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

William R. Lund, David P. Schwartz, William E. Mulvey, Karin E. Budding, and Bill D. Black

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UTAH GEOLOGICAL AND MINERAL SURVEY

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UTAH GEOLOGICAL AND MINERAL SURVEY
606 Black Hawk Way
Salt Lake City, Utah 84108-1280

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INTRODUCTION TO PALEOSEISMOLOGY OF UTAH SPECIAL STUDIES SERIES

William R. Lund, Series Editor
Utah Geological and Mineral Survey

This report on the Holocene behavior of the Provo segment of the Wasatch fault zone near Mapleton, Utah is the first in the Utah Geological and Mineral Survey "Paleoseismology of Utah" Special Studies series. Paleoseismology is the study of prehistoric earthquakes. Only large earthquakes that cause coseismic surface rupture or otherwise disturb the ground surface (liquefaction, earthquake-induced landslides, tectonic subsidence) leave evidence in the geologic record of their occurrence (Allen, 1986). Paleoseismic investigations commonly include mapping of fault scarps and associated geologic deposits, trenching across active fault traces, geomorphic analysis of fault-related or fault-modified features, and investigation of fault-zone structures in both consolidated and unconsolidated deposits (Slemmons and Depolo, 1986; Schwartz, 1988). Techniques for dating Quaternary sediments are used to constrain the timing of past events (Bucknam and Anderson, 1979a; Scott, 1981; Hanks and others, 1984; McCalpin, 1986; Forman, 1989; Hanks and Andrews, 1989). The resulting information on earthquake timing, recurrence, displacement, and fault geometry permit the characterization of seismic source zones and determination of the long-term earthquake potential of Quaternary faults (Schwartz and Coppersmith, 1986; Schwartz, 1988). Information on the size and timing of paleoearthquakes and on the ground deformation that accompanies them is fundamental to the evaluation of earthquake hazards and risk.

The Wasatch Front is located within a recognized zone of earthquake activity, the Intermountain seismic belt (Smith and Sbar, 1974), and is faced with the threat of significant property damage and loss of life due to large earthquakes (Crone, 1983a; Hays and Gori, 1984; Gori and Hays, 1987). Nearly eighty-five percent of Utah's population of 2.2 million people live within 16 km (10 mi) of the Wasatch fault zone; the longest and most active extensional fault in the western United States. Although the Wasatch fault zone has not experienced a surface-faulting earthquake in historical time, there is abundant geologic evidence to indicate that numerous events have occurred in the recent geologic past. Many other active faults are located in Utah (Anderson and Miller, 1979; Hecker, in press), and the historical seismic record (Arabasz and others, 1979; Richins and others, 1981, 1984; Brown and others, 1986) indicates that an unknown number of buried faults capable of causing damaging earthquakes are also present in the state.

In 1983, the U.S. Geological Survey (USGS) and the Utah Geological and Mineral Survey (UGMS) initiated a 5-year research program under the auspices of the National Earthquake Hazard Reduction Program to assess earthquake hazard and risk along the Wasatch Front. Although broadly based in all aspects of earthquake science, the "Wasatch Front Earthquake Hazard and Risk Assessment Program" particularly served to renew interest in the earthquake history of the Wasatch fault zone and the region's other active faults. Scientists from government, academia, and the private sector conducted a number of paleoseismic studies on the Wasatch and other fault zones as part of the Wasatch Front Program. The purpose of this Special Studies series is to make the results of those studies available to the general public, the scientific and engineering communities, and individuals and organizations charged with mitigating earthquake hazards and risk along the Wasatch Front.

SUMMARY OF PALEOSEISMIC INVESTIGATIONS IN UTAH

EARLY INVESTIGATIONS

Geologists have long recognized the hazard that large earthquakes present to Utah's heavily populated Wasatch Front. Grove Karl Gilbert, working in the interior basins of the American West more than 100 years ago, was the first geologist to recognize "piedmont" scarps as evidence that mountains in the Basin and Range physiographic province are the result of incremental movements along range-bounding faults during earthquakes (Gilbert, 1875, 1890, 1928). The Wasatch fault zone, particularly near Salt Lake City, played a major role in the formulation of Gilbert's theories about mountain building and earthquakes. In U.S. Geological Survey Monograph 1 (1890, p. 342), he provides a classic description of young faulting exposed along the Wasatch fault zone, and states "It was at the base of the Wasatch Range that the fault scarp was first discriminated as a distinct topographic feature ...." Gilbert showed an extraordinary understanding of the geologic processes and principles required for earthquake-hazard evaluations (Gilbert, 1890, 1907, 1909) and, in an 1883 newspaper article, he issued the first earthquake warning to Salt Lake City (Gilbert, 1884; Petersen, 1983). Recurrence intervals, elapsed time since the most recent surface-faulting event, fault segmentation, seismic gaps, fault geometry, ground deformation, and characteristic earthquakes are all topics of current paleoseismic research that were touched upon, in one form or another, by Gilbert (Wallace, 1980; Lund, 1988; Machette, 1988a; Scott, 1988).

MODERN STUDIES

Nearly a half century passed between the posthumous publication of Gilbert's last report on the geology of the western interior basins, *Studies of Basin and Range Structure* (1928), and a revival of awareness and concern about earthquake hazards along the Wasatch Front. R.E. Marsell, principally in his role as a consultant to the Utah Water and Power Board, was among the first to again draw attention to earthquake hazards in Utah (Marsell 1948, 1949, 1964a, 1964b, 1966a, 1966b). In recognition of his efforts to create a public awareness of not only earthquakes, but of all geologic hazards, the Utah Geological Association dedicated its benchmark volume *Environmental Geology of the Wasatch Front, 1971* (Hilpert, 1972) to his memory. Papers in the volume my Morisawa, Van Horn, Hintze, Cluff and others, and Cook deal with young faulting and earthquakes along the Wasatch Front.

The Utah Geological and Mineral Survey is required by law (Utah Code annotated 63-73-1 through 10) to "investigate areas of geologic and topographic hazards that could affect the citizens of Utah...." In the 1960s, the UGMS began the systematic study of the state's geologic hazards and also initiated a policy of making geologic-hazard evaluations for critical public facilities (fire stations, hospitals, water treatment plants, etc.). That policy continues to the present, with evaluations done when requested by local and state government agencies. Evidence of past surface faulting and other earthquake effects, and the potential hazard from future large seismic events, are an important part of those studies. Pertinent reports and maps published by the UGMS include: Osmond and others (1965), Kaliser (1967, 1971, 1976a, 1976b, 1980), Utah Geological and Mineral Survey (no date, 1969), Rogers (1978), Everitt (1979), Kaliser and Lund (1979a, 1979b), Lund (1979a, 1979b, 1979c, 1981a, 1981b), Gill (1980), Christenson (1983, 1986), Christenson and Deen (1983), Klauk (1985, 1986), Mabey (1985), Lund and Case (1986), Mulvey and Gill (1986), Nelson (1986, 1987), Klauk and Mulvey (1987), Robison (1987), Olig (1989), and Bruhn and others (1990). The UGMS sponsored two Governor's Conferences on Geologic Hazards, one in 1967 (UGMS, 1970) and the other in 1983 (UGMS, 1983); earthquake hazards were a principal topic of discussion at both meetings.

The UGMS also maintains a computerized geologic-hazards bibliography that includes geotechnical studies by private consulting firms for facilities located throughout the state. Consultants' reports currently in the bibliography that pertain directly to investigations of active faults include: Dames and Moore (1978, 1979), Woodward-Clyde Consultants (1980), Chen and Associates (1987), EarthStore (1987a, 1987b), and Kaliser (1987).

By the early 1970s it was evident that insufficient information was available about the Wasatch and other active faults in Utah to permit detailed seismic-hazard analyses for critical facilities. To begin filling that data gap, the UGMS contracted with Woodward-Clyde Consultants (later Woodward-Lundgren and Associates) in 1970 to make an earthquake fault investigation and evaluation of the Wasatch fault zone. Using specially flown, low-sun-angle aerial photographs, Woodward-Clyde produced a series 1:24,000 scale strip maps of the Wasatch fault zone extending from Gunnison to Brigham City (Cluff and others, 1970, 1973). Later, under contract to the USGS, Woodward-Clyde used the same technique to extend the mapping northward to Malad City, Idaho and northeastward to include faults in Cache Valley (Cluff and others, 1974). Although field checked at only selected locations, the Woodward-Clyde maps were generally the most detailed source of information available for the Wasatch and East Cache fault zones for many years. One notable exception is a map of the Sugar House quadrangle by Van Horn (1972) showing the relative ages of faults in that part of the Salt Lake City urban area. Cluff and others (1975) used the results of the Woodward-Clyde mapping to make a preliminary evaluation of recent activity on the Wasatch fault zone.

Between 1978 and 1983, Woodward-Clyde geologists, again under contract to the USGS, excavated trenches at four sites on the Wasatch fault zone and at one site on the East Cache fault zone. Those trench studies were not only the first detailed paleoseismic investigations conducted on active faults in Utah, but were also the first investigations of that kind made on normal-slip faults anywhere in the world. Results of the trenching provided the first detailed information on the timing and size of paleoearthquakes for both fault zones (Swan and others, 1978, 1979a, 1979b, 1980a, 1981a, 1981b, 1983; Schwartz and others, 1979, 1982, 1983, 1984; Hanson and others, 1981, 1982; Hanson and Schwartz, 1982).

In early synthesis papers, Cluff and others (1980) used the new Woodward-Clyde paleoseismology data to estimate the probability of the occurrence of surface faulting on the Wasatch fault zone, and Swan and others (1980b) speculated on the probable number of seismically independent segments that may exist along fault. In a later paper, Schwartz and Coppersmith (1984) used geodetic, geomorphic, geophysical, and paleoseismic data to identify six major segments of the Wasatch fault zone. They also introduced the concept of "characteristic earthquakes" to explain the absence of moderate-size earthquakes on the Wasatch fault zone in both the historical and geological records.

Brigham Young University researchers conducted a number of studies on the Wasatch and other active faults in Utah during the 1970s and 1980s. Hamblin (1976) examined patterns of displacement along the Wasatch fault zone, and Anderson (1977) studied the compound-faceted spurs characteristic of the Wasatch fault zone in north-central Utah as a possible indicator of recurrent fault movement. Hamblin and Best (1978) compared patterns and rates of recurrent movement along the Wasatch, Hurricane, and Sevier fault zones. Piekarski (1980) used scarp morphology to compare the relative ages of last movement on the Wasatch, Fish Springs, and House Range fault zones. Benson and Baer (1987) employed close-order gravity surveys to define buried faults in valley-fill sediments.

Initiation of the "Wasatch Front Earthquake Hazard and Risk Assessment Program" in 1983 greatly increased the number of paleoseismic investigations conducted on the Wasatch fault zone. Site-specific and summary reports resulting from the program include: Machette (1984), Personius (1986), Gill (1987), Lund and Schwartz (1987), Machette and Lund (1987), Nelson and others (1987), Parry and Bruhn (1987), Personius and Gill (1987), Machette (1988b), Nelson (1988), Personius (1988a), Schwartz and Lund (1988), Schwartz and others (1988), Forman and others (1989), Lund and others (1989, 1990, 1991), Jackson (in press), Personius (1991). Paleoseismic studies were also made on the Hansel Valley (McCalpin, 1985; Robison, 1986; McCalpin and others, 1987), West Valley (Keaton and others, 1987; Keaton and Currey, 1989), East Cache (McCalpin, 1987), James Peak (Nelson and Sullivan, 1987), East Great Salt Lake (Pechmann and others, 1987), Morgan (Sullivan and Nelson, 1987), and East and West Bear Lake (McCalpin, 1990) fault zones. The surficial geology of the Wasatch fault zone was mapped from Payson to just north of Deweyville at 1:24,000 scale and published at 1:50,000 scale (Personius, 1988b; Machette, 1989; Personius and Scott, 1990; Nelson and Personius, 1990). The surficial geology along part of the East Cache fault zone was mapped by Lowe (1987) at 1:24,000 scale, and McCalpin (1989) mapped the entire fault at 1:50,000 scale.

Initial results of the new geologic mapping and data from several of the early Wasatch Front Program paleoseismic investigations led Machette and others (1987) to propose a twelve-segment model for the Wasatch fault zone. The model has been modified by the results of more recent paleoseismic investigations (Lund and others, 1989; Lund and others, in press), and the Wasatch fault zone is now thought to consist of ten segments (Machette and others, 1989; Lund, 1990). New information on timing of paleoearthquakes produced by the Wasatch Front Program provides a chronology of surface-rupturing events for the six most active central segments of the Wasatch fault zone during the past 6000 years (Schwartz, 1988; Machette and others, 1989, in press).

The U.S. Bureau of Reclamation (USBR) has conducted paleoseismic investigations in Utah as part of siting studies for new facilities and for seismic-hazard evaluations of existing USBR dams. Faults investigated by Bureau geologists include the Strawberry fault (Nelson, 1982; Nelson and Van Arsdale, 1986), late Cenozoic faults in the back valleys of the Wasatch Range (Sullivan, 1982), late Cenozoic faults in the Heber and Keetley Valleys (Sullivan and Nelson, 1983), the Bear River fault (West, 1984, 1987), Quaternary faults on Towanta Flat (Nelson and Weisser, 1985), the Darby and Absaroka thrust faults (West, 1986a), the faults bordering Joes Valley graben (Foley, 1987), the James Peak fault (Nelson and Sullivan, 1987), the Morgan fault (Sullivan and Nelson, 1987), and the Provo segment of the Wasatch fault zone (Ostenaa, 1990). Seismotectonic studies conducted for dams and reservoirs include Soldier Creek Dam (Nelson and Martin, 1982); Taskeech Dam and Reservoir (Martin and others, 1985); Joes Valley, Scofield, and Huntington North Dams (Foley and others, 1986); Mona Dam and Reservoir (Sullivan and Baltzer, 1986); Monks Hollow Dam (Sullivan and others, 1987); and Jordanelle Dam (Sullivan and others, 1988a). West (1986b) evaluated the earthquake hazard to dams in southwestern Wyoming and north-central Utah, and Sullivan and others (1988b) prepared a synthesis report on the seismotectonics of the central Utah region.

Although Utah contains numerous potentially active Quaternary faults (Anderson and Miller, 1979, 1980; Hecker, in press), only a few detailed fault studies have been made outside of the Wasatch Front region. Everitt and Kaliser (1980) mapped Quaternary faults in Tooele and Rush Valleys and trenched the West Mercur fault zone. The USGS has trenched the Drum Mountains (Crone, 1983b) and Fish Springs (Bucknam and others, 1989) fault zones in west-central Utah, and Earth Sciences Associates (1982) examined the Hurricane, Washington, and Grand Wash fault zones as part of a seismic-safety investigation for eight U.S. Soil Conservation Service dams in southwestern Utah. An exposure of an unnamed fault in a wood-chip disposal pit at Sanford Creek near Panguitch in Garfield County was studied as part of a joint USGS/UGMS investigation of Quaternary faults and folds in the Cedar City 1° x 2° quadrangle (Anderson and Christenson, 1989). Sterr (1980) studied the late Quaternary history and morphologic evolution of fault scarps in southwestern Utah, and Bucknam and others (1980) examined patterns of faulting in western Utah. Ertec Western, Inc. (1981) estimated the ages of faults over a broad area in west-central Utah based on fault-scarp morphology, alluvial-fan morphology, and relations to pluvial-lake shoreline features as part of the siting study conducted for the MX Missile System. Currey (1982) compiled selected Lake Bonneville geomorphic features that have relevance to neotectonic analysis in western Utah. Crone and Harding (1984) examined the relationship of late Quaternary fault scarps to subjacent scarps in the Great Basin portion of Utah. Machette (1985) used stratigraphic and morphometric relations to estimate the age of faulting in the Beaver Basin in south-central Utah, and Anderson and Barnhard (1987) investigated the neotectonic framework of the central Sevier Valley. Arabasz and others (1987) compiled and/or estimated seismotectonic parameters for several faults in Tooele County to evaluate seismicity relevant to the siting of a Superconducting Supercollider. Barnhard (1988a, 1988b) reported on fault scarps along the west side of the Oquirrh and Stansbury Mountains. Nakata and others (1982) published a regional Quaternary fault map of the Basin and Range and Rio Grande Rift physiographic provinces that includes western Utah. Fault scarps formed on unconsolidated deposits in Utah have been mapped by Bucknam (1977), Anderson and Bucknam (1979), Bucknam and Anderson (1979b), Barnhard (1985), and Barnhard and Dodge (1988). Machette and others (1984) mapped fault scarps on unconsolidated deposits in the Beaver quadrangle in central Utah. Oviatt (1989, 1990, 1991) mapped fault scarps on unconsolidated segments in the Sevier and Black Rock Deserts of Millard County, and in the Scipio Valley area of Millard and Juab Counties. Sack (1990) did the same in Tule Valley, also in Millard and Juab Counties. Anderson and Miller (1979) and Hecker (in press) have prepared statewide compilations of Quaternary faults which include estimates of the time of most recent surface faulting.

CALL FOR PAPERS

The scope of the "Paleoseismology of Utah" Special Studies Series extends beyond the recently completed "Wasatch Front Earthquake Hazard and Risk Analysis Program." It is hoped that other investigators will take advantage of this series to publish the results of their studies of Quaternary faults in Utah. Numerous paleoseismic studies have been conducted in Utah, but only a few have been published in readily available scientific journals. The results of many investigations exist only as abstracts of talks presented at professional meetings, or as "gray" literature in agency reports of limited distribution. The authors of those studies are urged to contact the UGMS regarding publishing the results of their work in this series. The UGMS will also publish the results of future paleoseismic investigations in this series, so that new information on the past behavior of active faults in Utah is made available to those responsible for mitigating earthquake hazards and risk in Utah.

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FAULT BEHAVIOR AND EARTHQUAKE RECURRENCE ON THE PROVO SEGMENT OF THE WASATCH FAULT ZONE AT MAPLETON, UTAH COUNTY, UTAH

by

William R. Lund, David P. Schwartz**, William E. Mulvey*, Karin E. Budding**, and Bill D. Black**

ABSTRACT

The results of a cooperative program between the Utah Geological and Mineral Survey and the United States Geological Survey to excavate trenches across the proposed Spanish Fork segment of the Wasatch fault zone (WFZ) provide new data on the size and timing of prehistoric earthquakes in the southern part of Utah Valley. The study was undertaken to determine if the subdivision of the original Provo segment of the WFZ into the proposed American Fork, Provo (restricted sense), and Spanish Fork segments could be substantiated on the basis of differences in timing of past earthquakes on the proposed segments.

