the Rocky Mountain States: Journal of Geophysical Research, v. 90, no. B12, p. 10,310-10,320.

Schwartz, D.P., and Coppersmith, K.J., 1984, Fault behavior and characteristic earthquakes — Examples from the Wasatch and San Andreas fault zones: Journal of Geophysical Research, v. 89, no. B7, p. 5681-5698.

——1986, Seismic hazards — New trends in analysis using geologic data, *in* Active Tectonics: National Academy Press, Washington, D.C., p. 215-230.

Schwartz, D.P., Hanson, K.L., and Swan, F.H. III, 1983, Paleoseismic investigations along the Wasatch fault zone — an update; *in* Gurgel, K.D., editor, Geologic Excursions in Neotectonics and Engineering Geology in Utah, Geological Society of America Rocky Mountain and Cordilleran Sections Meeting, Salt Lake City, Utah, Field Trip Guidebook — Part IV: Utah Geologic and Mineral Survey Special Studies 62, p. 45-48.

Schwartz, D.P., and Lund, W.R., 1988, Paleoseismicity and earthquake recurrence at Little Cottonwood Canyon, Wasatch fault zone, Utah, *in* Machette, M.N., editor, In the Footsteps of G.K. Gilbert — Lake Bonneville and Neotectonics of the Eastern Basin and Range Province: Utah Geological and Mineral Survey Miscellaneous Publication 88-1, p. 82-85.

Scott, W.E., McCoy, W.D., Shroba, R.R., and Rubin, Meyer, 1983, Reinterpretation of the exposed record of the two last lake cycles of Lake Bonneville, western United States: Quaternary Research, v. 20, no. 3, p. 261-285.

Scott, W.E., and Shroba, R.R., 1985, Surficial geologic map of an area along the Wasatch fault zone in the Salt Lake Valley, Utah: U.S. Geological Survey Open-File Report 85-448, pamphlet and 2 plates, scale 1:24,000.

Shelkoplyas, V.N., and Morozov, G.V., 1965, Some results of an investigation of Quaternary deposits by the thermoluminescence method, *in* Materials on the Quaternary Period of the Ukraine: VIIth International Quaternary Association Congress, Naukova, Duma, Kiev, p. 83-90.

Sieh, Kerry, Stuiver, Minze, and Brillinger, David, 1989. A more precise chronology of earthquakes produced by the San Andreas fault in southern California: Journal of Geophysical Research, v. 94, p. 603-623.

Singhvi, A.K., Sharma, Y.P., and Agrawal, D.P., 1982, Thermoluminescence dating of sand dunes in Rajastan, India: Nature, v. 295, p. 313-315.

Smith, R.B., and Bruhn, R.L., 1984, Intraplate extensional tectonics of the eastern Basin and Range — Inferences on structural style from seismic reflection data, regional tectonics, and thermomechanical models of brittle-ductile deformation: Journal of Geophysical Research, v. 89, p. 5733-5762.

Stuiver, Minze, and Reimer, P.J., 1986, A computer program for radiocarbon age calibration: Radiocarbon, v. 28, p. 1022-1033.

Swan, F.H., III, Schwartz, D.P., and Cluff, L.S., 1980, Recurrence of moderate to large earthquakes produced by surface faulting on the Wasatch fault zone: Bulletin of the Seismological Society of America, v. 70, p. 1431-1462.

Wallace, R.E., 1977, Profiles and ages of young fault scarps in north central Nevada: Geological Society of America Bulletin, v. 88, p. 102-107.

Wesson, R.L., 1988, Dynamics of fault creep: Journal of Geophysical Research, v. 93, no. 38, p. 8929-8951.

Wintle, A.G., and Catt, J.A., 1985, Thermoluminescence dating of soils developed in the Late Devensian loess at Pegwell Bay, Kent: Journal of Soil Science, v. 36, p. 293-298.

Wintle, A.G., and Huntley, D.J., 1979, Thermoluminescence dating of a deep sea sediment core: Nature, v. 279, p. 710-712.

——1980, Thermoluminescence dating of ocean sediments: Canadian Journal of Earth Sciences, v. 17, p. 348-360.

Wintle, A.G., and Proszynska, H., 1983, TL dating of loess in Germany and Poland: PACT (Journal of the European Study Group of Physical, Chemical and Mathematical Techniques Applied to Archaeology), v. 9, p. 547-554.