Trenches were excavated across the WFZ on the proposed Spanish Fork segment at two closely spaced sites in Mapleton, Utah. At the north site, the WFZ is defined by a single scarp and graben in Holocene alluvial-fan deposits. Calendar-calibrated radiocarbon dates on charcoal from pre- and post-event deposits constrain the timing of the most recent surface faulting at 600 (± 80) yr B.P. Scarp profiles and the height of a buried scarp free face exposed by trenching indicate that an estimated 1.4 to 3.0 m (4.6-9.8 ft) of net vertical tectonic displacement occurred during the most recent surface-faulting earthquake (MRE) at the north trench site. At the south trench site, the WFZ consists of two subparallel scarps that displace an upper Holocene alluvial fan. Trench exposures showed evidence for two prehistoric surface-faulting earthquakes. The MRE could not be dated at the south trench site. The penultimate surface-faulting earthquake occurred shortly before 2820 (+150, -130) yr B.P., based on radiocarbon and thermoluminescence age estimates obtained from a buried soil that was displaced prior to burial. The weak zonal development of the buried soil suggests that the penultimate earthquake occurred close in time to soil burial. The MRE at Mapleton is estimated to have had a maximum surface-wave magnitude of M_S 6.9 to 7.3 and an inferred moment magnitude of M_S 6.8 to 7.3.

The time range for the MRE at the Mapleton site (600 ± 80 yr B.P.) overlaps that of the MRE at the American Fork Canyon site (550 ± 100 yr B.P.) on the proposed American Fork segment about 50 km (30 mi) to the north. Although less well constrained, timing of the penultimate event at Mapleton (shortly before 2820 +150, -130 yr B.P.) partially overlaps that of the penultimate event at the American Fork Canyon site (2650 ± 150 yr B.P.). The similarity in timing of the past two surface-faulting earthquakes at these two sites strongly suggests that both locations experienced the same surface-rupturing events and, therefore, define a single rupture segment (original Provo segment) of the Wasatch fault zone (WFZ) as suggested by Schwartz and Coppersmith (1984).

INTRODUCTION

This report presents the results of a cooperative study by the Utah Geological and Mineral Survey and the United States Geological Survey to investigate the timing and size of past earthquakes on the proposed Spanish Fork segment of the Wasatch fault zone (WFZ). It is one of several such studies conducted by the two agencies as part of a multi-year regional assessment of earthquake hazard and risk along Utah's Wasatch Front (Gori and Hays, 1987).

The WFZ was originally partitioned by Schwartz and Coppersmith (1984) into six independent segments, each believed capable of generating large surface-faulting earthquakes (figure 1). Subsequently, the WFZ was tentatively subdivided by Machette and others (1986) into 12 segments. Three of the new or redefined segments were created by dividing the original Provo segment into the American Fork, Provo (restricted sense), and Spanish Fork segments (figure 1). Scarp morphology and patterns of surface-fault rupture were the principal criteria used to define the new segments. However, conclusive evidence for fault segmentation is only demonstrated by nonsynchronous timing of earthquakes on adjacent sections of a fault. The purpose of this study is to determine the earthquake history of the proposed Spanish Fork segment. The results of this study and similar studies on the American Fork (Machette and Lund, 1987; Machette, 1988; Forman and others, 1989) and Provo (restricted sense) (Lund and others, in

*Utah Geological and Mineral Survey, Salt Lake City, Utah 84108

**United States Geological Survey, Menlo Park, California 94025

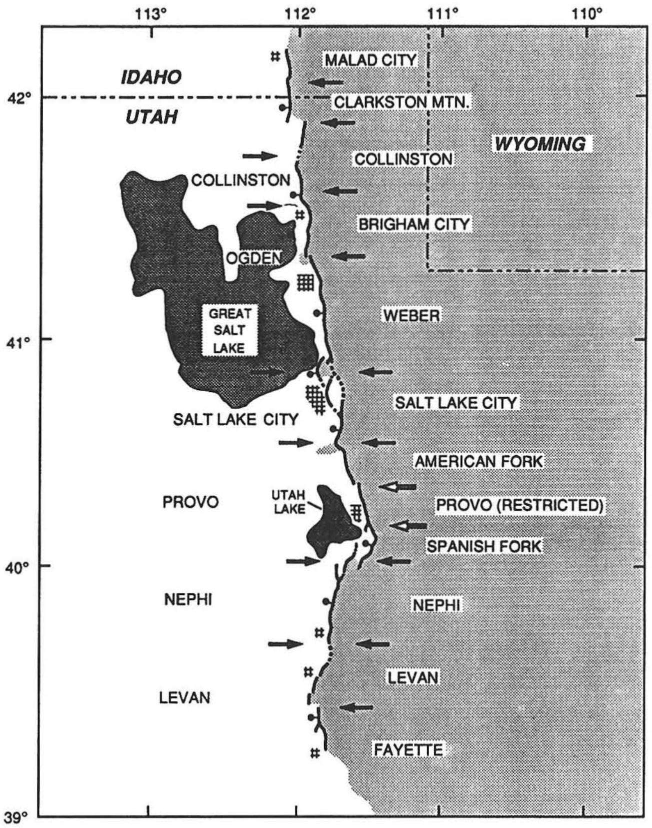


Figure 1. Segmentation of the Wasatch fault zone as proposed by Schwartz and Coppersmith (1984; left column) and Machette and others (1986; right column).

preparation) segments will help determine if the proposed three-segment model is appropriate for the WFZ in Utah Valley. Determining the number and length of the segments comprising the WFZ is important because these parameters are directly related to the frequency and the magnitude of earthquakes that occur on the fault zone. Fewer long segments mean less frequent, but larger, earthquakes. A greater number of short segments means more frequent, but smaller, earthquakes. Such information is critical to the evaluation of earthquake hazards along the Wasatch Front where 80 percent of Utah's population resides (Sargent, 1989).

This investigation included geologic mapping of surficial deposits, profiling fault scarps, excavating five trenches across the WFZ at two closely spaced sites, mapping the geology exposed in the walls of three trenches, and radiocarbon and thermoluminescence (TL) dating of stratigraphic units in the trenches. The stratigraphic dating provides age estimates for past surface-rupturing earthquakes and depositional events. Radiocarbon dates were converted to calendric dates using computer software developed by the Quaternary Isotope Laboratory at the Quaternary Research Center, University of Washington (Stuiver and Reimer, 1986). The software calculates the calendar-calibrated dates to the nearest year (table 1) but, in this report, all calendric dates are rounded to the nearest decade and reported with one sigma error limits (table 1).

SETTING AND GEOLOGY

The Mapleton site is in the southeastern part of Utah Valley within the city limits of Mapleton, Utah (figure 2). Trenches were excavated across the WFZ at two locations about 0.8 km (0.5 mi) apart. Two trenches were excavated at the Mapleton North site and three at the Mapleton South site (figure 3). Both trench sites are below the highest stand of Pleistocene Lake Bonneville, termed the Bonneville shoreline (1552 m or 5092 ft; estimated age 15,300-14,500 yr B.P.; figure 3). Approximately 14,500 years ago, Lake Bonneville breached its outlet in the Zenda-Red Rock Pass area of southern Idaho, rapidly incised to a bedrock sill (Red Rock threshold), and established equilibrium at the Provo shoreline (1445 m or 4740 ft; estimated age 14,500-14,000 yr B.P.) (Scott and others, 1983; Currey and others, 1984; Jarrett and Malde, 1987; Currey and Burr, 1988). The Provo shoreline is lower than, and west of, the Mapleton site. Lowering of Lake Bonneville below the Provo shoreline began about 14,200 years ago (Currey and Burr, 1988) due to climatic changes that caused evaporation to exceed inflow into the lake (Scott and others, 1983). By approximately 13,000 years ago, Lake Bonneville had receded to an elevation below 1372 m (4500 ft), leaving Utah Valley above the level of the shrinking lake (Machette, 1988).

At Mapleton North, the WFZ consists of a west-dipping main fault and an accompanying east-dipping antithetic fault that displace upper and middle Holocene alluvial fans (af_1 and af_2; figure 3). The west-facing main fault scarp is 18 m (60 ft) high and becomes as high as 30 m (100 ft) a few hundred meters to the south, where the fault displaces lake sediments associated with the Bonneville high stand (lbs) and pre-Bonneville alluvial-fan deposits (af_3). A middle Holocene alluvial fan (af_2) has been displaced down-to-the-west by multiple surface-faulting events, leaving the apex of the fan stranded on the upthrown side of the fault. Post-faulting erosion has deeply incised the af_2 fan surface on the upthrown block and has resulted in deposition of an upper Holocene alluvial fan (af_1) which partially buries the af_2 fan on the downthrown block. The af_1 fan has been displaced by the most recent surface-faulting earthquake (MRE), and perhaps by an older event, and is back-tilted to the east. The graben formed by the main and antithetic faults is nearly filled with recent debris-flow deposits and scarp-derived colluvium (algf).

The WFZ at Mapleton South consists of a west-dipping main fault with a west-facing scarp more than 20 m (66 ft) high. A subparallel fault, about 10 m (33 ft) to the west of the main fault, also dips to the west (figure 3) and is expressed at the surface by a 5-m-high (16 ft), west-facing scarp. Both faults displace a small upper Holocene alluvial fan (af_1). The fan surface is back-tilted to the east between the two faults. A wide zone of anomalously low ground parallels the main fault at Mapleton South (figure 3). Although having the general appearance of a graben, the low area does not appear to be bounded by antithetic fault scarps on the west. The absence of evidence for antithetic faulting may be due to modification of the land surface by agricultural activity or inactivity on the faults during the MRE. It is also possible that the western boundary of this postulated graben is one of warping and back-tilting rather than discrete faulting.

In addition to being exposed along the main fault scarp, Bonneville lake sediments crop out in a number of low bluffs west of the WFZ (Machette, 1989; figure 3). There, they consist of fine sand

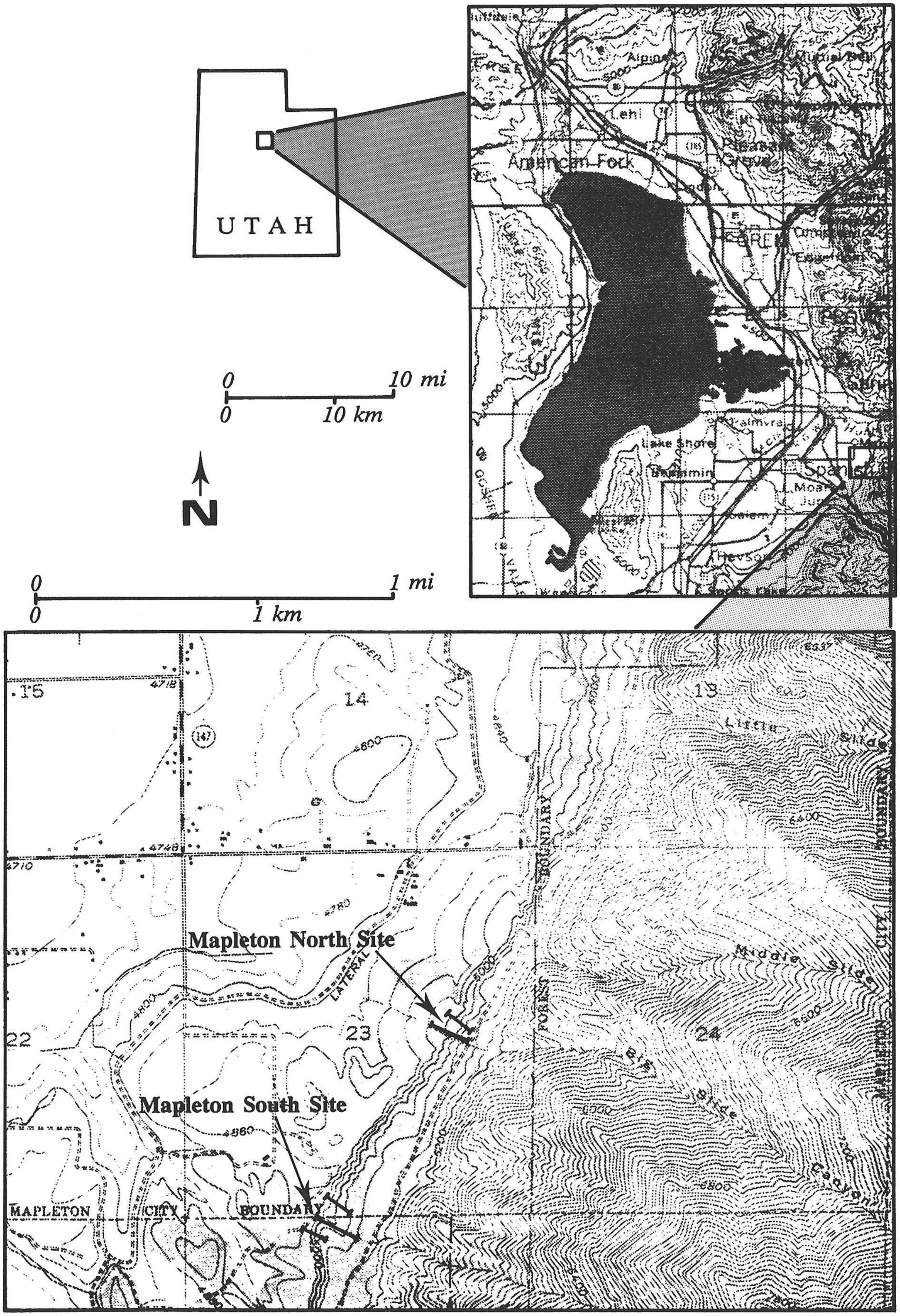


Figure 2. Index and location maps of the Mapleton site, Utah County, Utah.

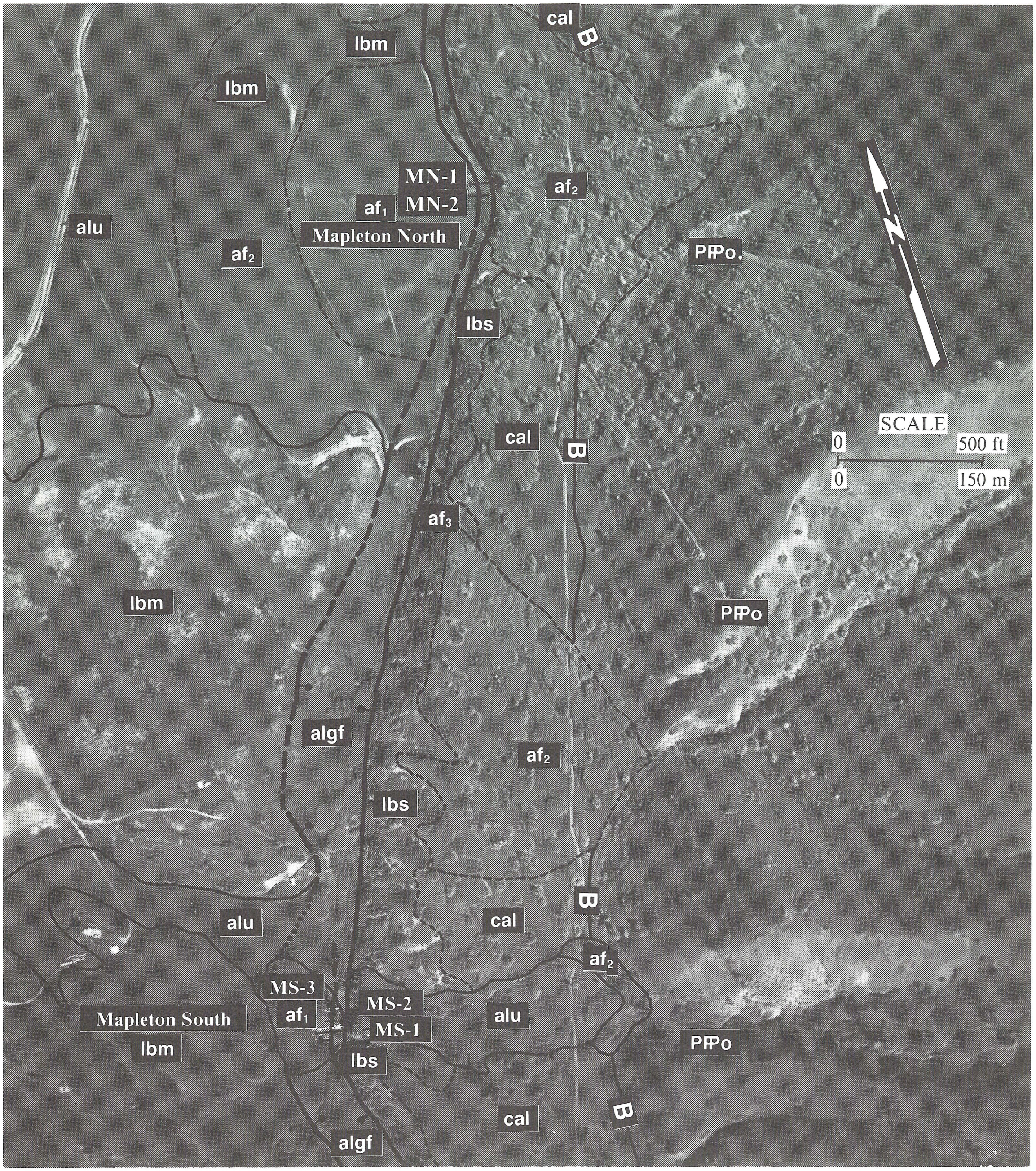


Figure 3. Aerial photograph geologic map of the Mapleton site (geology modified from Davis, 1983; Machette, 1989).

EXPLANATION

Geologic Unit Descriptions

cal Colluvium and alluvium undivided (Holocene to upper Pleistocene): Includes talus, hillslope colluvium, and small alluvial-fan deposits that postdate the highest stand of Lake Bonneville (Bonneville shoreline).

alu Alluvium undivided (Holocene to upper Pleistocene): Fine- to coarse-grained stream alluvium that postdates the high stand of Lake Bonneville and grades to the Provo shoreline; includes local areas of slope-wash colluvium.

algf Graben-fill alluvium and colluvium undivided (upper to middle Holocene): Fine- to coarse-grained alluvium deposited by debris flows or debris floods in graben which resulted from surface faulting along the Wasatch fault zone; includes scarp-derived colluvium adjacent to fault traces.

af_1 Fan alluvium (upper Holocene): Cobbley to locally bouldery gravel, matrix predominantly sand with silt and clay; frequently derived from the erosion of alluvial-fan deposits (af_2) on the upthrown side of the Wasatch fault zone.

af_2 Fan alluvium (middle Holocene): Cobbley to locally bouldery gravel, matrix predominantly sand with silt and clay; deposited following regression of Lake Bonneville to the Provo shoreline; fan surfaces on the upthrown block of the Wasatch fault zone are moderately to deeply entrenched.

af_3 Fan alluvium (upper Pleistocene): Cobbley to locally bouldery gravel, matrix predominantly sand with silt and clay deposited prior to and, at higher elevations, during the transgression of Lake Bonneville to the Bonneville shoreline; exposed in the main scarp of the Wasatch fault zone below the Lake Bonneville sediments.

lbs Lacustrine sand related to the Lake Bonneville high stand (upper Pleistocene): Fine to coarse sand deposited near shore as Lake Bonneville transgressed to and stood at the Bonneville shoreline.

lbm Lacustrine silt and fine sand related to the Lake Bonneville high stand (upper Pleistocene): Thin-bedded silt and fine sand deposited in deep water as Lake Bonneville transgressed to and stood at the Bonneville shoreline.

PIPo Oquirrh Formation (Pennsylvanian and lower Permian): Gray to light-brown quartzitic limestone, brown quartzite, and gray to black limestone and cherty limestone.

Geologic Symbols

Geologic contact, dashed where approximately located, dotted where concealed.

Normal fault, bar and ball on downdropped side, dashed where approximately located, dotted where concealed.

B Bonneville shoreline

CORRELATION OF GEOLOGIC UNITS AT THE MAPLETON SITE

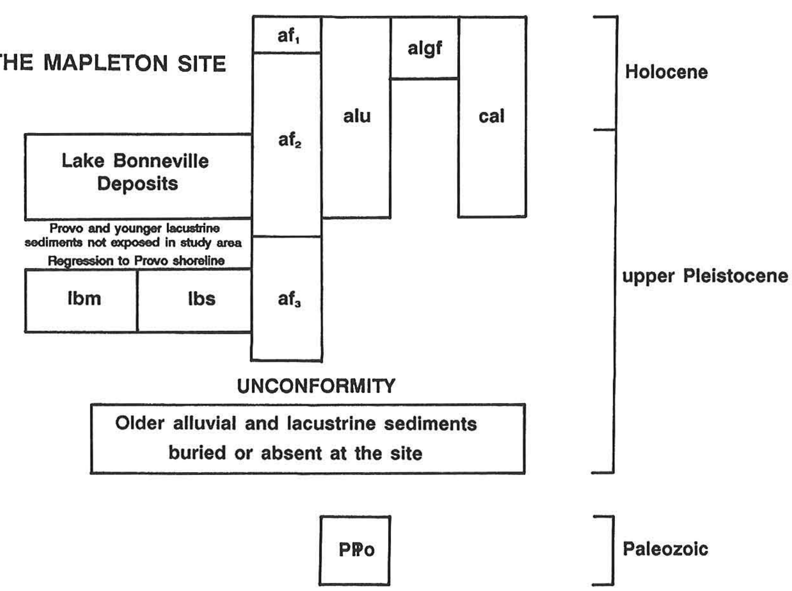


Table 1.
Radiocarbon ages and thermoluminescence (TL) age estimates from the Mapleton North (MN) and Mapleton South (MS) trench sites.

Trench	Field Sample Number	Laboratory Identification Numbers	Material Type and Geologic Unit	Radiocarbon age (^{14}C B.P.)	Calibrated[1] Charcoal and AMRT ages (1 σ error)[2]	TL age estimate	Remarks
MN-1	MN1-RC1	[3]Beta-21306	Charcoal from burn layer	445[4] (±70)	510[4] (+120, -190)	——	Post-MRE
MN-1	MN1-RC2	[5]Pitt-0188	Charcoal from burn layer	490 (± 65)	520 (+120, -60)	——	Post-MRE
MN-1	MN1-RC3	Pitt-0189	Charcoal from unit 4s soil	730 (± 40)	680 (+40, -20)	——	Pre-MRE
MN-2	MN2-RC1	Pitt-0191	Charcoal at unit 6/8 contact	330 (± 50)	430, 360, 330 (+70, -40)	——	Charcoal at same stratigraphic position as burn layer in trench MN-1.
MN-2	MN2-RC2	Beta-21733	Charcoal from unit 2s soil	770 (± 100)	690 (+230, -140)	——	2s soil in trench MN-2 correlates with 4s soil in trench MN-1.
MN-2	MN2-RC3	Pitt-1092	Charcoal from unit 11A	850 (± 35)	740 (+160, -50)	——	Detrital charcoal stratigraphically out of place.
MS-1	MS-RC1	Beta-23528 ETH-3544	Charcoal from unit 4F	1350 (± 100)	1290 (+130, -230)	——	Accelerator Mass Spectrometry (AMS) date.
MS-1	MS-RC2	Beta-23527 ETH-3543	Charcoal from unit 2s soil	2810 (± 95)	2930, 2900, 2890 (+280, -130)	——	AMS date
MS-1	MS-AMRT1	Beta-26117 GRL-787-0	Organics from unit 2s soil	2890 (± 80)	2820 (+150, -130)	——	200 years subtracted from radiocarbon age prior to calendar calibration to account for mean residence time of buried soil.
MS-1	MS-TL1	[6]ITL-70	Unit 2s soil	——	——	3300 (± 300)	Collected at same location as sample MS-AMRT 1

[1]Calibration procedure after Stuiver and Reimer (1986); CALIB & DISPLAY software distributed by Quaternary Isotope Laboratory, Quaternary Research Center, University of Washington.
[2]Radiocarbon age calibrated with CALIB software: 20-year atmospheric record, lab error multiplier of 2, method A used to calculate intercepts and age range, age span of 0 except for MS-AMRT1 for which an age span of 250 years was assigned to the organic soil fraction. See text for a discussion of AMRT-dating considerations. All calendar-corrected dates rounded to the nearest decade.
[3]Beta Analytic Inc., Coral Gables, FL 33124.
[4]All radiocarbon ages are reported in years before present (yr B.P.); by convention, present is considered A.D. 1950.
[5]University of Pittsburgh, Applied Research Center Radiocarbon Laboratory, Pittsburgh, PA 15238.
[6]University of Colorado, Center for Geochronological Research, Boulder, CO 80309.

and silt (lbm) deposited in deep water as Lake Bonneville transgressed to and stood at the Bonneville shoreline (1552 m; 5092 ft). Undifferentiated alluvium (alu) occupies abandoned stream drainages graded to the Provo shoreline west of the WFZ (figure 3), and post-Bonneville colluvium and alluvium (cal) mantle the Bonneville shoreline erosional escarpment. Bedrock in the Wasatch Range east of the Mapleton site is quartzite and limestone of the Pennsylvanian Oquirrh Formation (PPo; figure 3) (Davis, 1983).

SEQUENCE OF DEPOSITION AND FAULTING EXPOSED IN TRENCHES

MAPLETON NORTH

Two trenches, MN-1 and MN-2, were excavated at the Mapleton North trench site (figures 2 and 3). Due to the variable nature of deposition on the af_1 alluvial-fan surface, each excavation exposed a somewhat different stratigraphic sequence of geologic units. For that reason, numbering of the geologic units on the trench logs (figures 4 and 5) is specific to each log. However, some geologic units could be identified in both excavations. Figure 6 shows the correlations that could be made between deposits and faulting events in the two trenches. Detailed descriptions of the geologic units shown on the trench logs are presented in the appendix.

Trench MN-1

Trench MN-1 was 56 m (184 ft) long and extended across the main trace of the WFZ and its associated graben to the west (figures 3 and 4). The trench contained evidence for two surface-faulting earthquakes on this section of the WFZ. The oldest geologic unit (1) exposed in the trench was a debris-flow deposit that postdates the Bonneville shoreline (younger than about 14,200 yr B.P.). Evidence for the penultimate (second to last) surface-faulting earthquake is sparse. It consists of a small deposit of scarp-derived colluvium (unit 2) that overlies unit 1 adjacent to a secondary antithetic fault at station 34.5 (figure 4). Additionally, the antithetic fault offsets unit 1 more than overlying units. The difference in offset indicates that unit 1 was displaced by surface faulting prior to the deposition and faulting of the younger geologic units. No material suitable for radiocarbon or TL dating was found in either units 1 or 2.

Following the penultimate earthquake, a series of debris-flow and fluvial units (units 3 through 7; figure 4) was deposited on the alluvial-fan surface. The absence of soil development on either units 1 or 2 suggests that a comparatively short time separated their deposition and subsequent burial by unit 3. However, soil A horizons (units 4s and 5s) on debris-flow deposits (units 4 and 5) indicate that a significant, but unknown, amount of time elapsed between the first and second surface-faulting earthquakes. Radiocarbon analysis of charcoal collected from unit 4s (station 39; figure 4) gave a calendar-calibrated age of 680 (+40, -20) yr B.P. This soil provided an excellent stratigraphic and chronologic horizon in trench MN-1 (figure 4). The 4s soil was buried by a light-brown debris flow (unit 5) on which a weak soil (unit 5s) formed. Units 3 through 5 were then locally eroded by a stream that subsequently deposited alluvial units 6A and 6B (figure 4). A debris flow (unit 7) exhibiting a coarse-grained, openwork, clast-supported structure was the last unit deposited prior to the most recent surface faulting.

The MRE displaced geologic units 2 through 7 for the first time and created a scarp on the main fault that was at least 6.3 m (20.7 ft) high as indicated by the height of the buried scarp free face at station 4.5 (figure 4). A total of 2.8 m (9.2 ft) of down-to-the-east displacement occurred on the main antithetic fault during the MRE (station 30; figure 4). This antithetic fault created a graben approximately 24 m (78 ft) wide in which younger, post-MRE units were deposited. Small antithetic faults formed both within and west of the graben, and at least one pre-existing antithetic fault near station 34.5 was reactivated during the MRE. Deformation within the main fault zone was complex and involved both discrete slip (normal and reverse) and folding (figure 4). Fault-scarp colluvium from the penultimate earthquake is absent along the main fault and was likely downdropped to an elevation below the base of the trench by the most recent surface faulting. A large fissure created during the MRE at the base of the scarp on the main fault (station 4.5) was filled with scarp-derived colluvium (unit 8) soon after the event. Additional colluvium accumulated as scarps on the main fault and main antithetic fault continued to erode. A debris flow (unit 9) was deposited in the east end of the graben (figure 4). Following deposition of unit 9, a fire crossed the site leaving a charcoal-rich burn layer on the floor of the partially filled graben. The burn layer was marked locally by a thin zone of red, oxidized, baked earth. Charcoal from the burn layer (station 24; figure 4) yielded calendar-calibrated ages of 510 (+120, -190) yr B.P. and 520 (+120, -60) yr B.P. (table 1). The burn layer, which laps onto unit 9, was then buried by a debris flow (unit 10; figure 4). Additional debris flows (units 11 through 14) eventually filled the graben. Unit 14 contained pieces of barbed wire, indicating that it was deposited during historical time.

Trench MN-2

Trench MN-2 was excavated across the western boundary of the MRE graben a few meters south of trench MN-1 (figures 3 and 5). The trench was 16 m (52 ft) long and exposed evidence of the most recent surface faulting. A well-developed soil A horizon (unit 2s) provided a distinctive marker within the exposed stratigraphic sequence (figure 5). This A horizon is correlated with unit 4s in trench MN-1 (figure 6) on the basis of stratigraphic position, relation to surface faulting, and a calendar-calibrated radiocarbon date on charcoal from the unit (station 4.5; figure 5) of 690 (+230, -140) yr B.P. (table 1). Overlying fluvial gravel (unit 4) and debris-flow (unit 5) deposits could be correlated with geologic units 6 and 7 in trench MN-1 (figure 6). A coarse-grained debris-flow/debris-flood deposit (unit 6) in trench MN-2 was the last unit deposited prior to the MRE. It has no stratigraphic equivalent in trench MN-1 (figures 4, 5, and 6).

Offset across the west side of the graben in trench MN-2 was accommodated in stairstep fashion on three antithetic faults (figure 5). Total down-to-the-east displacement was 2.6 m (8.5 ft). The two westernmost faults (stations 5 and 9) produced appreciable scarps along which scarp-derived colluvium (unit 7) accumulated. The easternmost fault (station 2) may have also produced a scarp and colluvium but, if so, they were removed by later erosion. At some point after the MRE, a debris flow (unit 8) was deposited in the graben, burying the scarp-derived colluvium adjacent to the middle scarp (station 5) as well as pieces of detrital charcoal

SOUTH WALL OF MAPLETON NORTH TRENCH 1, WASATCH FAULT ZONE, MAPLETON, UTAH

Mapped by W. R. Lund and D. P. Schwartz, 1987
Planimetric base constructed on a 1 m x 1 m grid using horizontal level lines
Drafted by Bill D. Black

1 Debris Flow (matrix supported)
2 Fault-scarp Colluvium (penultimate event)
3 Debris Flow (matrix supported)
4 Debris Flood (matrix supported)
    4s Soil A-Horizon on units 3 and 4
5 Debris Flow (matrix supported)
    5s Weak Soil A-Horizon on Unit 5
6 Fluvial Gravel
    6A Sandy gravel with cobbles
    6B Sandy gravel (well sorted)
    6U Sandy gravel (sheared)
7 Debris Flow (clast supported)
8 Sheared Fault-zone Material and Fault-scarp Colluvium (most recent event)

Main Fault Zone

8A Fissure fill
8B Block from Unit 1

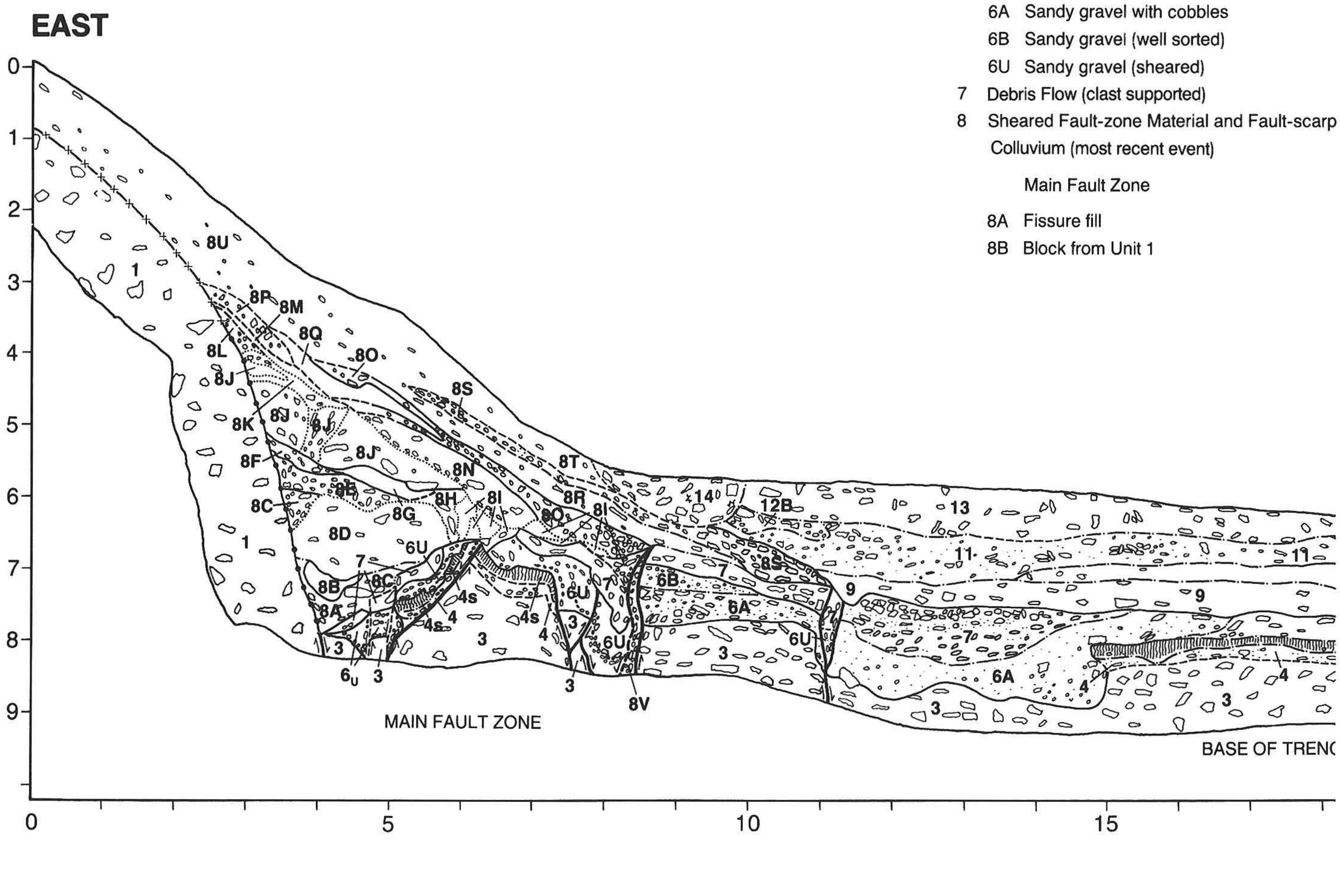


Figure 4.

EXPLANATION

GEOLOGIC UNITS
(See Appendix in text for complete unit descriptions)

8C Fissure fill
8D Block from Unit 3
8E Fissure fill
8F Fault-scarp colluvium
8G Block of Unit 4S Soil A-Horizon
8H Fissure fill
8I Blocks from Unit 7
8J Blocks from Unit 1
8K Fault-scarp colluvium (from Units 1 and 3)
8L Fault-scarp colluvium (from Unit 1)
8M Fault-scarp colluvium
8N Fault-scarp colluvium
8O Fault-scarp colluvium
8P Fault-scarp colluvium
8Q Fault-scarp colluvium
8R Fault-scarp colluvium
8S Fault-scarp colluvium
8T Fault-scarp colluvium
8U Fault-scarp colluvium
8V Fault shear zone

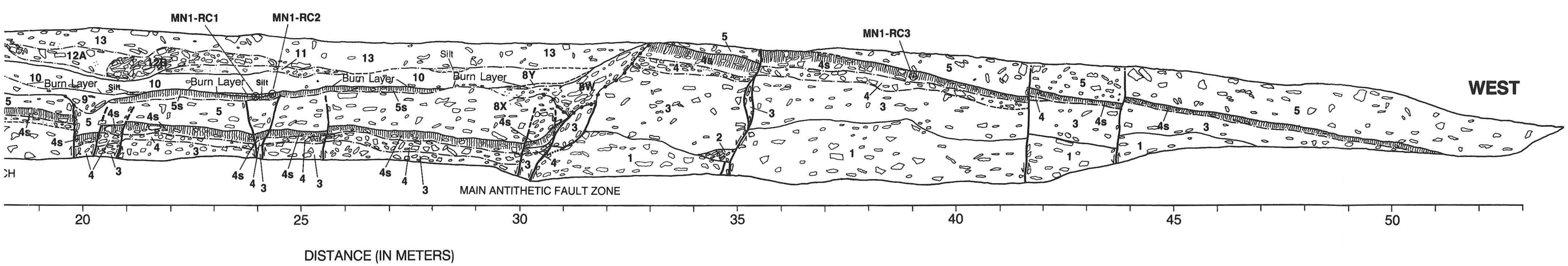
Main Antithetic Fault Zone

8W Fault-scarp colluvium
8X Fault-scarp colluvium
8Y Fault-scarp colluvium
9 Debris Flow (matrix supported)
10 Debris Flow (matrix supported)
11 Debris Flow (matrix supported)
12 Debris Flow
12A Cobbley silty gravelly sand (matrix supported)
12B Boulders and cobbles (clast supported)
13 Debris Flow (matrix supported)
14 Debris Flow (matrix supported; historic)

SYMBOLS

SOIL A-HORIZON
ROCK
FAULT
CRACK
SCARP FREE FACE
ERODED SCARP
SHARP CONTACT (1-3 cm)
GRADATIONAL CONTACT (3-5 cm)
GRADATIONAL CONTACT (5-10 cm)
INDISTINCT CONTACT
CHARCOAL RADIOCARBON DATES (Calendar Calibrated)

MN1-RC1 510 (+120,-190) yr B.P.
MN1-RC2 520 (+120,-60) yr B.P.
MN1-RC3 680 (+40,-20) yr B.P.