Zoback, M.L., 1983, Structure and Cenozoic tectonism along the Wasatch fault zone, Utah: Geological Society of America Memoir 157, p. 3-27.

Appendix 1

Dose-rate data for samples from the Water Canyon and Mapleton Canyon trenches, Spanish Fork subsegment, Deep Creek exposure and Skinner Peaks trench, Levan segment, and the Red Canyon trench, Nephi segment, Wasatch fault zone, Utah.

Sample	Bulk alpha count (ks/cm[2])	Th[(1)] (ppm)	U[(1)] (ppm)	U/S[(2)]	K (%)	H_2O (%)	a value[(3)]	Dose Rate[(4)] (Gy/ka)
ITL-49	0.61 ± 0.012	6.81 ± 1.11	3.10 ± 0.34	0.99	2.09 ±0.02	15 ± 3	0.121 ±0.01	2.20 ±0.15
ITL-71	0.71 ± 0.013	8.44 ± 1.24	3.48 ± 0.39	1.03	1.87 ±0.02	15 ± 3	0.100 ±0.01	4.74 ±0.18
ITL-97		5.39 ± 1.02	3.32 ± 0.32	1.01	1.96 0.02	10 ± 3	0.070 ±0.01	3.89 ±0.13
ITL-69	0.86 ± 0.016	3.11 ± 1.01	6.33 ± 0.33	1.01	1.78 ±0.02	15 ± 3	0.225 ±0.01	7.05 ±0.21
ITL-70	0.59 ± 0.012	2.78 ± 0.71	3.87 ± 0.23	1.06	1.84 ±0.02	15 ± 3	0.130 ±0.01	4.23 ±0.14
ITL-50	0.39 ± 0.010	4.94 ± 0.84	2.04 ± 0.26	0.97	1.59 ±0.02	10 ± 3	0.250 ±0.01	4.27 ±0.09
ITL-64	0.73 ± 0.015	9.63 ± 1.47	3.30 ± 0.45	0.98	2.26 ±0.02	10 ± 3	0.120 ±0.01	5.48 ±0.11
ITL-65	0.87 ± 0.016	10.58 ± 1.53	4.20 ± 0.50	1.02	2.67 ±0.03	10 ± 3	0.260 ± 0.01[(5)]	8.84 ±0.20
ITL-48	0.64 ± 0.012	4.19 ± 1.10	4.26 ± 0.34	0.99	1.43 ±0.02	15 ± 3	0.091 ±0.01	3.76 ±0.17
ITL-66	0.60 ± 0.012	6.77 ± 1.12	3.06 ± 0.35	1.00	1.47 ±0.02	15 ± 3	0.090 ±0.01	3.62 ±0.20
ITL-67	0.52 ± 0.011	4.99 ± 0.97	3.04 ± 0.35	1.01	1.31 ±0.01	15 ± 3	0.225 ±0.01[(5)]	3.24 ±0.19
ITL-88	0.60 ± 0.012	4.97 ± 0.99	3.60 ± 0.29	1.00	1.49 ±0.01	15 ± 3	0.110 ±0.01	3.80 ±0.31
ITL-90	0.61 ± 0.011	4.38 ± 0.84	3.82 ± 0.25	1.14	0.94 ±0.01	15 ± 3	0.081 ±0.01	2.73 ±0.22

(1) Th and U calculated from bulk alpha count rate assuming secular equilibrium.
(2) Unsealed versus sealed bulk alpha count ratio. Ratios of >0.95 indicate little or no radon loss.
(3) Alpha radiation efficiency factor as defined by Aitken and Bowman (1975)
(4) Dose rate includes a 0.14 ± 0.01 Gy/ka contribution from cosmic radiation.
(5) Replicate a value determinations.
All errors are at one sigma.

Appendix 2

Laboratory-reported and calendar-corrected radiocarbon dates for samples cited in this study.