SOUTH WALL OF MAPLETON NORTH TRENCH 2, WASATCH FAULT ZONE MAPLETON, UTAH

Mapped by W.E. Mulvey, K.E. Budding, W.R. Lund, and D.P. Schwartz, 1987
Planimetric base constructed on a 1 m x 1 m grid using horizontal level lines
Drafted by Bill D. Black

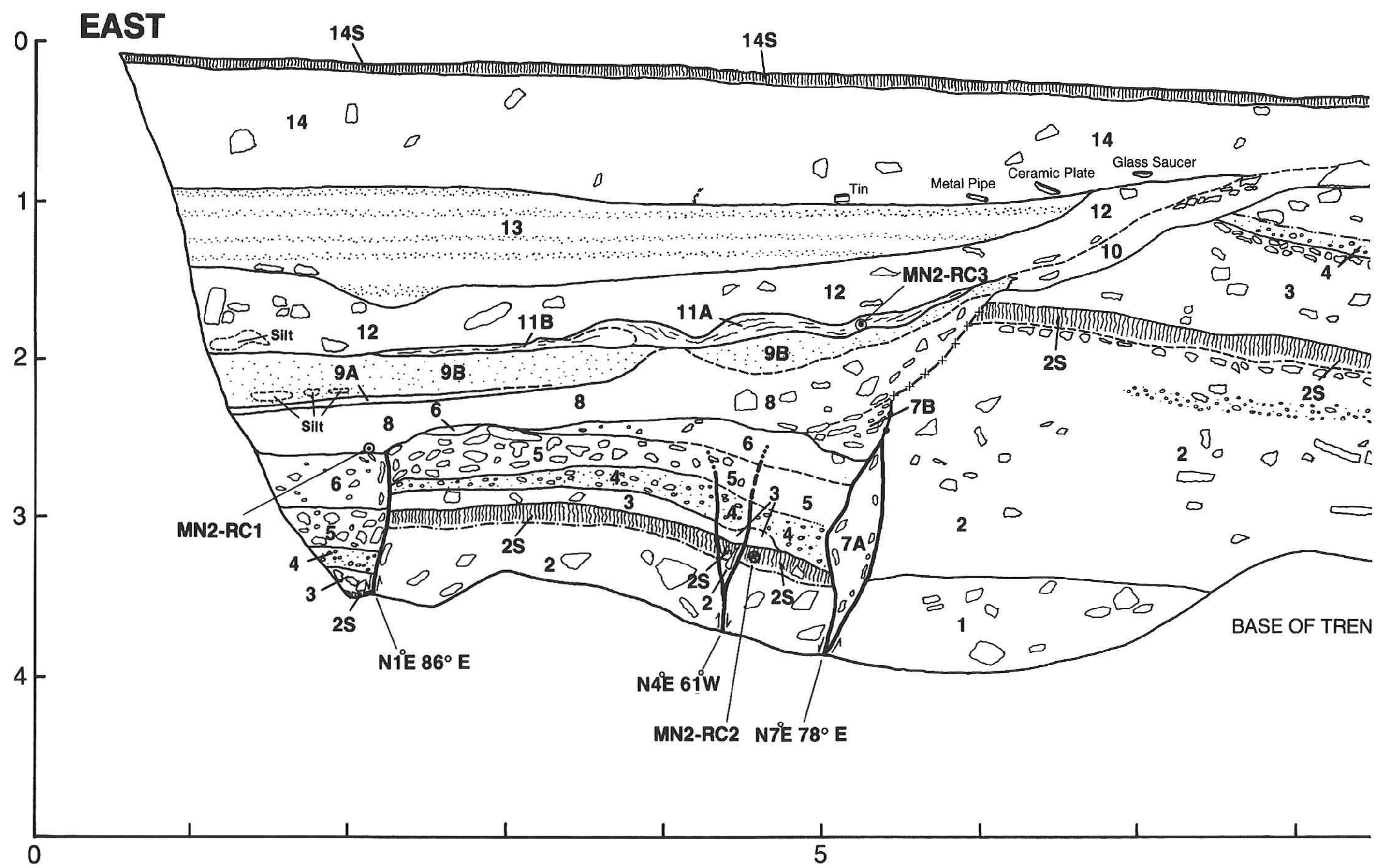


Figure 5.

EXPLANATION

GEOLOGIC UNITS

(See Appendix in text for complete unit descriptions)

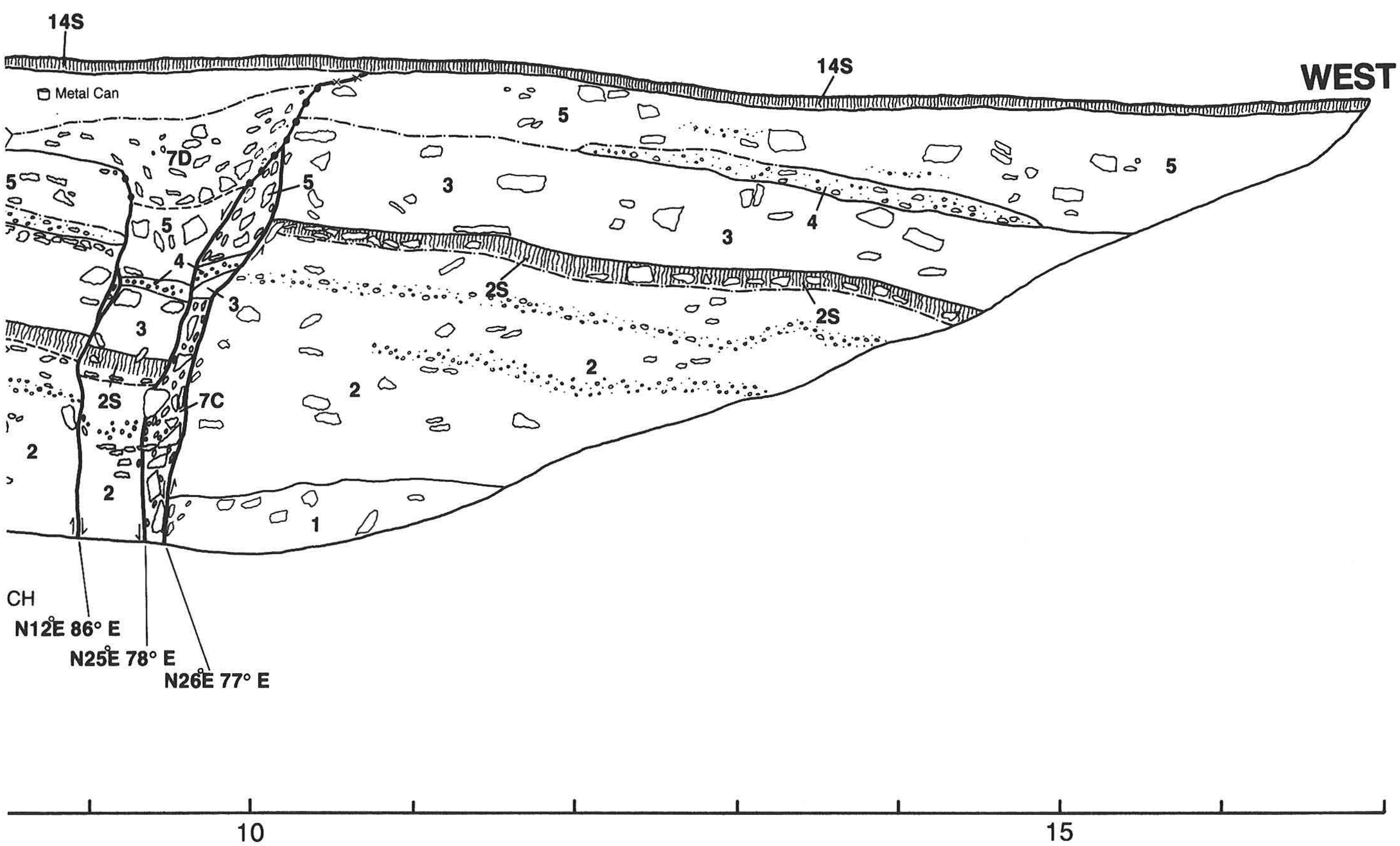
1 Debris Flow (matrix supported)
2 Debris Flow (matrix supported)
  2s Soil A-Horizon on unit 2
3 Debris Flow (matrix supported)
4 Fluvial Gravel/Sand
5 Debris Flow (matrix/clast supported)
6 Debris Flow/Debris Flood (clast supported)
7 Sheared Fault-zone Material and Fault-scarp Colluvium (most recent event)
  7A Shear zone material
  7B Fault-scarp colluvium
  7C Shear zone material
  7D Fault-scarp colluvium
8 Debris Flow (matrix supported)
9 Pond Deposit
  9A Clayey silt
  9B Sandy silt
10 Colluvium
11 Pond Deposit
  11A Silty sand
  11B Silt
12 Debris Flow (matrix supported)
13 Pond Deposit
14 Debris Flow (matrix supported; historical)
  14s Soil A-Horizon on unit 14

SYMBOLS

SOIL A-HORIZON
ROCK
FAULT
SCARP FREE FACE
ERODED SCARP
SHARP CONTACT (1-3 cm)
GRADATIONAL CONTACT (3-5 cm)
GRADATIONAL CONTACT (5-10 cm)
INDISTINCT CONTACT
CHARCOAL RADIOCARBON DATES (Calendar Calibrated)

MN2-RC1 **430, 360, 330 (+70,-40) yr B.P.**
MN2-RC2 **690 (+230,-140) yr B.P.**
MN2-RC3 **740 (+160,-50) yr B.P.**

N12°E 86°E STRIKE AND DIP OF FAULT



present on the graben floor. The charcoal yielded three possible calendar-calibrated radiocarbon dates of 430, 360, and 330 (+70, -40) yr B.P. (table 1). The charcoal occupied the same stratigraphic position (floor of the graben) as the burn layer in trench MN-1 (figures 4 and 5). However, the charcoal in trench MN-2 was less abundant than in the burn layer and was not associated with a zone of baked earth.

Debris-flow deposits (unit 10 in trench MN-1 and unit 8 in trench MN-2) overlie the dated charcoal collected at the graben floor in both Mapleton North trenches (figures 4 and 5). Based on color and textural characteristics, the two units do not appear to represent the same debris flow. The time at which the two units were deposited is poorly constrained, other than they both postdate the MRE and the charcoal in each trench. The disparity in the dates (510 and 520 yr B.P. in trench MN-1 versus 430, 360, or 330 yr B.P. in trench MN-2) from similar material collected at the same stratigraphic position in both trenches indicates that the two units (8 and 10) represent two individual debris flows that were deposited separately, and that the charcoal in each trench resulted from fires that occurred at different times.

Subsequent deposition in the graben consisted of interbedded pond (units 9, 11A, 11B, and 13) and debris-flow (units 12 and 14) deposits. Unit 11A exhibits soft-sediment deformation (figure 5) probably caused by the weight of the overlying debris flow (unit 12) that was deposited on the wet pond sediment. A discordant calendar-calibrated age of 740 (+160, -50) yr B.P. (table 1) for charcoal from unit 11A (station 5; figure 5) indicates that the charcoal is detrital and is stratigraphically out of place. Artifacts (bottles, ceramic plates, tin cans, broken farm implements, and other items) were found at the contact between the youngest pond deposit (unit 13) and the youngest debris-flow deposit (unit 14) in the graben (figure 5). The artifacts date from near the turn of the century (1900-1920; Norman Thulin, personal communication, 1987) and provide a maximum age for the debris-flow deposit (unit 14), which may correlate with unit 14 in trench MN-1 (figure 6). Lack of soil development on the scarp-derived colluvium and other graben-fill deposits (units 7-14) indicates that sedimentation occurred rapidly in the graben following the MRE.

MAPLETON SOUTH

Three trenches were excavated at the Mapleton South trench site (figure 3). Only trench MS-1 was logged in detail. The other two excavations did not contain material suitable for dating and therefore could not provide additional information on the timing of past surface faulting.

Trench MS-1

Trench MS-1 contained evidence for two episodes of surface faulting. Stratigraphic and structural relations combined with radiocarbon and TL age estimates constrained the timing of the penultimate earthquake (undated at Mapleton North) but provided only limited information on the timing of the most recent surface faulting.

Trench MS-1 was 33 m (108 ft) long and extended from the main trace of the WFZ across the back-tilted, alluvial-fan surface (af1) and the subparallel fault to the west (figures 3 and 7). Lake Bonneville sediments (units 1A and 1B) were exposed only on the upthrown side of the main fault zone (figure 7). On the downthrown side of the main fault zone, the oldest units exposed were post-Lake Bonneville alluvial-fan deposits (units 2A through 2D) that predate both episodes of surface faulting. A buried soil A horizon (unit 2s) is present on a debris-flow deposit (unit 2C) within the alluvial-fan sequence (figure 7). Two calendar-calibrated radiocarbon dates and a TL age estimate partially constrain the age of the soil. Radiocarbon analysis of charcoal collected from the 2s soil (station 15.5; figure 7) gave the following range of possible calendric ages: 2930, 2900, and 2890 (+280, -130) yr B.P. (table 1). An apparent-mean-residence-time (AMRT) radiocarbon age of 2820 (+150, -130) yr B.P. was obtained for the bulk organics in the soil (station 12; figure 7), and the TL age estimate, from the same location as the AMRT date, was 3300 (±300) years (Jackson, 1988; table 1). Although providing neither an upper nor a lower boundry on the time of soil formation, the age estimates do indicate that the 2s soil was forming on the surface of the unit 2C debris-flow deposit between about 3300 and 2800 years ago.

The penultimate surface-faulting earthquake occurred after development of the 2s soil A horizon and its partial burial by unit 2D. Units 3A through 3E consist of scarp-derived colluvium resulting from the penultimate event. No material suitable for dating was found in the unit 3 deposits. Displacement along several faults in trench MS-1 was limited to units 1 and 2 (figure 7) indicating that those faults were active only during the penultimate earthquake. The absence of a soil on the unit 3 scarp colluvium indicates that sedimentation occurred at a rapid rate adjacent to the main scarp following the penultimate event. Units 4A through 4J consist of debris-flow, debris-flood, fluvial, and colluvial material deposited in the interval between the penultimate and most recent surface-faulting earthquakes. Unit 4 deposits overlie penultimate-event scarp colluvium (unit 3) near the main fault and the 2s soil at other locations in the trench (figure 7). Charcoal from unit 4F, a debris flow about the middle of the unit 4 sequence (station 6.5; figure 7), gave a calendar-calibrated age of 1290 (+130, -230) yr B.P. (table 1), which is 1600 to 2000 years younger than the estimated age of the 2s soil. A weak soil A horizon (unit 4Gs) developed on unit 4G, a debris-flow/debris-flood deposit that overlies unit 4F, represents a period of nondeposition in the interval between the two surface-faulting events. Renewed deposition (units 4H, 4I, and 4J) buried the soil on unit 4G prior to the most recent surface faulting.

Evidence for the MRE in trench MS-1 consists of numerous faults and cracks that displace units 1 through 4, and the presence of unfaulted, scarp-derived colluvium (units 5A through 5P) resulting from the MRE adjacent to both the main and west fault zones (figure 7). Pre-existing stratigraphic and structural relations in the main fault zone were complicated by the most recent surface faulting. Scarp-derived colluvium from the penultimate earthquake (unit 3) and unit 4 deposits (4G, 4I, and 4J) was displaced by both normal faults and high-angle thrust faults. Unit 4 deposits were not found in some areas of the main fault zone and, where they

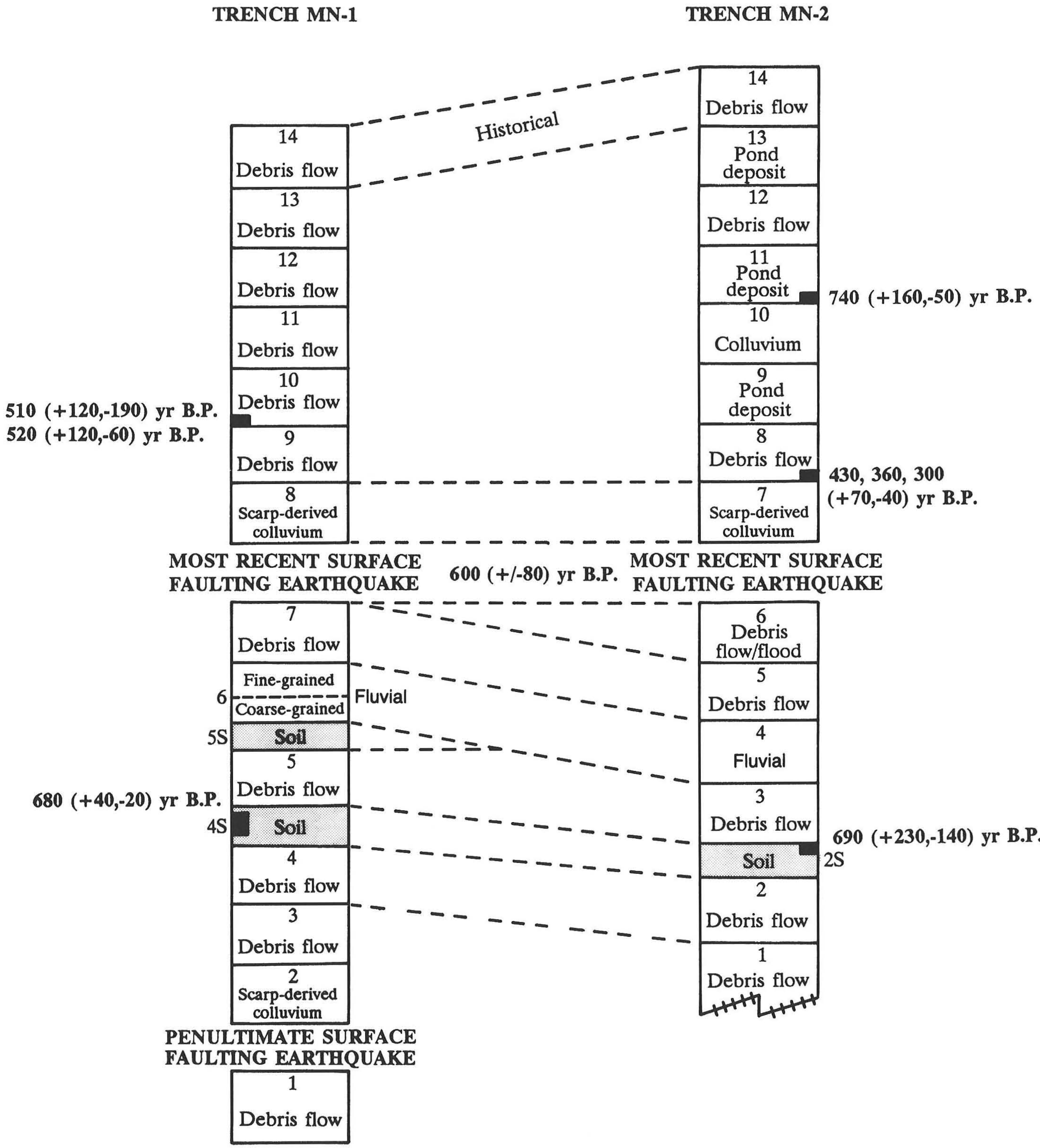


Figure 6. Stratigraphic columns showing correlations between geologic units and evidence for surface faulting recognized in Mapleton North trenches MN-1 and MN-2.

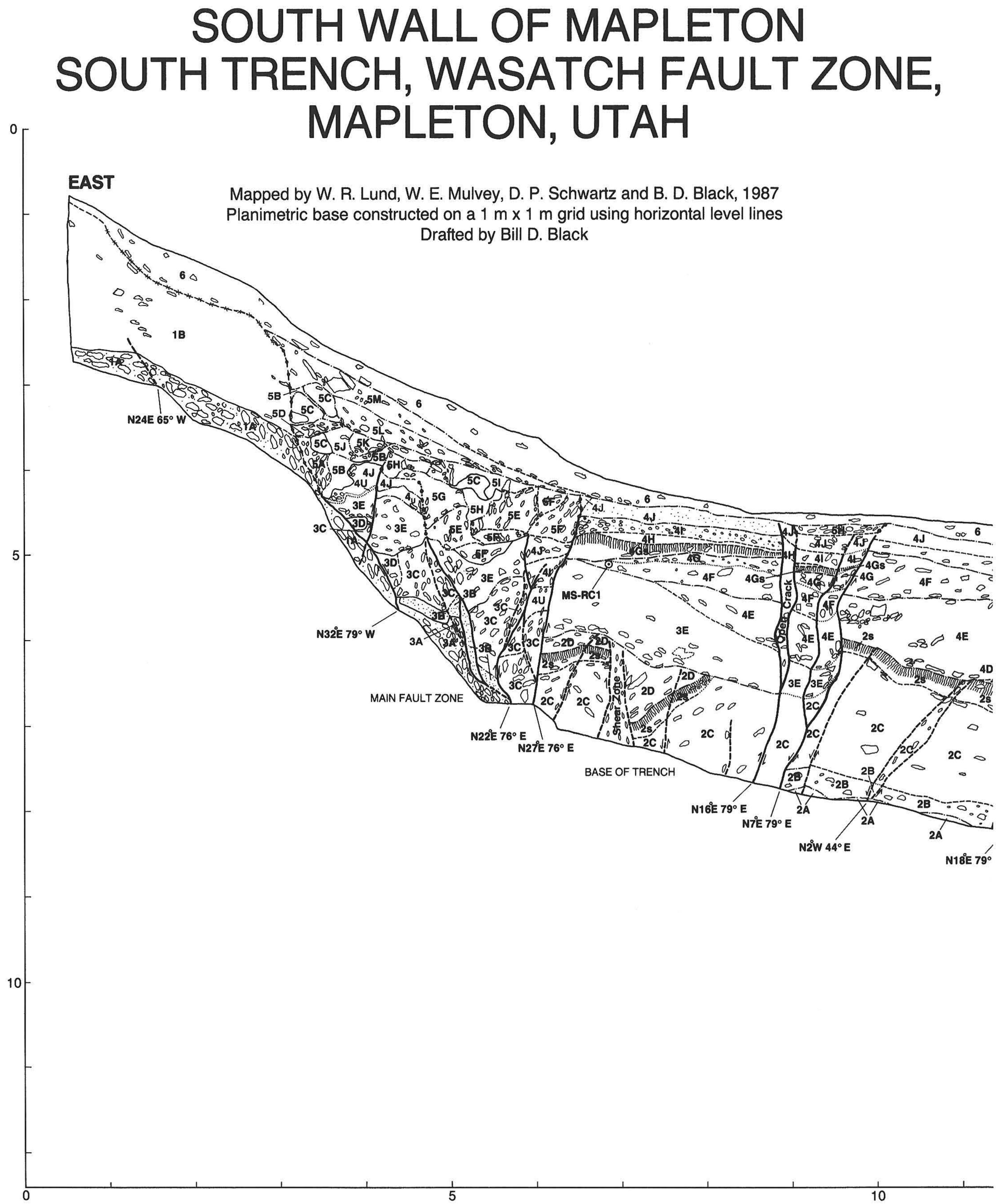

SOUTH WALL OF MAPLETON
SOUTH TRENCH, WASATCH FAULT ZONE,
MAPLETON, UTAH
EAST
Mapped by W. R. Lund, W. E. Mulvey, D. P. Schwartz and B. D. Black, 1987
Planimetric base constructed on a 1 m x 1 m grid using horizontal level lines
Drafted by Bill D. Black
N24E 65° W
N32E 79° W
MAIN FAULT ZONE
N22E 76° E
N27E 76° E
BASE OF TRENCH
MS-RC1
Shear Zone
Open Crack
N16E 79° E
N7E 79° E
N2W 44° E
N18E 79°
0
5
10

Figure 7.

EXPLANATION

GEOLOGIC UNITS

(See Appendix in text for complete unit descriptions)

1 Lake Bonneville Deposits
- 1A Transgressive shoreline gravels
- 1B Deep-water sand and silt

2 Pre-Penultimate Event Debris Flows and Fluvial Deposits
- 2A Debris flow (matrix supported)
- 2B Fluvial gravel
- 2C Debris flow (matrix supported)
- 2s Soil A-horizon on Unit 2C
- 2D Debris flow (matrix supported)

3 Penultimate Event Fault-scarp Colluvium
- 3A Fault-scarp colluvium from Unit 1A
- 3B Fault-scarp colluvium from Unit 1B
- 3C Blocks from Unit 2
- 3D Blocks from Unit 1B
- 3E Fault-scarp colluvium

4 Post-Penultimate Event Debris-flow and Graben-fill Deposits
- $4A_U$ Debris flow (undifferentiated)
- $4A_1$ Debris flow (below sand lense)
- $4A_2$ Debris flow/fluvial deposit (thin sand lense)
- $4A_3$ Debris flow (above sand lense)
- 4B Fluvial gravel
- 4C Fluvial sand
- 4D Fluvial gravel
- 4E Debris flow (matrix supported)
- 4F Debris flow (clast supported)
- 4G Debris flow/debris flood (clast supported)
- 4Gs Soil A-horizon on Unit 4G
- 4H Slope colluvium
- 4I Fluvial gravel
- 4J Slope colluvium
- 4U Unit 4 undifferentiated in fault zone

5 Most Recent Event Fault-scarp Colluvium

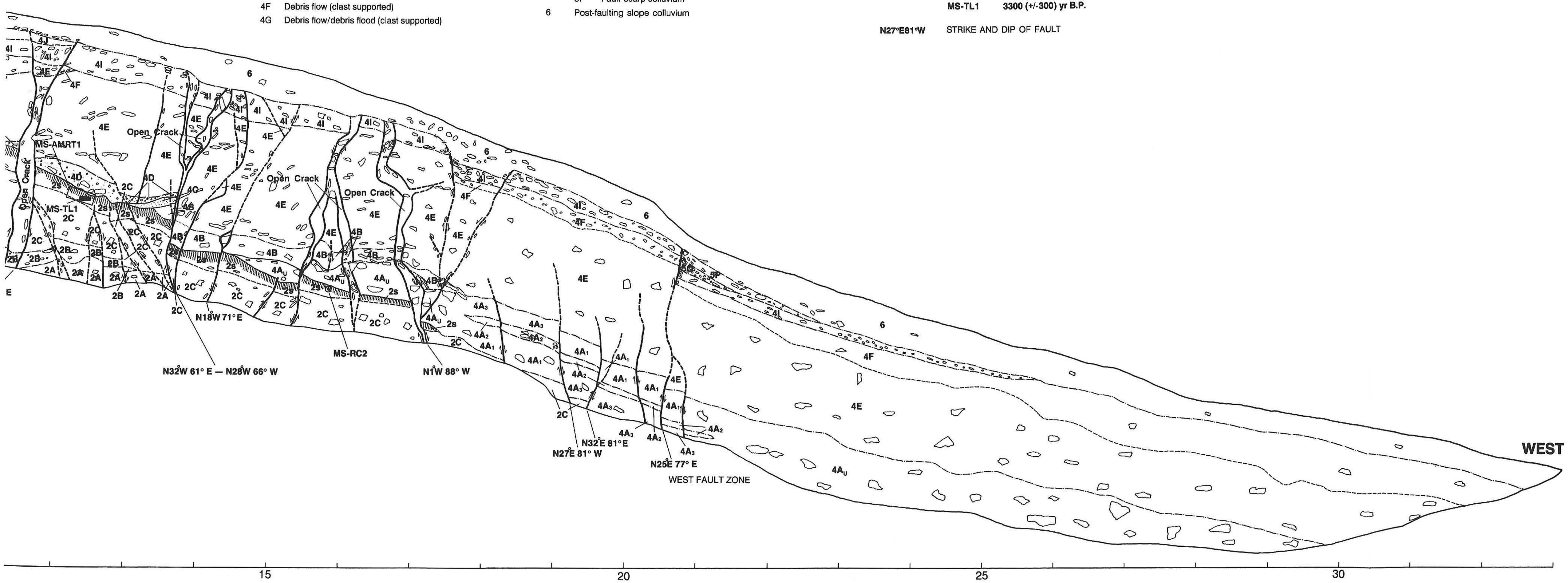
Main Fault Zone
- 5A Fault-scarp colluvium from Unit 1A
- 5B Fault-scarp colluvium from Unit 1B
- 5C Blocks from Unit 1B and/or 3E
- 5D Fault-scarp colluvium
- 5E Blocks from Units 2 and 4?
- 5F Fault-scarp colluvium
- 5G Fault-scarp colluvium
- 5H Blocks of A-horizon soil
- 5I Fault-scarp colluvium
- 5J Fault-scarp colluvium
- 5K Fault-scarp colluvium
- 5L Fault-scarp colluvium
- 5M Fault-scarp colluvium
- 5N Graben-fill colluvium (antithetic fault zone)

West Fault Zone
- 5O Fault-scarp colluvium
- 5P Fault-scarp colluvium

6 Post-faulting slope colluvium

SYMBOLS

- SOIL A-HORIZON
- ROCK
- FAULT
- CRACK
- SCARP FREE-FACE
- ERODED SCARP
- SHARP CONTACT (1-3 cm)
- GRADATIONAL CONTACT (3-5 cm)
- GRADATIONAL CONTACT (5-10 cm)
- INDISTINCT CONTACT
- CHARCOAL RADIOCARBON DATE (Calendar Calibrated)
  - **MS-RC1 1290 (+130,-230) yr B.P.**
  - **MS-RC2 2930, 2900, 2890 (+280,-130) yr B.P.**
- AMRT AGE ESTIMATE FROM ^{14}C DATE ON BULK SOIL SAMPLE (Calendar Calibrated)
  - **MS-AMRT 1 2820 (+150,-130) yr B.P.**
- THERMOLUMINESCENCE AGE ESTIMATE
  - **MS-TL1 3300 (+/-300) yr B.P.**
- N27°E81°W STRIKE AND DIP OF FAULT



DISTANCE (IN METERS)

were present, it was sometimes necessary to map them as undifferentiated (4u) because a positive correlation could not be made with individual unit 4 strata outside of the main fault zone. The absence of some unit 4 deposits, and the difficulty in identifying others, is attributed to a combination of lateral changes in the characteristics of the deposits, pinch-outs (nondeposition) of some units in the main fault zone prior to the MRE, the complexities of faulting, and possible post-MRE erosion. At the west fault zone, only geologic units postdating the penultimate event were exposed in the trench (figure 7). These units were faulted during the MRE, but the possibility of activity on the west fault zone during the penultimate earthquake could not be evaluated. Movement on numerous, small, east- and west-dipping normal and thrust faults between the main and west fault zones created a series of graben and horst structures. Large, open cracks, some extending to within a few centimeters of the ground surface, were common in the trench (figure 7). Unit 6 consists of slope colluvium deposited after the scarp created by the most recent surface faulting in the main fault zone achieved a more stable configuration; no material suitable for dating was found in unit 6.

EARTHQUAKE TIMING AND RECURRENCE

TIMING OF THE MOST RECENT SURFACE FAULTING

Information from the Mapleton North and South trench sites indicates that two surface-faulting earthquakes have occurred on this part of the WFZ in late Holocene time (the past 3000 years). Radiocarbon dates on charcoal from the Mapleton North trenches allow the timing of the MRE to be more closely constrained than possible at other trench sites on the WFZ. In trench MN-1 (figure 4), the 4s soil predates the MRE and provides a maximum limiting age for the MRE of 680 (+40, -20) yr B.P. Charcoal from the post-MRE burn layer provides minimum limiting ages for the MRE of 510 (+120, -190) and 520 (+120,-60) yr B.P. Considering the uncertainties associated with the radiocarbon ages, the period in which the MRE could have occurred is 720 to 320 yr B.P. However, the preferred time range is the 160-year window bracketed by the reported dates of 680 and 520 yr B.P. Burial of the 4s soil by pre-MRE debris-flow and fluvial deposits (units 5, 6, and 7) indicates that an interval of time, but less than 160 years, elapsed between development of the 4s soil and the most recent surface faulting. Therefore, the preferred estimate for the timing of the MRE has been placed in the middle of the 160-year window at 600 (±80) yr B.P.

Radiocarbon dates as well as stratigraphic and structural relations in trench MN-2 support a similar interpretation of the age estimate for the most recent surface faulting. The 2s soil (figure 5), which predates the MRE, contains charcoal that gave a calendar-calibrated age of 690 (+230, -140) yr B.P. and provides a maximum limiting age for the event. Charcoal collected at the contact between the youngest faulted deposit (unit 6) and the oldest post-MRE deposit in the graben (unit 8; figure 5) yielded possible calendar-calibrated ages of 430, 360, and 330 (+70, -40) yr B.P., which provide an upper limit on timing of the most recent surface faulting. The two radiocarbon results provide a broad time range for the MRE of between 920 and 290 yr B.P., with a preferred 260-year time window between the reported dates of 690 and 430 yr B.P. The 2s soil was buried by a series of debris flows (units 3 through 6; figure 5) prior to the MRE, indicating that, as in trench MN-1, an unknown amount of time, but less than 260 years, elapsed between soil formation and the MRE. Therefore, the best estimate for the timing of the MRE in trench MN-2 was also placed in the middle of the preferred time window at 560 (±130) yr B.P.

The estimates for the timing of the MRE determined from the two Mapleton North trenches fall within 40 years of each other. Such close correlation in time indicates that the same event is recorded in both excavations. The time interval for the MRE determined from trench MN-2 completely encompasses the interval determined for the same event in trench MN-1 (figure). For that reason, the 600 (± 80) yr B.P. date from trench MN-1 is considered the best constrained and is the preferred estimate for the timing of the most recent surface faulting.

At Mapleton South, timing of the MRE is poorly constrained. Lack of datable material in post-MRE deposits prevented determination of a minimum limiting age for the most recent surface faulting. A maximum limiting age is provided by the 1290 (+130, -230) yr B.P. date obtained for the charcoal from unit 4F (figure 7; table 1). However, stratigraphic and soil relations in trench MS-1 indicate that the MRE is significantly younger than 1290 yr B.P. Following deposition of unit 4F and prior to the MRE, at least four additional debris-flow units (4G through 4J) were deposited, and a weakly developed soil A horizon (4Gs) formed on unit 4G (figure 7). The length of time represented by the debris flows and the soil is unknown. However, unit 3 and 4 sediments deposited between the formation of the 2s soil and deposition of unit 4F are similar in thickness to units 4G through 4J, and represent a minimum of 1200 years of elapsed time. Although it is unlikely that a direct correlation exists between the time required for deposition of the sediments above and below unit 4F, the comparison does give an indication of the late Holocene sedimentation rate on the alluvial-fan surface. The soil A horizon (4Gs) is further evidence that a substantial interval of time elapsed between deposition of unit 4F and the most recent faulting. The alluvial-fan surface had to remain stable (neither accumulating sediment nor significantly eroding) for a considerable time (possibly hundreds of years) for the 4Gs soil to form. The close proximity of the two Mapleton trench sites (0.8 km, 0.5 mi; figure 3) suggests that the same MRE is recorded at both locations. The amount of post-unit 4F sedimentation prior to the MRE and the time required for the 4Gs soil to form indicate that a substantial interval elapsed between the deposition of unit 4F at 1290 yr B.P. and the MRE at Mapleton South. Therefore, the stratigraphic and soil relations exposed in trench MS-1 suggest an age for the MRE that is significantly younger than 1290 yr B.P., which is consistent with the 600 (±80) yr B.P. date determined for the MRE at Mapleton North.

TIMING OF THE PENULTIMATE SURFACE FAULTING

The penultimate surface-faulting earthquake at Mapleton North predates the 680 (+40, -20) yr B.P. date obtained from charcoal in the 4s soil in trench MN-1. Lack of datable material prevented the event from being more closely constrained at the northern site.

At Mapleton South, the penultimate surface-faulting earthquake displaced units 1 and 2 and the 2s soil in trench MS-1. Two radiocarbon dates (one on bulk soil organics and the other on charcoal) and a TL age estimate were obtained for the 2s soil. The organics from the 2s soil yielded a radiocarbon age of 2890 (±80) yr B.P. (table 1). The radiocarbon age is a measure of the combined ages of all the various organic fractions within the soil. An estimate of the elapsed time since the 2s soil was buried can be obtained by subtracting the mean residence time (MRT) of the organics from the radiocarbon age of the soil (Forman and others, 1989). Mean residence time refers to the age of the organics in the soil at the time of burial. The MRT for a buried soil (paleosol) must be estimated and is approximated by making a comparison with the age of organics in modern soils exhibiting similar profile development. A. R. Nelson (Forman and others, 1989) has determined that modern soil A horizons along the Wasatch Front commonly have an MRT of 100 to 300 years. Forman and others (1989) used an MRT of 200 years for buried soils similar to the 2s soil in trench MS-1 in their study of surface faulting at American Fork Canyon on the proposed American Fork segment of the WFZ. Subtracting 200 years from the 2890 (±80) yr B.P. date for the 2s soil organics and making the appropriate calendar correction (Stuiver and Reimer, 1986) results in an AMRT age estimate of 2820 (+150, -130) yr B.P. for the time of 2s soil burial.

The AMRT age estimate was obtained west of the main fault zone near station 12 (figure 7) where the 2s soil is buried by a debris flow (unit 4D) that postdates the penultimate earthquake. Therefore, the 2s soil was exposed at the ground surface and continued to develop for an unknown amount of time following the penultimate event, until it was eventually buried by the 4D debris flow. The 2s soil was faulted prior to burial, therefore, the penultimate event predates the 2820 (+150, -130) yr B.P. AMRT date obtained for the soil burial. Lacking additional datable material, a maximum limiting age for the event could not be determined. However, the absence of a zonal soil profile, even at station 12 where the 2s soil continued to develop for some time following the penultimate earthquake, argues for a young soil age at the time of burial. For that reason, the penultimate event probably is not much older than the estimated time of soil burial; it could be as young as 2690 yr B.P. (2820 minus the 130-year error limit), or somewhat older than 2970 yr B.P. (2820 plus the 150-year error limit).