Lab Sample Number		Material Sampled	Lab Reported Radiocarbon age	MRTC[1] (years)	Calibrated[2] calendar age (yrs B.P.)	Location
Beta-24200		Charcoal	1850 ± 70	-----	1733 +167/-173	Skinner Peaks
Beta-24201		Charcoal	3720 ± 90	100	3949 +169/-173	Skinner Peaks
Schwartz and Coppersmith (1984)		Charcoal	1750 ± 350	-----	1646 +454/-346	Pigeon Creek
Schwartz and Coppersmith (1984)		Charcoal	7300 ± 1000	-----	not converted	Deep Creek
Beta-25185	JRC-16	A horizon	3550± 150	200	3622 +357/-356	Red Canyon
Beta-24186	JRC-17	A horizon	1380± 120	100	1261 +139/-311	Red Canyon
Beta-25402	JRC-14	A horizon	2900± 90	100	2907 +300/-148	Red Canyon
Beta-25184	JRC-15	A horizon	3690± 170	100	3896 +513/-427	Red Canyon
Bucknam (1978)		Charcoal	4580± 250	-----	5300 +600/-739	Red Canyon
WC-12-80-7[(4)]		A horizon	3640±75	100	3981 +241/-250	North Creek
		A horizon	1650± 50	100	1545 +152/-125	North Creek
WC-12-80-7		A horizon[(3)]	3894 +288/-278	100	4374 +671/-795	North Creek
		A horizon[(3)]	1645 +270/-262	100	1541 +752/-551	North Creek
WC-12-80-9		Charcoal[(3)]	1389 +181/-177	-----	1289 +398/-358	North Creek
WC-12-80-5		Charcoal	1350± 70	-----	1287 +95/-127	North Creek
WC-12-80-6		Charcoal	1110± 60	-----	1032 +138/-101	North Creek

1 Mean residence time correction for organic material in soil A horizons
2 Conventional radiocarbon ages converted to calender years (Stuiver and Reimer, 1986)
All errors are at 1 sigma
3 Samples dated by accelerator mass spectrometry.
4 All WC dates from Hanson and Schwartz (1984)

Description of Units

Unit 1 Scarp-derived colluvium and slope wash. Light brown to brown (7.5 YR 5/2, dry), poorly sorted, subangular to angular, medium to fine sand with 20% subangular to rounded alluvial clasts.

Unit 2 Scarp-derived colluvium (crack fill). Light brown (7.5 YR 5/2, dry), massive, poorly consolidated, angular to sub-angular clasts derived from units 3 and 4 on the upthrown block of the fault.

Unit 3 Debris Flow. Light grey to pale brown (10 YR 6/2, dry), very poorly sorted, subangular to angular limestone clasts (5-10cm), in a fine sand and silt matrix. A thin, but continuous, carbonate-rich C-horizon topped by a moderately developed soil A-horizon overlies unit 3.

Unit 4 Debris Flow. The same as unit 3 but with a slightly smaller clast size (< 5 cm).