Charcoal from the 2s soil yielded three possible calendar-calibrated radiocarbon dates of 2930, 2900, and 2890 (+280, -130) yr B.P. The charcoal appeared to be detrital rather than a root and is believed to have been incorporated into the soil as the A horizon developed. The charcoal was from a location (station 16; figure 7) where the 2s soil remained at the ground surface and continued to develop following the penultimate earthquake. The soil was eventually buried by a post-event debris flow (unit 4Au). There is no evidence to indicate when the charcoal was incorporated into the soil; it could have occurred either before or after the penultimate event. Therefore, the approximate 2900 yr B.P. date obtained from the charcoal indicates that the 2s soil was still forming and had not been buried at that time, but it does not otherwise constrain the time of faulting.

The TL age estimate of 3300 ± 300 yr (Jackson, 1988; table 1) was obtained for the 2s soil from the same location (station 12; figure 7) as the AMRT date. Thermoluminescence dating provides an estimate of the elapsed time since the material being analyzed was last exposed to sunlight (Forman and others, 1989). Because the TL and AMRT dates are from the same location, and because the TL technique is also a measure of elapsed time since burial, the same considerations regarding the timing of the penultimate earthquake that apply to the AMRT dating method also apply to the TL technique. Based on the TL age estimate, the penultimate event could be as young as 3000 yr B.P. (3300 minus the 300-year error limit) or somewhat older than 3600 yr B.P. (3300 plus the 300-year error limit). In their study of surface faulting at the American Fork Canyon site, Forman and others (1989) concluded that the multiple uncertainties associated with the TL method limited its maximum resolution to about 500 years for Holocene deposits from the WFZ. For that reason, the age estimate obtained for the penultimate earthquake using the AMRT dating method (shortly before 2820 (+150, -130) yr B.P.) is the preferred estimate for the Mapleton site.

EARTHQUAKE RECURRENCE INTERVAL

Timing of the MRE at the Mapleton site is well constrained at 600 (±80) yr. B.P. Timing of the penultimate event is less well defined, but occurred before 2820 (+150, -130) yr B.P. The elapsed time between the two events is at least 2010 years (2690 years minus 680 years), and could be more than 2450 years (2970 years minus 520 years). An unknown length of time must be added to the interval separating the two events to account for the elapsed time between the penultimate earthquake and burial of the 2s soil, but the absence of a zonal soil profile indicates that the 2s soil was young at the time of burial, and that the interval was a few hundred years at most. Therefore, assuming about 200 years separates the penultimate earthquake and burial of the 2s soil, a reasonable minimum estimate of the time separating the two surface-faulting events at Mapleton is 2200 to 2700 years. However, without datable material to more closely constrain the timing of the penultimate earthquake, this interval represents a best estimate; the actual interval could be either somewhat shorter or possibly considerably longer.

Swan and others (1980) determined that six and possibly seven surface-faulting earthquakes have occurred since Provo time (14,000 years; estimated Provo shoreline age at the time of the Swan and others study) on the WFZ at Hobble Creek 5 km (2.5 mi) north of the Mapleton site (figure 1). The Hobble Creek site is also on the proposed Spanish Fork segment of the WFZ. Three of the earthquakes are believed to have occurred in mid- to late Holocene time, but individual events could not be dated. An average recurrence interval of 1500 to 2600 years over the past 14,000 years was calculated for surface faulting at Hobble Creek. Those values represent the maximum and minimum intervals obtained considering both the number of events (six or seven) and the various possibilities for timing of the first and last events since Provo time (Swan and others, 1980). Their longer term value for the recurrence of surface faulting at Hobble Creek is consistent with the single interval determined at Mapleton.

FAULT DISPLACEMENT, SLIP RATE, AND ESTIMATED EARTHQUAKE MAGNITUDE

FAULT DISPLACEMENT

Net vertical tectonic displacement (NVTD) refers to the net vertical slip that occurs at the ground surface (figure 8) during a surface-faulting earthquake. The NVTD for the past two such earthquakes at the Mapleton site could not be directly measured, because geologic units could not be correlated across the main fault zone at either trench site (figures 4 and 7). Scarp profiles were measured at both sites but provided little information on displacement due to difficulty in correlating equivalent surfaces across the fault zone. At Mapleton North, the surface of the af2 alluvial fan on the downdropped block is buried for a considerable distance west of the fault zone by younger af1 fan deposits (figure 3). The remnant of the af2 fan on the upthrown side of the fault is so deeply eroded that its original surface could not be identified with confidence. The total height of the main fault scarp is 18 m (60 ft), but that value reflects multiple surface-faulting events and includes the effects of back-tilting and antithetic faulting (figure 8). Similar problems exist at Mapleton South, where erosion on the upthrown side of the main fault and formation of a broad, poorly defined graben on the downdropped side prevent identification of equivalent morphologic surfaces across the fault zone.

It is possible to estimate the NVTD produced by the MRE at Mapleton North from the height of the buried scarp free face in trench MN-1 and from the morphology of the main fault scarp. The scarp-derived colluvium resulting from the MRE deposited adjacent to the main fault (unit 8; A through U; figure 4) buried the scarp free face to a depth of 6.3 m (20.7 ft), indicating that the MRE scarp was at least that high. Examination of the scarp showed a marked decrease in slope a few meters east (upslope) from the projected intersection of the main fault with the face of the scarp. The break in slope is the top of the eroded MRE scarp free face and indicates that the MRE scarp may have been as high as 7.9 m (25.9 ft) following the event. The scarp height includes the NVTD produced by the MRE and any displacement related to back-tilting of the ground surface and antithetic faulting (figure 8). The NVTD can be approximated by removing the effects of the back-tilting and antithetic faulting. In the graben adjacent to the main fault, the ground surface slopes about 2° to the west toward Utah Valley. The westward slope reflects deposition of post-MRE alluvium in the graben. Near station 17 in trench MN-1 (figure 4), the buried 4s soil abruptly changes dip from about 2° to the west to about 4° to the east. The 2° of westward dip corresponds to the present slope of the ground surface in the graben, indicating that the 4s soil west of station 17 may represent the relatively undeformed, pre-MRE surface of the graben. If so, the 6° change in dip of the 4s soil represents the back-tilting produced by the most recent surface faulting. Removing the effect of 6° of back-tilting results in a scarp height of 4.4 to 6.0 m (14.4 - 19.7 ft). If the back-tilting produced by the MRE was more or less than 6°, and a reasonable case can be made for a few degrees either way, the resulting scarp height would be proportionately smaller or larger. The net slip on antithetic faults (figure 8) also must be subtracted from the height of the main fault scarp when estimating net vertical tectonic displacement. At

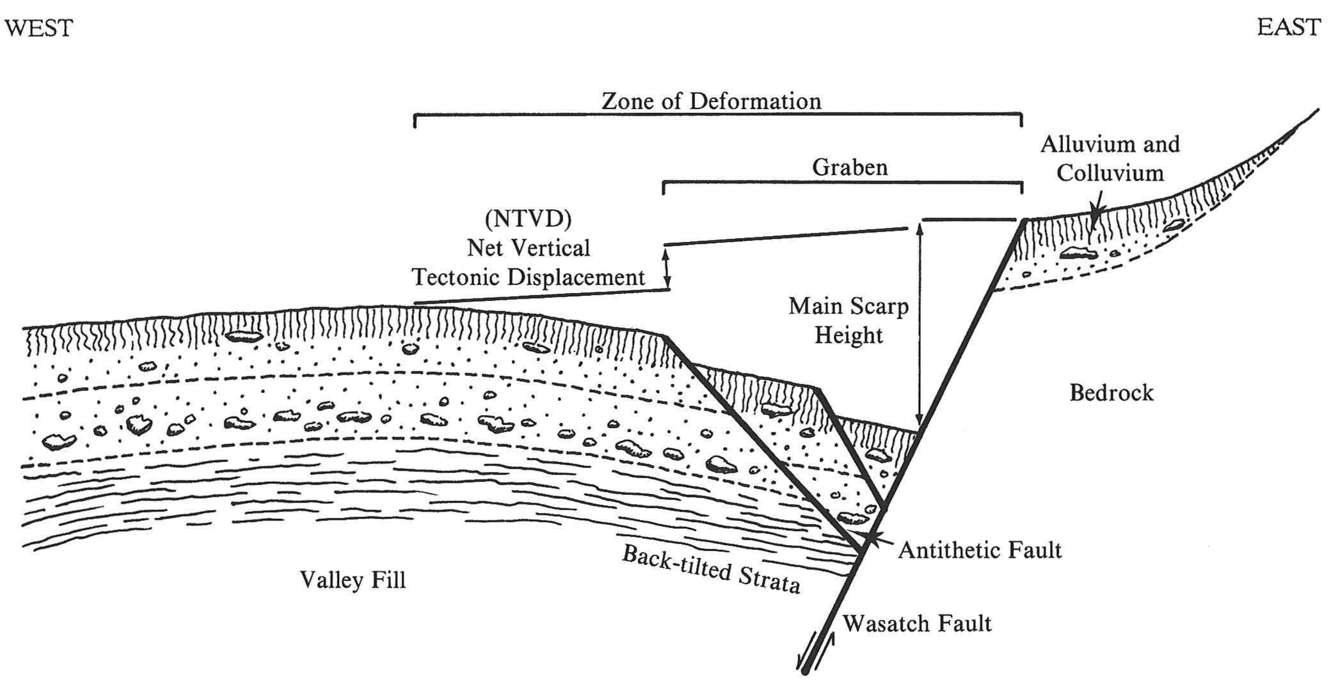


Figure 8. Schematic diagram showing the relations between scarp height, back-tilting, antithetic faulting, and net vertical tectonic displacement for normal-slip faults (adapted from Robison, 1987).

Mapleton North, antithetic faults displaced the ground surface about 3.0 m (9.9 ft) down to the east during the most recent surface faulting (figure 4). Subtracting that displacement from the main (corrected) scarp height results in a NVTD of 1.4 to 3.0 m (4.6 - 9.8 ft) for the MRE at Mapleton North. Swan and others (1980) determined that the average NVTD for the past six to seven surface-faulting earthquakes at Hobble Creek ranged from 0.8 to 2.8 m (2.6 - 9.2 ft), which compares well with the values estimated for the MRE at Mapleton North.

The complexity of the faulting exposed in trench MS-1 made the amount of back-tilting produced by the MRE at Mapleton South difficult to evaluate. In addition, down-to-the-east displacement across the possible graben to the west could not be determined without additional extensive trenching. Therefore, an estimate of the NVTD produced by the MRE could not be made at Mapleton South.

SLIP RATE

Because of the variability in both the estimated recurrence interval (2200-2700 years) and NVTD (1.4-3.0 m or 4.6-9.8 ft) at the Mapleton site, calculation of fault slip rates produced a range of possible values. Using an estimated minimum displacement of 1.4 m (4.6 ft) and an estimated maximum recurrence interval of 2700 years yields a minimum slip rate for Mapleton of 0.52 mm/yr (0.02 in/yr). An estimated maximum displacement of 3.0 m (9.8 ft) and an estimated minimum recurrence interval of 2200 years gives a maximum slip rate of 1.36 mm/yr (0.05 in/yr). Using median values of 2.2 m (7.2 ft) and 2450 years, the resulting slip rate is 0.90 mm/yr (0.04 in/yr). Because of the variability associated with both the recurrence interval and NVTD, the median value (0.90 mm/yr; 0.04 in/yr) is the preferred slip rate for the Mapleton site. For comparison, Swan and others (1980) determined an average slip rate of 1.3 mm/yr (0.05 in/yr) for middle to late Holocene time at the Hobble Creek site.

ESTIMATED EARTHQUAKE MAGNITUDE

Maximum Surface-Wave Magnitude

Methods for assigning maximum magnitudes to prehistoric earthquakes have been developed from empirical relations that attempt to correlate surface-wave magnitude (M_S) with various fault parameters. A regression of magnitude on displacement for normal and oblique-slip normal faults developed by Bonilla and others (1984) was used to estimate maximum surface-wave magnitudes for the MRE at Mapleton (table 2). The estimated NVTD at Mapleton is 1.4 to 3.0 (4.6-9.8 ft). However, it is not known if the 3.0 m (9.8 ft) value represents the maximum displacement on the rupture segment, or if, as is more likely, it is a submaximum value. Therefore, a maximum surface-wave magnitude was also determined (table 2) for a hypothetical NVTD of 4.5 m (14.8 ft), whicih is the largest NVTD reported to date for the WFZ, as determined from scarp profiles measured at the Dry Creek site on the Salt Lake City segment of the WFZ (Schwartz and Lund, 1988).

For comparison, the two largest historical earthquakes in the Intermountain seismic belt, the 1959 Hebgen Lake, Montana and 1983 Borah Peak, Idaho earthquakes, had surface-wave magnitudes of M_S 7.5 (Doser, 1985) and M_S 7.3 (Smith and others, 1985), respectively. The Hebgen Lake earthquake ruptured the ground surface for about 25 km (16 mi) and produced up to 6.7 m (22 ft) of surface displacement (Myers and Hamilton, 1964). The Borah Peak earthquake ruptured the ground surface for 36 km (22.5 mi) and produced a maximum net surface displacement of 2.7 m (8.9 ft) (Crone and others, 1985).

Inferred Moment Magnitude

Seismic moment (M_O) and inferred moment magnitude (M) are considered more meaningful measures of earthquake energy and magnitude for engineering purposes because the various Richter magnitude scales (M_L, M_S, and M_b) become saturated (provide a nonlinear estimate of earthquake force) at higher magnitudes (Hanks and Kanamori, 1979; Machette, 1986). Inferred moment magnitude is calculated using the following equation from Hanks and Kanamori (1979).

$$M = 2/3\ (\log M_O) - 10.7$$

Where values of seismic moment ($M_O = u \times A \times D$) are based on: a shear modulus for bedrock (u) of 3.3×10^{11} dynes/cm^2; (Brune, 1968); the surface area of the fault plane (A) in cm^2; and a net surface displacement (D) in cm.

A range of inferred moment magnitudes were determined for the proposed Spanish Fork and original Provo segments (table 3) using rupture lengths of 31.5 km (19.7 mi) and 72.5 km (45.3 mi), respectively (Machette and others, 1987), a focal depth for the earthquake of 15 km (9.4 mi), an average dip for the fault plane of 50°, and the values of NVTD estimated for the Mapleton site (1.4 - 3.0 m; 4.6 - 9.8 ft). Both the earthquake focal depth and the average dip of the fault plane selected are consistent with observations from historical surface faulting (Hebgen Lake, Montana and Borah Peak, Idaho) in the Intermountain seismic belt (Pechmann, oral communication, University of Utah Seismograph Stations, 1990). Because it is not known if the estimated maximum value of NVTD (3.0 m; 4.6 ft) determined at the Mapleton site represents the maximum displacement on the WFZ in Utah Valley, an inferred moment magnitude was also calculated for a hypothetical maximum NVTD of 4.5 m (14.8 feet) (table 3).

For comparison, the 1959 Hebgen Lake, Montana earthquake produced a moment magnitude of M 7.3 (Stein and Bucknam, 1985). The 1983 Borah Peak, Idaho earthquake had a moment magnitude of M 7.0 (Stein and Bucknam, 1985).

Table 2.

Estimated maximum surface-wave magnitudes (Bonilla and others, 1984) for the MRE at the Mapleton site based on values of NVTD determined in Mapleton North trench MN-1.

Estimated NVTD (meters)	Estimated maximum surface-wave magnitude (M_S)
1.4	6.9
2.2 (median)	7.1
3.0	7.2
Hypothetical maximum NVTD on proposed Spanish Fork segment	
4.5	7.3

Table 3.
Inferred moment magnitudes (Hanks and Kanamori, 1979) for the MRE[1] on the proposed Spanish Fork[2] and original Provo[3] segments of the WFZ, based on values of NVTD determined in Mapleton North trench MN-1.

Estimated NVTD (meters)	Moment Magnitudes (M) Spanish Fork segment	original Provo segment
1.4	6.8	7.0
2.2 (median)	6.9	7.1
3.0	7.0	7.2
4.5[4] (hypothetical maximum for segment)	7.1	7.3

[1]Focal depth 15 km, dip of fault plane 50°
[2]Rupture length 31.5 km (Machette and others, 1987)
[3]Rupture length 72.5 km (Machette and others, 1987)
[4]Largest NVTD reported to date on the WFZ, determined from scarp profiles measured at Dry Creek on the Salt Lake City segment (Schwartz and Lund, 1988).