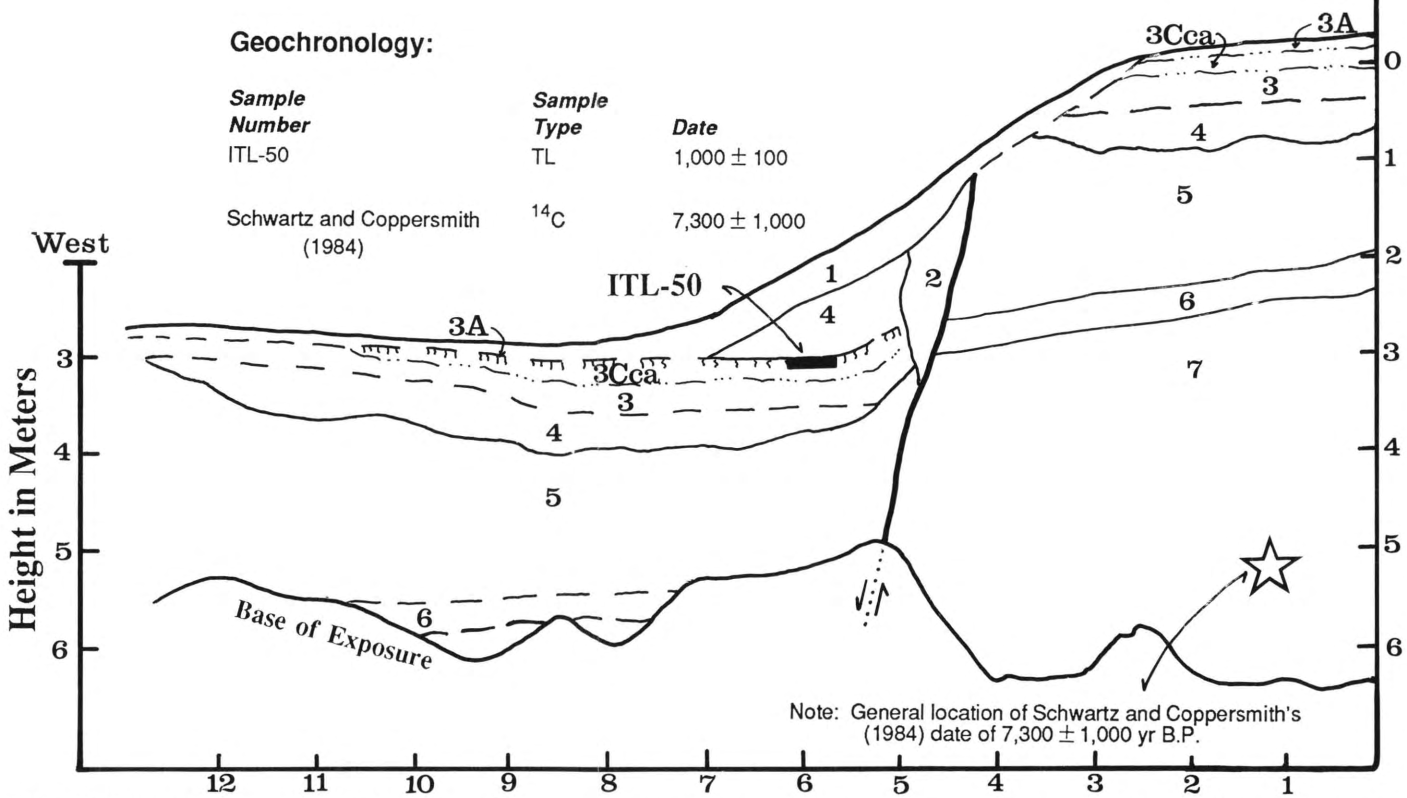
Unit 5 Debris Flow. Light grey to pale brown (10 YR 6/2, dry), thick, massive, poorly sorted, and poorly stratified unit composed of angular to subangular clasts (5-20 cm) of limestone in a fine sand and silt matrix.

Unit 6 Debris Flow. The same as unit 5, but with more consistent clast size (10 cm).

Unit 7 Debris Flow. Light grey to pale brown (10 YR 6/2, dry), thick, massive, poorly sorted, and poorly stratified unit composed of angular to subangular clasts (5-20 cm) of limestone in a fine sand and silt matrix. The unit contains ~1% large clasts (20-50cm).

Geochronology:

Sample Number	*Sample Type*	*Date*
ITL-50	TL	1,000 ± 100
Schwartz and Coppersmith (1984)	^{14}C	7,300 ± 1,000



Note: 0.5 m of antithetic displacement on an eastward dipping fault located 50 m to the west.

Scale 1.5 cm = 1 m

Plate 1. Stratigraphic Log of the Deep Creek Natural Exposure, Wasatch Fault Zone, Levan Segment, Utah.

Description of Units

Unit 1 Slope-wash and eolian deposits. Light brown (10 YR 5/2, dry), moderately sorted, medium to fine sand with evidence of disturbance by range animals.

Unit 2-1 Scarp-derived colluvium. Light brown to brown (7.5 YR 5/2, dry), poorly sorted, subangular to angular, medium to fine sand with 10% subangular to rounded, alluvial clasts of chert, tuff, and sandstone.

Unit 2-2 Scarp-derived colluvium (crack fill). Light brown to brown (7.5 YR 5/2, dry), very poorly sorted, subangular to angular sand in a fine silt matrix, with 20% angular to rounded clasts of sandstone and tuff (<10 cm).

Unit 3 Mudflow deposit. Light to medium brown (7.5 YR 5/2, dry), massive, fine-to medium-grained sand with a mantle of eolian sand. Vertical crack structures in the mid- to-bottom portion or the unit suggest this was the paleo-ground surface prior to the most recent event.