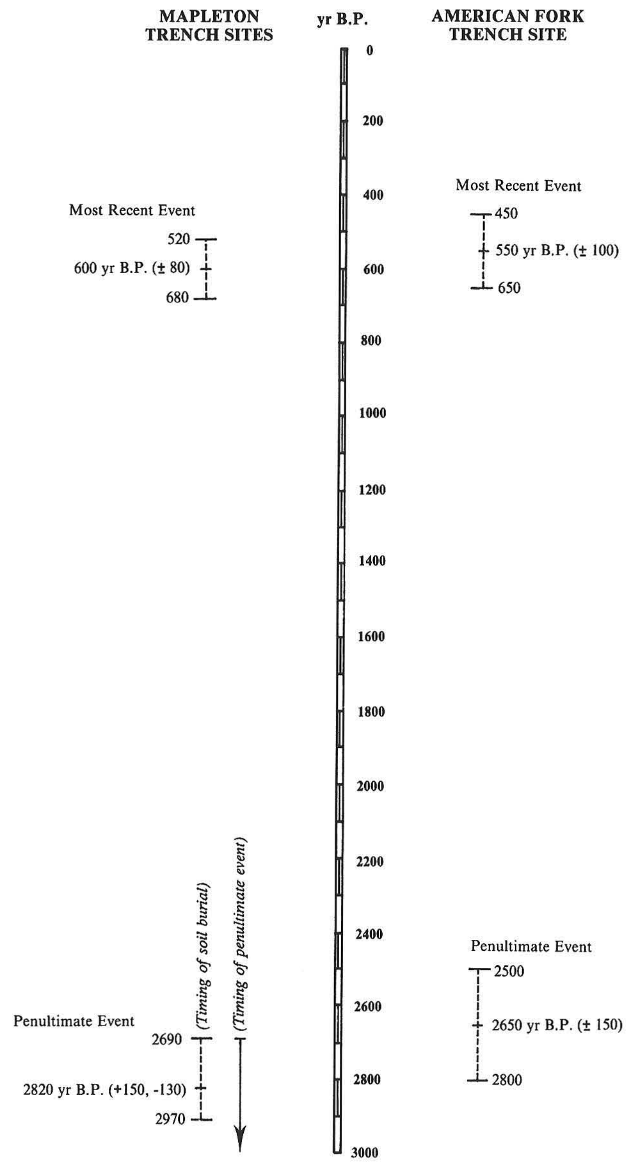


Figure 9. *Timing of the past two surface-faulting earthquakes at the Mapleton and American Fork Canyon trench sites. Timing of the penultimate event at Mapleton (upper time line) is shown in relation to the post-event burial (lower time line) of a paleosol (unit 2s) exposed in trench MS-1 at the Mapleton South trench site.*

SUMMARY AND DISCUSSION

SUMMARY OF RESULTS

Results of trenching the WFZ at the Mapleton site show that two surface-faulting earthquakes have occurred there in late Holocene time. The most recent event is well constrained at 600 (±80) yr B.P. Timing of the penultimate event is less well constrained but is thought to have occurred shortly before 2820 (+150, -130) yr B.P. Considering the uncertainty associated with the timing of the penultimate event, a reasonable estimate of the interval between the two earthquakes is believed to be 2200 to 2700 years. The NVTD for the MRE at Mapleton could not be directly measured but is estimated to be between 1.4 and 3.0 m (4.6 - 9.8 ft). The maximum and minimum values of displacement and recurrence determined for the WFZ at Mapleton yield a range of slip rates between 0.52 and 1.36 mm/yr (0.02 - 0.05 in/yr). Using median values of displacement (2.2 m; 7.2 ft) and recurrence (2450 years) results in a slip rate of 0.90 mm/yr (0.04 in/yr), which is the preferred slip rate for the Mapleton site. The estimated maximum surface-wave magnitude expected for an earthquake producing 1.4 to 3.0 m (4.6 - 9.8 ft) of NVTD is between M_S 6.9 and 7.2. The maximum surface-wave magnitude for a median displacement of 2.2 m (7.2 ft) is M_S7.1 and the estimated magnitude for a hypothetical maximum NVTD of 4.5 m (14.8 ft) is M_S 7.3. Inferred moment magnitudes calculated for an earthquake producing 1.4 to 3.0 m (4.6-9.8 ft) of NVTD on the proposed Spanish Fork segment ranged from M 6.8 to 7.0, and from M 7.0 to 7.2 for the original Provo segment, with median values for each segment of M 6.9 and M 7.1, respectively. The inferred moment magnitudes for a hypothetical maximum NVTD of 4.5 m (14.8 ft) is M 7.1 on the proposed Spanish Fork segment and M 7.3 on the original Provo segment.

SIGNIFICANCE TO WASATCH FAULT ZONE SEGMENTATION

Results of this study show a close correlation in time between the MRE at the Mapleton site and the American Fork Canyon site on the proposed American Fork segment (figure 9). At American Fork Canyon, the MRE has been assigned an age of 550 (±100) yr B.P. (Forman and others, 1989). This date is concordant with the 600 (±80) yr B.P. date obtained for the MRE at Mapleton. At American Fork Canyon, the penultimate earthquake has been assigned an age of 2650 (±150) yr B.P. The timing of the penultimate event at Mapleton is less well constrained, but it occurred prior to burial of a soil exposed in trench MS-1 at Mapleton South. The soil burial postdates the penultimate event and occurred about 2820 (+150, - 130) yr B.P., based on an AMRT age estimate obtained from the bulk organic fraction of the soil. The poor zonal profile development (cummulic A horizon only) of the buried soil argues for placing the penultimate event close in time to the soil burial. The range of uncertainty associated with the AMRT age estimate allows soil burial to have occurred between about 2970 and 2690 yr B.P. Therefore, the penultimate event could be as young as 2690 yr B.P. Thus, the uncertainty limits associated with the timing of the penultimate events at Mapleton and American Fork Canyon also overlap part of their ranges (figure 9). The close correlation in timing of the MRE at the Mapleton and American Fork Canyon sites, and the possible correlation of the penultimate event, suggest that during the MRE, and possibly during the penultimate event, the original Provo segment of Schwartz and Coppersmith (1984) ruptured along its entire length (figure 1). Of questionable significance are the 2 km (1.2 mi) left step in the surface trace of the WFZ at the mouth of Provo Canyon and the 3 km (1.8 mi) overlap and bifurcation of the fault zone near Springville identified by Machette and others (1986) as possible segment boundaries (figure 1). However, they may represent nonpersistent segment barriers that serve to limit surface rupture on the Provo segment during smaller surface-faulting events (Machette and others, 1989).

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APPENDIX

DESCRIPTION OF GEOLOGIC UNITS MAPLETON NORTH TRENCHES MN-1, MN-2 AND MAPLETON SOUTH TRENCH MS-1

DESCRIPTION OF GEOLOGIC UNITS MAPLETON NORTH TRENCH 1

(see figure 4)

Note: Reported size fraction percentages are field estimates, Munsell colors were recorded from dry materials.

Unit 1 DEBRIS FLOW *(matrix supported) — Silty sandy gravel with cobbles: Light yellowish brown (10YR 6/4); 15 percent cobbles (76 mm - 305 mm), 35 percent gravel (4.75 mm -76 mm), 30 percent sand (0.074 mm - 4.75 mm), 20 percent fines (<0.074 mm), maximum clast size 300 mm, subangular; low to no plasticity; poorly stratified, some parallel alignment of elongate clasts; thin, discontinuous $CaCO_3$ coatings on clasts, weakly cemented; thick undifferentiated alluvial-fan unit exposed on the upthrown block of the main fault and on the downthrown block west of the main graben-bounding antithetic fault.*

PENULTIMATE SURFACE-FAULTING EARTHQUAKE

Unit 2 FAULT-SCARP COLLUVIUM — *Silty cobbley gravel: Brown (10YR 5/3); 25 percent cobbles, 50 percent gravel, 10 percent sand, 15 percent fines, maximum clast size 150 mm, subangular; low plasticity; poorly stratified, some alignment of clasts parallel to scarp free face; noncemented; small wedge-shaped deposit on a minor antithetic fault (station 34.5) west of the graben formed during the first surface-faulting earthquake recorded in trench MN-1; material derived from erosion of unit 1.*

Unit 3 DEBRIS FLOW *(matrix supported) — Cobbley clayey sandy gravel: Dark brown (10YR 3/3); 15 percent cobbles, 35 percent gravel, 30 percent sand, 20 percent fines, maximum clast size 200 mm, subrounded to subangular; low plasticity; poorly stratified, some alignment of elongate clasts parallel to flow direction; thin, discontinuous $CaCO_3$ coatings on clasts, weakly cemented; distinctive "dark" color.*

Unit 4 DEBRIS FLOW *(matrix supported) — Sandy silty gravel with cobbles grading eastward to sandy gravel: Brown (10YR 5/3); 10 percent boulders, 10-20 percent cobbles, 50-90 percent gravel, 20-30 percent sand, 20-30 percent fines, maximum clast size 350 mm, subangular to subrounded; low to no plasticity; nonstratified; thin, discontinuous $CaCO_3$ coatings on clasts, weakly cemented; thin coarse-grained unit, possibly an upper more fluid phase of unit 3.*

4s *Soil A-Horizon Developed On Units 3 And 4 — Gravelly clayey silt: Dark gray to dark grayish brown (10YR 4/1 - 4/2): 5 percent cobbles, 25 percent gravel, 70 percent fines, maximum clast size 300 mm, subangular to subrounded; low plasticity; poorly developed blocky soil structure; thin, discontinuous $CaCO_3$ coatings on clasts, weak to no cementation; highly organic, charcoal collected from this pre-MRE unit gave a calendar-calibrated radiocarbon age of 680 (+40, -20) yr B.P.*

Unit 5 DEBRIS FLOW *(matrix supported) — Clayey gravelly sand: Yellowish brown (10YR 5/4), 5 percent cobbles, 30 percent gravel, 50 percent sand, 15 percent fines, maximum clast size 200 mm, subangular; low plasticity; nonstratified; thin, discontinuous coatings of $CaCO_3$ on clasts become more prominent toward the west end of the trench, weakly cemented.*

5s *Weak Soil A-Horizon Developed On Unit 5 — Gravelly clayey sand: Dark grayish brown (10YR 5/2); 5 percent cobbles, 25 percent gravel, 50 percent sand, 20 percent clay, maximum clast size 120 mm, subangular to subrounded; low plasticity; nonstratified; noncemented; post-MRE burn layer is at the top of this stratigraphic horizon.*

Unit 6 FLUVIAL GRAVEL

6A *Sandy gravel with cobbles: Yellowish brown to light yellowish brown (10YR 5/4-6/4); 15 percent cobbles, 50 percent gravel, 25 percent sand, 10 percent fines, maximum clast size 300 mm, subangular to subrounded; nonplastic; stratified (beds 20-50 mm thick); noncemented; occupies paleostream channel which was eroded into underlying units west of main fault zone.*

6B *Sandy gravel: Yellowish brown (10YR 5/4); 5 percent cobbles, 75 percent gravel, 20 percent sand, maximum clast size 100 mm, subangular to rounded; nonplastic; stratified (beds 12-25 mm thick); thin, discontinuous coatings of $CaCO_3$ on clasts, weakly cemented; well-sorted fluvial unit overlying more coarse-grained gravel (unit 6A) in cut-and-fill structure; truncated by a later debris flow (unit 7).*

6U *Sandy gravel: Similar to 6A and 6B above, but bedding and other distinguishing features have been destroyed by shearing and folding related to faulting in and near the main fault zone.*

Unit 7 DEBRIS FLOW *(clast supported) — Clayey sandy gravel grading to sandy silty gravel with local coarse-grained cobble horizons: Brown (10YR 5/3); 15-30 percent cobbles and boulders, 30-60 percent gravel, 20-30 percent sand, 10-20 percent fines, maximum clast size 350 mm, subangular to subrounded; low to no plasticity; nonstratified to thinly bedded; noncemented; complex debris flow or possibly multiple small debris flows in a former stream channel.*

MOST RECENT SURFACE-FAULTING EARTHQUAKE

Unit 8 SHEARED FAULT-ZONE MATERIAL AND FAULT-SCARP COLLUVIUM — *Sheared material in the main fault zone and colluvium and fissure-fill deposits derived from erosion of fault scarps produced by the most recent surface faulting.*

MAIN FAULT ZONE

8A *Fissure Fill — Sandy gravel with silt: Mottled very dark grayish brown (10YR 3/2) and brown (10YR 5/3); 5 percent cobbles, 65 percent gravel, 20 percent sand, 10 percent fines, maximum clast size 150 mm, subangular to subrounded; low to no plasticity; nonstratified, noncemented.*

8B *Block of Unit 1 — Block derived from erosion of main fault scarp.*

8C *Fissure Fill — Cobbley sandy gravel: Brown/dark brown (10YR 4/3); 20 percent cobbles, 60 percent gravel, 20 percent sand, maximum clast size 200 mm, subangular; nonplastic; nonstratified; noncemented.*

8D *Block of Unit 3 — Large block, approximately 2 m (6.6 ft) in long dimension.*

8E *Fissure Fill — Sandy silty gravel with cobbles: Brown/dark brown (10YR 4/3); 10 percent cobbles, 50 percent gravel, 20 percent sand, 20 percent fines, maximum clast size 200 mm, subangular to subrounded; low plasticity; nonstratified; noncemented.*

8F *Fault-Scarp Colluvium — Silty sandy gravel with cobbles: Brown/dark brown (10YR 4/3); texturally similar to unit 8E; parallel alignment of elongate clasts indicates deposition along a slope (scarp free face) rather than in a fissure.*

8G *Block of Unit 4s Soil A-Horizon — Gravelly sandy silt: Dark brown (10YR 3/3); 5 percent cobbles, 20 percent gravel, 20 percent sand, 55 percent fines, maximum clast size 100 mm, subangular to subrounded; low plasticity; nonstratified; noncemented; probably derived from unit 4s soil. The sharp upper and lower contacts, abrupt pinch-outs at the ends of the unit, and its absence elsewhere within the scarp-derived colluvium clearly show that this unit is a detached block of material deposited at the base of the scarp and not a soil horizon that formed in place.*

8H *Fissure Fill — Gravelly silt with sand and cobbles: Dark grayish brown (10YR 4/2); 10 percent cobbles, 25 percent gravel, 10 percent sand, 55 percent fines, maximum clast size 250 mm, subangular; low plasticity; nonstratified; noncemented; fills spaces between blocks.*

8I *Blocks of Unit 7 — Several small blocks at various orientations, possible remnants of larger blocks that shattered on impact after rolling or falling from the main scarp.*

8J *Blocks of Unit 1 — Blocks at various orientations, possible remnants of a larger block that shattered on impact after rolling or falling from the main scarp, distinctive "pale brown" color.*

8K *Fault-Scarp Colluvium (derived from units 1 and 3) — Silty sandy gravel with cobbles: Mottled yellowish brown (10YR 5/4) and dark grayish brown (10YR 4/2); 10 percent cobbles, 50 percent gravel, 20 percent sand, 20 percent fines, maximum clast size 200 mm, subangular; low to no plasticity; poorly stratified, some alignment of elongate clasts parallel to scarp slope; non-cemented.*

8L *Fault-Scarp Colluvium (derived from unit 1) — Sandy silty gravel with cobbles: Light yellowish brown (10YR 6/4); 10 percent cobbles, 40 percent gravel, 30 percent sand, 30 percent silt, maximum clast size 250 mm, subangular; low to no plasticity; poorly stratified, some alignment of elongate clasts parallel to scarp slope; noncemented.*

8M *Fault-Scarp Colluvium — Sandy gravelly silt: Dark grayish brown (10YR 4/2); 5 percent cobbles, 25 percent gravel, 20 percent sand, 50 percent fines, maximum clast size 150 mm, subangular; low to moderate plasticity; nonstratified; thin, discontinuous $CaCO_3$ coatings on clasts and filaments in matrix, weak to moderate cementation; organic-rich colluvial deposit.*

8N *Fault-Scarp Colluvium — Gravelly silt with cobbles: Brown/dark brown (10YR 4/3); 10 percent cobbles, 20 percent gravel, 10 percent sand, 60 percent fines, maximum clast size 300 mm, subangular; low plasticity; poorly stratified, some alignment of elongate clasts parallel to scarp slope; noncemented; organic-rich colluvial deposit.*

8O *Fault-Scarp Colluvium — Sandy silty gravel grading to a coarse-grained, openwork of cobbles and gravel; Brown (10YR 5/3); 10-50 percent cobbles, 30-50 percent gravel, 20 percent sand, 5-40 percent fines, maximum clast size 200 mm, subangular; low plasticity; stratified, alignment of elongate clasts parallel to scarp slope; non-cemented.*

8P *Fault-Scarp Colluvium — Cobbley sandy silty gravel: Brown (10YR 5/3), 20 percent cobbles, 40 percent gravel, 20 percent sand, 20 percent fines, maximum clast size 200 mm, subangular; low plasticity; nonstratified; noncemented.*

8Q *Fault-Scarp Colluvium — Sandy silty gravel/sandy gravelly silt: Brown/dark brown (10YR 4/3), 10 percent cobbles, 30-50 percent gravel, 20 percent sand, 30-50 percent fines, maximum clast size 150 mm, subangular; low plasticity; stratified, alignment of elongate clasts parallel to slope; noncemented; texture varies throughout unit.*

8R *Fault-Scarp Colluvium — Sandy silty gravel: Brown (10YR 4/3); 5 percent cobbles, 45 percent gravel, 20 percent sand, 30 percent fines, maximum clast size 200 mm, subangular to subrounded; low plasticity; poorly stratified, some alignment of elongate clasts parallel to scarp slope; noncemented; grades to unit 8T in an upslope (eastward) direction.*

8S *Fault-Scarp Colluvium — Cobbley gravel: Dark brown (10YR 3/3); 40 percent cobbles, 50 percent gravel, 10 percent sand, maximum clast size 300 mm, subangular; nonplastic; stratified, alignment of elongate clasts parallel to scarp slope; noncemented; coarse-grained gravel deposit that grades downslope (westward) into an even more coarse-grained, openwork, scree deposit.*

8T *Fault-Scarp Colluvium — Sandy silt with gravel: Dark grayish brown (10YR 4/2); 5 percent cobbles, 10 percent gravel, 25 percent sand, 60 percent fines, maximum clast* *size 100 mm, subangular to subrounded; low plasticity; nonstratified; noncemented; grades to unit 8U in an upslope (eastward) direction.*

8U *Fault-Scarp Colluvium — Silty gravelly sand/silty sandy gravel: Dark grayish brown (10YR 4/2); 5 percent cobbles, 30-50 percent gravel, 30-50 percent sand, 25 percent fines, maximum clast size 150 mm, subangular; low plasticity; nonstratified; noncemented; texture varies throughout unit, but generally becomes finer in a downslope (westward) direction.*

8V *Fault Shear Zone Material — Sandy gravel with silt and cobbles: Dark brown (10YR 3/3); 10 percent cobbles, 50 percent gravel, 30 percent sand, 10 percent fines, maximum clast size 100 mm, subangular to subrounded; nonplastic; well-developed shear fabric includes alignment of clasts parallel to fault plane; noncemented.*

MAIN ANTITHETIC FAULT ZONE (station 31)

8W *Fault-Scarp Colluvium — Sandy silty gravel/sandy gravelly silt: Brown (10YR 5/3); 5 percent cobbles, 30-60 percent gravel, 20 percent sand, 30-60 percent fines, maximum clast size 200 mm, subangular; low plasticity; poorly stratified, some alignment of elongate clasts parallel to scarp slope; noncemented; grades from fine-to coarse-grained in a downslope (westward) direction.*

8X *Fault-Scarp Colluvium — Gravelly sandy silt: Brown (10YR 5/3); 5 percent cobbles, 20 percent gravel, 20 percent sand, 55 percent fines, maximum clast size 120 mm, subangular to subrounded; low plasticity; nonstratified; noncemented; predates post-MRE burn layer.*

8Y *Fault-Scarp Colluvium — Sandy gravelly silt/sandy silty gravel: Dark grayish brown (10YR 4/2); 10 percent cobbles, 20-30 percent gravel, 10-20 percent sand, 40 percent fines, maximum clast size 250 mm, subangular; low plasticity; stratified, alignment of elongate clasts parallel to scarp slope; noncemented; unit postdates burn layer; variable texture.*

Unit 9 DEBRIS FLOW *(matrix supported) — Silty gravelly sand/silty sandy gravel: Grayish brown (10YR 5/2); 5-10 percent cobbles, 30-50 percent gravel, 30-50 percent sand, 20-30 percent fines, maximum clast size 250 mm, angular to subangular; low plasticity; poorly stratified, some alignment of elongate clasts parallel to flow direction; noncemented; texture varies throughout unit; post-MRE burn layer at upper contact; thin, discontinuous lenses of light gray (10YR 7/2) silt locally in low spots along contact with the overlying debris flow (unit 10).*

POST-MRE BURN LAYER — *Thin, nearly continuous layer of charcoal within the MRE graben resulting from a fire that crossed the Mapleton site following the MRE and subsequent deposition of unit 9 (debris flow) in the graben. Charcoal collected from the burn layer gave calendar-calibrated radiocarbon ages of 510 (+120, -190) and 520 (+120, -60) yr B.P. A thin zone of red, oxidized earth underlies the burn layer locally.*