Unit 4 Mudflow-Fluvial deposit. White to tan (10 YR 6/2, dry), massive, fine sand and silt mudflow with interbedded channels of subangular to angular fluvial deposits.

Unit 5 Mudflow. Grey to light brown (10 YR 5/2, dry), massive, poorly sorted, medium to fine sand with 20% pink, subangular, tuff gravel.

Unit 6 Mudflow-Fluvial deposit. Light grey to pale brown (10 YR 7/2.5, dry), massive, medium to fine sand and silt with interbedded layers and pockets of pink, subangular, tuff gravel.

Unit 7 Fluvial deposit. Light grey to pale brown (10 YR 7/2.5, dry), moderately stratified, rounded, fluvial channel deposit of chert, tuff, and sandstone.

Unit 8 Mudflow deposit. Brown to olive (10 YR 7/2, dry), massive, course to medium sand, with 10% pink, subangular, tuff gravel.

Unit 9 Mudflow-Fluvial deposit. Light brown to olive (10 YR 6/3, dry), massive, poorly sorted, subangular course gravel, composed mainly of pink volcanic tuff with minor green sandstone clasts.

Unit 10 Fluvial and eolian deposit. Light brown to green (10 YR 6/3, dry), massive, poorly consolidated, fine-to medium-grained sandstone with one large (10 cm) clast of chert.

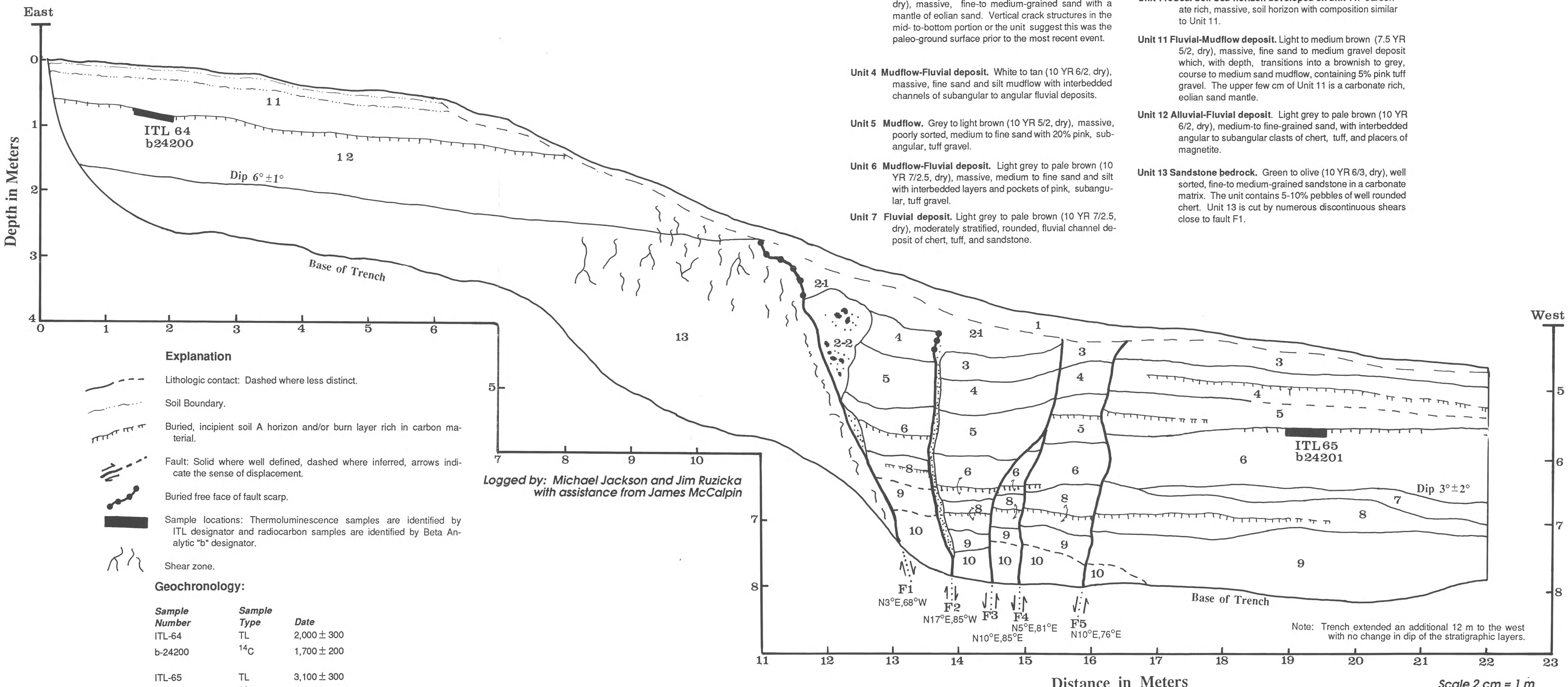
Unit 11sA Soil A-horizon developed on unit 11. Poorly developed (1-2 cm), disturbed soil A-horizon, dark grey to black (10 YR 3/1, dry).

Unit 11sCca. Soil Cca-horizon developed on unit 11. Carbonate rich, massive, soil horizon with composition similar to Unit 11.

Unit 11 Fluvial-Mudflow deposit. Light to medium brown (7.5 YR 5/2, dry), massive, fine sand to medium gravel deposit which, with depth, transitions into a brownish to grey, course to medium sand mudflow, containing 5% pink tuff gravel. The upper few cm of Unit 11 is a carbonate rich, eolian sand mantle.

Unit 12 Alluvial-Fluvial deposit. Light grey to pale brown (10 YR 6/2, dry), medium-to fine-grained sand, with interbedded angular to subangular clasts of chert, tuff, and placers of magnetite.

Unit 13 Sandstone bedrock. Green to olive (10 YR 6/3, dry), well sorted, fine-to medium-grained sandstone in a carbonate matrix. The unit contains 5-10% pebbles of well rounded chert. Unit 13 is cut by numerous discontinuous shears close to fault F1.



Explanation

- Lithologic contact: Dashed where less distinct.
- Soil Boundary.
- Buried, incipient soil A horizon and/or burn layer rich in carbon material.
- Fault: Solid where well defined, dashed where inferred, arrows indicate the sense of displacement.
- Buried free face of fault scarp.
- Sample locations: Thermoluminescence samples are identified by ITL designator and radiocarbon samples are identified by Beta Analytic "b" designator.
- Shear zone.

Geochronology:

Sample Number	*Sample Type*	*Date*
ITL-64	TL	2,000 ± 300
b-24200	^{14}C	1,700 ± 200
ITL-65	TL	3,100 ± 300
b-24201	^{14}C	4,000 ± 200

Plate 2. Log of Trench Across the Wasatch Fault Zone at Skinner Peaks, Levan Segment, Utah.

Description of Units

Unit 1 Mudflow and slope-wash deposit. Grey to light brown (10 YR 5/2, dry), poorly sorted, subangular sandy silt, with 10% 1-2 cm limestone clasts.

Unit 2 Scarp-derived colluvium. Dark grey to black (10 YR 3/1, dry), gravelly to sandy silt containing 25% angular to subangular pebbles and cobbles (<10 cm).

Unit 3s Soil developed on unit 3. Dark grey to black (10 YR 3/1, dry), gravelly to sandy silt, organic rich, with <1% limestone clasts (< 3 cm). Soil is capped by a layer of <10 cm long clasts.

Unit 3 Scarp derived colluvium. Dark grey to black (10 YR 3/1, dry), gravelly, sandy silt containing 25% angular to subangular pebbles and cobbles (<10 cm).

Unit 4s Soil developed on unit 4. Dark grey to black (10 YR 3/1, dry), gravelly, sandy silt, organic rich, with <1% limestone clasts (< 3 cm). Soil is capped by a layer of <10 cm long clasts.

Unit 4 Scarp-derived colluvium. Dark grey to black (10 YR 3/1, dry), gravelly, sandy silt, containing 25% angular to subangular pebbles and cobbles (<20 cm).

Unit 5 Scarp-derived colluvium (crack fill). Greyish brown (10 YR 5/2, dry), very poorly sorted mixture of limestone gravel and clasts (<20 cm) and sandstone clasts (<10 cm) in a poorly consolidated sandy matrix.

Unit 6s-A Soil A-horizon developed on unit 6. Poorly to moderately developed soil A-horizon, dark grey to black (10 YR 3/1, dry).

Unit 6sCca- Soil Cca-horizon developed on unit 6. Carbonate rich, massive, soil horizon with composition similar to Unit 6.

Unit 6 Alluvial and colluvial deposits. Light grey to pale brown (10 YR 7/2.5, dry), angular to sub angular limestone clasts in a matrix of fine-to medium-grained limestone sand. The unit contains a few large boulders (<40 cm). All clasts and boulders contain continuous 1-2 mm coatings of carbonate.

Unit 7 Alluvial and colluvial deposit. Light grey to pale brown (10 YR 7/2.5, dry), poorly stratified, angular cobbles and gravel with 2% very large (20 cm) limestone clasts and <1% boulders (25cm).

Unit 8 Alluvial-fan deposit. Light grey to pale brown (10 YR 6/2, dry), poorly sorted, subangular gravel with 2% limestone clasts (10-20 cm) in a matrix of fine sand and silt cemented with calcium carbonate.

Unit 9 Alluvial-fan and mudflow deposits. Grey to light brown (10 YR 5/2, dry), poorly sorted, subangular gravel with 5% limestone clasts (<15 cm) with a few limestone clasts >25 cm, interbedded with fine to medium sand and subangular gravel deposits containing 2% limestone clasts. All clasts have 1mm coatings of calcium carbonate .

Unit 10 Alluvial deposit. Light grey to light red (10 YR 6/2, dry), well stratified, gravel and silty sand with 1% limestone and sandstone clasts (< 10 cm).

Unit 11 Alluvial-fan and mudflow deposits. Light brown to reddish brown (7.5 YR 5/2, dry), interbedded sequence of poorly sorted, subangular gravel, in a red sand matrix and reddish, sandy silt fluvial channels containing 2% gravel and 1% sandstone clasts (up to 5 cm long).

Unit 12 Alluvial-fan deposit. Light grey to pale brown (10 YR 6/2, dry), poorly sorted, subangular gravel with 2% limestone clasts (10-20 cm) in a matrix of fine sand and silt cemented with calcium carbonate.

Unit 13 Fluvial deposit. Light grey to light brown (10 YR 6/2, dry), well sorted and stratified pebble gravel (limestone) in a red sandy matrix. Less than 1% clasts (<5mm).

Unit 14 Alluvial-fan deposit. Greyish brown (10 YR 7/2, dry), poorly sorted, subangular gravel with 3% limestone clasts < 5 cm in carbonate matrix.

Unit 15 Fluvial deposit. Light grey (10 YR 7/2.5, dry), massive, well sorted limestone gravel in a matrix of red sand.

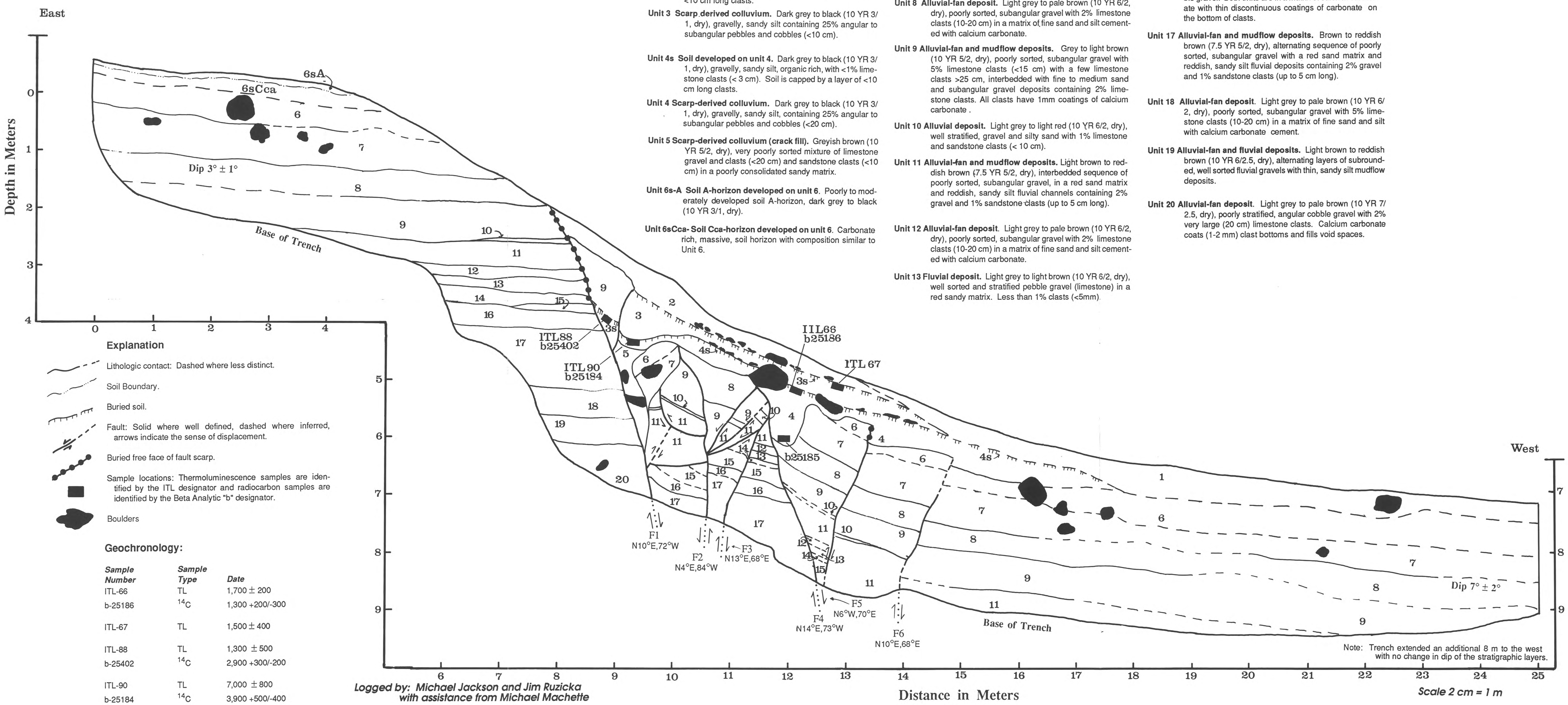
Unit 16 Alluvial-fan and mudflow deposits. Greyish brown (10 YR 5/2, dry), interbedded, course, sandy silt containing 2% limestone clasts (up to 10 cm) and silty, sandy cobble gravel. Both units are in a matrix of calcium carbonate with thin discontinuous coatings of carbonate on the bottom of clasts.

Unit 17 Alluvial-fan and mudflow deposits. Brown to reddish brown (7.5 YR 5/2, dry), alternating sequence of poorly sorted, subangular gravel with a red sand matrix and reddish, sandy silt fluvial deposits containing 2% gravel and 1% sandstone clasts (up to 5 cm long).

Unit 18 Alluvial-fan deposit. Light grey to pale brown (10 YR 6/2, dry), poorly sorted, subangular gravel with 5% limestone clasts (10-20 cm) in a matrix of fine sand and silt with calcium carbonate cement.

Unit 19 Alluvial-fan and fluvial deposits. Light brown to reddish brown (10 YR 6/2.5, dry), alternating layers of subrounded, well sorted fluvial gravels with thin, sandy silt mudflow deposits.

Unit 20 Alluvial-fan deposit. Light grey to pale brown (10 YR 7/2.5, dry), poorly stratified, angular cobble gravel with 2% very large (20 cm) limestone clasts. Calcium carbonate coats (1-2 mm) clast bottoms and fills void spaces.



Explanation

Lithologic contact: Dashed where less distinct.

Soil Boundary.

Buried soil.

Fault: Solid where well defined, dashed where inferred, arrows indicate the sense of displacement.

Buried free face of fault scarp.

Sample locations: Thermoluminescence samples are identified by the ITL designator and radiocarbon samples are identified by the Beta Analytic "b" designator.

Boulders

Geochronology:

Sample Number	*Sample Type*	*Date*
ITL-66	TL	1,700 ± 200
b-25186	^{14}C	1,300 +200/-300
ITL-67	TL	1,500 ± 400
ITL-88	TL	1,300 ± 500
b-25402	^{14}C	2,900 +300/-200
ITL-90	TL	7,000 ± 800
b-25184	^{14}C	3,900 +500/-400
b-25185	^{14}C	3,600 +400/-400

Plate 3. Log of Trench Across the Wasatch Fault Zone at Red Canyon, Nephi Segment, Utah.