Unit 10 DEBRIS FLOW *(matrix supported) — Silty sandy gravel/silty gravelly sand: Brown/dark brown (10YR 4/3); 10-15 percent cobbles, 30-50 percent gravel, 30-50 percent sand, 30 percent fines, maximum clast size 250 mm, angular to subangular; low plasticity; nonstratified; noncemented; texture varies throughout unit; overlies the post-MRE burn layer and silt lenses.*

Unit 11 DEBRIS FLOW *(matrix supported) — Sandy gravel with cobbles: Brown (10YR 5/3); 10 percent cobbles, 50 percent gravel, 30 percent sand, 10 percent fines, maximum clast size 250 mm, subangular to subrounded; low to no plasticity; poorly stratified, some alignment of elongate clasts parallel to flow direction; noncemented; texture variable, locally has appearance of a fluvial unit; eroded by units 12A and 12B; a thin, discontinuous silt lens located between stations 28 and 29 may have been deposited by water draining from this unit.*

Unit 12 DEBRIS FLOW

12A *Cobbley silty gravelly sand: Dark grayish brown (10YR 3/2); 15 percent cobbles, 25 percent gravel, 40 percent sand, 20 percent fines, maximum clast size 300 mm, subangular; low to no plasticity; nonstratified; noncemented; interbedded with a coarse-grained, fluvial-appearing unit (12B); erodes unit 11.*

12B *Fluvial Boulders and Cobbles — very coarse-grained openwork deposit: Varicolored, but generally brown (10YR 5/3); 30 percent boulders, 30 percent cobbles, 30 percent gravel, 10 percent sand, maximum clast size 350 mm, subangular; nonplastic; nonstratified; noncemented; coarse-grained unit of limited extent interbedded with a more matrix-rich debris flow (unit 12A); represents either a water-rich (fluvial) phases of the debris flow or a penecontemporaneous flood deposit from the same storm event; erodes unit 11.*

Unit 14 DEBRIS FLOW *(matrix supported) — Silty gravelly sand grading westward to gravelly sandy silt: Brown/dark brown (10YR 4/3); 10 percent cobbles, 20-40 percent gravel, 20-40 percent sand, 20-50 percent fines, maximum clast size 200 mm, subangular; low to moderate plasticity; nonstratified; noncemented.*

Unit 14 DEBRIS FLOW *(matrix supported, historical) — Silty sandy gravel with cobbles: Brown/dark brown (10YR 4/3); 10 percent cobbles, 40 percent gravel, 30 percent sand, 20 percent fines, maximum clast size 200 mm, subangular; low plasticity; nonstratified; noncemented; contains pieces of barbed wire.*

DESCRIPTION OF GEOLOGIC UNITS MAPLETON NORTH TRENCH 2

(see figure 5)

Unit 1 DEBRIS FLOW *(matrix supported) — Sandy gravel with cobbles: Yellowish brown (10YR 5/4); 10 percent cobbles, 60 percent gravel, 20 percent sand, 10 percent fines, maximum clast size 150 mm, subangular to subrounded; low plasticity; nonstratified; thin, discontinuous $CaCO_3$ coatings on clasts, weakly cemented.*

Unit 2 DEBRIS FLOW *(matrix supported) — Sandy silty gravel with cobbles: Dark brown (10YR 3/3) to brown (10YR 5/3); 10 percent cobbles, 50 percent gravel, 15 percent sand, 25 percent fines, maximum clast size 200 mm, subangular to subrounded; low plasticity; poorly stratified, some alignment of elongate clasts parallel to flow direction; thin, discontinuous $CaCO_3$ coatings on clasts and some filaments in matrix, weakly cemented; unit contains several thin, fluvial-appearing horizons that may represent a more fluid phase of the debris flow; correlates with unit 3 in trench MN-1.*

2s *Soil A-Horizon Developed On Unit 2 — Gravelly clayey silt: Brown (10YR 5/3); 5 percent cobbles, 35 percent gravel, 10 percent sand, 50 percent fines, maximum clast size 150 mm, subangular to subrounded; low to moderate plasticity; nonstratified; thin, discontinuous $CaCO_3$ coatings on clasts, filaments in matrix, weakly cemented; correlates with unit 4s in trench MN-1, but is not as strongly developed and is more coarse grained; charcoal collected from this unit gave a calendar-calibrated radiocarbon age of 690 (+230, -140) yr B.P.*

Unit 3 DEBRIS FLOW *(matrix supported) — Gravelly silty sand/gravelly sandy silt: Pale brown (10YR 6/3); 10 percent cobbles, 20-30 percent gravel, 20-40 percent sand, 20-50 percent fines, maximum clast size 250 mm, subangular to subrounded; low plasticity; nonstratified; continuous $CaCO_3$ coatings on the bottom of clasts, abundant filaments in matrix, weakly to moderately cemented; texture varies throughout unit; distinctive "white" color; correlates with unit 5 in trench MN-1, but lacks the soil development found on unit 5 in trench MN-1.*

Unit 4 FLUVIAL GRAVEL/SAND — *Sandy gravel/gravelly sand: Yellowish brown (10YR 5/4); 5 percent cobbles, 45 percent gravel, 45 percent sand, 5 percent fines, maximum clast size 100 mm, subangular to subrounded; nonplastic; prominent bedding (25-50 mm thick); thin, discontinuous $CaCO_3$ coatings on clasts, weakly cemented; discontinuous, moderately sorted fluvial unit; may correlate with unit 6 in trench MN-1.*

Unit 5 DEBRIS FLOW *(matrix and locally clast supported) — Silty sandy gravel with cobbles and boulders: Brown/dark brown (10YR 4/3); 10 percent cobbles and boulders, 40 percent gravel, 30 percent sand, 20 percent fines, maximum clast size 350 mm, subangular to subrounded; low plasticity; nonstratified; noncemented; may correlate with unit 7 in trench MN-1; becomes thinner and progressively more coarse grained to the east.*

Unit 6 DEBRIS FLOW/DEBRIS FLOOD *(clast supported) — Silty gravelly sand: Dark brown (10YR 3/3); 5 percent cobbles, 30 percent gravel, 50 percent sand, 15 percent fines, maximum clast size 150 mm, subangular to subrounded; nonplastic; nonstratified; noncemented; last unit deposited prior to the MRE; locally eroded by post-MRE debris flows.*

MOST RECENT SURFACE-FAULTING EARTHQUAKE

Unit 7 SHEARED FAULT-ZONE MATERIAL AND FAULT-SCARP COLLUVIUM — *Sheared material in fault zones and colluvial deposits derived from erosion of antithetic scarps produced by the MRE; corresponds to unit 8 in trench MN-1.*

ANTITHETIC FAULT (station 5)

7A *Shear Zone Material — Sandy gravel with cobbles: Mottled yellowish brown (10YR 5/4) and dark brown (10YR 3/3); 10 percent cobbles, 60 percent gravel, 20 percent sand, 10 percent fines, maximum clast size 150 mm, subangular to subrounded; low to no plasticity; well-developed shear fabric parallel to fault plane; noncemented; material within the shear zone is derived primarily from units 1 and 2, but the zone is so disturbed by shearing that individual geologic units could not be recognized.*

7B *Fault-Scarp Colluvium — Sandy gravel: Brown/dark brown (10YR 4/3); 5 percent cobbles, 60 percent gravel, 25 percent sand, 10 percent fines, maximum clast size 150 mm, subangular to subrounded; nonplastic; poorly stratified, some alignment of elongate clasts parallel to scarp free face; noncemented; small wedge of scarp-derived colluvium deposited adjacent to an antithetic fault resulting from the most recent surface-faulting earthquake.*

ANTITHETIC FAULT ZONE (station 9)

7C *Shear Zone Material — Cobbley gravelly sand: Brown (10YR 5/3); 25 percent cobbles, 30 percent gravel, 35 percent sand, 10 percent fines, maximum clast size 200 mm, subangular to subrounded; nonplastic; well-developed shear fabric parallel to fault plane; noncemented; material within the shear zone is derived primarily from units 2 and 3, but the zone is so disturbed by shearing that individual geologic units could not be recognized.*

7D *Fault-Scarp Colluvium — Sandy silty gravel/sandy gravelly silt: Brown/dark brown (10YR 4/3); 10 percent cobbles and boulders, 20-40 percent gravel, 20 percent sand, 30-50 percent fines, maximum clast size 350 mm, subangular to subrounded; low plasticity; poorly stratified, some alignment of elongate clasts parallel to scarp slope; noncemented; texture varies throughout unit.*

Unit 8 DEBRIS FLOW *(matrix supported) — Silty gravelly sand: Brown/dark brown (10YR 4/3); 10 percent cobbles, 30 percent gravel, 40 percent sand, 20 percent fines, maximum clast size 200 mm, subangular to subrounded; low plasticity; poorly stratified, some alignment of elongate clasts parallel to the flow direction; noncemented; charcoal collected at the floor of the MRE graben (contact between unit 6, underlying, and unit 8, overlying) gave three possible calendar-calibrated radiocarbon ages of 430, 360, and 330 (+70, -40) yr B.P.*

Unit 9 POND DEPOSIT

9A *Clayey silt: Dark grayish brown (10YR 4/2); 5 percent sand, 95 percent fines, maximum particle size approximately 0.5 mm (fine sand), subangular to subrounded; low to moderate plasticity; nonstratified; noncemented; thin organic unit marking the bottom of a former pond in the MRE graben.*

9B *Sandy silt: Brown (10YR 5/3); 25 percent sand, 75 percent silt, maximum particle size approximately 0.5 mm (fine sand), subangular to subrounded; low plasticity; thinly bedded (beds 3-12 mm thick), contains thin, discontinuous layers of fine silty sand; noncemented; interfingers upslope (westward) with unit 10 (slope colluvium).*

Unit 10 SLOPE COLLUVIUM — *Silty gravelly sand: Brown/dark brown (10YR 4/3); 5 percent cobbles, 30 percent gravel, 40 percent sand, 25 percent silt, maximum clast size 150 mm, subangular; low plasticity; stratified, elongate clasts aligned parallel to the side slope of graben; noncemented; interfingers downslope (eastward) with unit 9B.*

Unit 11 POND DEPOSIT

11A *Silty sand: Pale brown (10YR 6/3); 75 percent sand, 25 percent fines, maximum particle size approximately 0.5 mm (fine sand), angular to subangular; low to no plasticity; very thinly stratified (beds 1-3 mm thick), bedding highly deformed, probably the result of excessive loading of the soft, wet sediments during the deposition of unit 12; noncemented; detrital charcoal collected from this unit gave a calendar-calibrated radiocarbon age of 740 (+160, -230) which is stratigraphically out of place.*

11B *Silt: Brown (10YR 5/3); 10 percent sand, 90 percent fines, maximum particle size approximately 0.5 mm (fine sand), angular to subangular; low to no plasticity; thin, highly contorted bedding (1-3 mm thick); noncemented.*

Unit 12 DEBRIS FLOW *(matrix supported) — Gravelly sandy silt/gravelly silty sand: Grayish brown (10YR 3/2); 5 percent cobbles, 20 percent gravel, 20-50 percent sand, 30-60 percent silt, maximum clast size 300 mm, subangular to subrounded; low to no plasticity; nonstratified; noncemented; texture varies throughout unit; contains thin, discontinuous, contorted layers of silt incorporated from unit 11 as the debris flow entered the pond and caused the soft-sediment deformation seen in unit 11.*

Unit 13 POND DEPOSIT — *Sandy silt with thin interbeds of silty sand: Yellowish brown (10YR 3/3); 25 percent sand, 75 percent fines with interbeds of 75 percent sand and 25 percent fines, maximum particle size approximately 0.5 mm (fine sand), subangular to subrounded; low to no plasticity; nonstratified except for thin (5-10 mm thick) sand lenses; noncemented.*

Unit 14 DEBRIS FLOW *(matrix supported, historical) — Gravelly sandy silt/ gravelly silty sand: Brown (10YR 3/2); 5 percent cobbles, 20 percent gravel, 25 percent sand, 50 percent fines, maximum clast size 200 mm, subangular to subrounded; low plasticity; nonstratified; noncemented; historic debris flow that buries artifacts (plates, shoes, worn out farm implements) which were lying on the alluvial-fan surface (in the pond); occupies same stratigraphic position as unit 14 in trench MN-1.*

14s *Weak Soil A-Horizon Developed On Unit 14 — Gravelly silty sand: Brown/dark brown (10YR 4/3); weak organic soil horizon developed on historical debris flow.*

DESCRIPTION OF GEOLOGIC UNITS MAPLETON SOUTH TRENCH 1

(see figure 7)

Unit 1 LAKE BONNEVILLE DEPOSITS

1A *Lake Bonneville Transgressive Shoreline Gravels — Cobbley sandy gravel with boulders: Color ranges from strong brown (7.5YR 5/8) to yellowish red (5YR 5/6) depending on color of large clasts; 5 percent boulders, 20 percent cobbles, 50 percent gravel, 25 percent sand, maximum clast size 350 mm, subrounded to rounded; nonplastic; poorly bedded; continuous coatings of $CaCO_3$ weakly cements some clasts together; unit caved continuously, causing the south wall at the east end of the trench to be undermined; exposed only in the footwall of the main fault zone; larger clasts adjacent to the main fault have been rotated parallel to the fault plane.*

1B *Lake Bonneville Deep-Water Sands and Silts — Silty sand/sandy silt: Very pale brown (10YR 7/3); 50 percent sand, 50 percent fines, maximum particle size approximately 0.5 mm (fine sand), subrounded to rounded; nonplastic; nodules and filaments of $CaCO_3$, weakly cemented; nonstratified; exposed only in the footwall of the main fault zone; evidence of bioturbation near upper contact.*

Unit 2 PRE-PENULTIMATE EVENT DEBRIS FLOWS AND FLUVIAL DEPOSITS

2A *Debris Flow (matrix supported) — Gravelly silty sand: Yellowish brown (10YR 5/4); 5 percent cobbles, 20 percent gravel, 45 percent sand, 30 percent fines, maximum clast size 150 mm, subangular to subrounded; low to no plasticity; nonstratified; thin, discontinuous $CaCO_3$ coatings on clasts, weakly cemented.*

2B *Fluvial Gravel — Sandy gravel with cobbles: Yellowish brown (10YR 5/4); 10 percent cobbles, 60 percent gravel, 25 percent sand, 5 percent silt, maximum clast size 250 mm, subrounded to rounded; nonplastic; layer of coarse gravel and cobbles at upper contact; thin, discontinuous $CaCO_3$ coatings on clasts, weakly cemented; deposited by a flood that crossed the alluvial-fan surface.*

2C *Debris Flow (matrix supported) — Sandy silty gravel with cobbles: Yellowish brown (10YR 5/4); 10 percent cobbles, 40 percent gravel, 25 percent sand, 25 percent fines, maximum clast size 250 mm, mostly angular to subangular with some subrounded clasts; low plasticity; poorly stratified, some alignment of elongate clasts parallel to flow direction; thin, discontinuous $CaCO_3$ coatings on clasts, weakly cemented.*

2s *Soil A-Horizon Developed On Unit 2C — Sandy silt with gravel: Brown (10YR 5/3); 5 percent cobbles, 10 percent gravel, 25 percent sand, 60 percent fines, maximum clast size 150 mm, subangular to subrounded; low to medium* *plasticity; nonstratified; thin, discontinuous $CaCO_3$ coatings on clasts, weakly cemented; backtilted near main fault zone; dark color is distinctive; charcoal collected from this unit gave three possible calendar-calibrated radiocarbon dates of 2930, 2900, and 2890 (+280, -130) yr B.P., an AMRT age estimate obtained from bulk soil organics indicates the time of burial of this unit by an overlying debris flow (unit 4D) was 2820 (+150, -130) yr B.P., and a TL age estimate obtained for the time of soil burial was 3300 (± 300) years ago.*

2D *Debris Flow (matrix supported) — Sandy silty gravel with cobbles: Yellowish brown (10YR 5/4); 10 percent cobbles, 35 percent gravel, 25 percent sand, 30 percent fines, maximum clast size 200 mm, subangular to subrounded; low plasticity; poorly stratified, some alignment of elongate clasts parallel to flow direction; thin, discontinuous $CaCO_3$ coatings on clasts, weakly cemented; only locally present within trench MS-1.*

PENULTIMATE SURFACE-FAULTING EARTHQUAKE

Unit 3 PENULTIMATE EVENT FAULT-SCARP COLLUVIUM

3A *Fault-Scarp Colluvium Derived From Lake Bonneville-Shoreline Sediments (unit 1A) — Cobbley sandy gravel: Very pale brown (10YR 7/4); 20 percent cobbles, 50 percent gravel, 30 percent sand, maximum clast size 200 mm, subrounded to rounded; nonplastic; poorly stratified, some alignment of clasts parallel to scarp free face; noncemented; loose sand and gravel from unit 1A that quickly caved and accumulated near the bottom of the main scarp following the penultimate earthquake.*

3B *Fault-Scarp Colluvium Derived From Lake Bonneville Deep-Water Sediments (unit 1B) — Silty sand: Very pale brown (10YR 7/4); 60 percent sand, 40 percent fines, maximum particle size approximately 2 mm (medium sand), subangular to subrounded; nonplastic; thinly bedded (1-5 mm thick) parallel to the slope of the scarp; thin, discontinuous layer of loose sand that accumulated quickly near the bottom of the main scarp following the penultimate earthquake.*

3C *Rotated Blocks From Unit 2 Debris Flows — Sandy silty gravel to sandy gravel: Light yellowish brown (10YR 6/4); 10 percent cobbles, 50 percent gravel, 20-40 percent sand, 10-20 percent fines, maximum clast size 200 mm, subangular to subrounded; low to no plasticity; blocks are at various orientations, most show some evidence of original stratification due to parallel alignment of elongate clasts, however, some clast alignment may be due to later shearing; weak, relict $CaCO_3$ cementation.*

3D *Rotated Blocks of Lake Bonneville Deep-Water Sediments (unit 1B) — Silty sand/sandy silt: Light yellowish brown (10YR 6/4); 50 percent sand, 50 percent fines, maximum particle size approximately 0.5 mm (fine sand), subrounded to rounded; nonplastic; blocks are at various orientations; weak, relict $CaCO_3$ cementation.*

3E *Fault-Scarp Colluvium (derived primarily from unit 2 debris-flow and fluvial units) — Silty sand with gravel: Generally brown (10YR 5/3), but locally mottled yellowish brown (10YR 5/4) and brown/dark brown (10YR 4/3); 10 percent gravel, 50-60 percent sand, 25-35 percent fines, maximum clast size 200 mm, subangular to subrounded; low to no plasticity; poorly stratified, some alignment of elongate clasts parallel to scarp slope; thin, discontinuous, sometimes powdery $CaCO_3$ coatings on clasts, weakly cemented; remnant of a thick colluvial-wedge deposit that formed adjacent to the main fault scarp following the penultimate earthquake.*

Unit 4 POST-PENULTIMATE EVENT DEBRIS-FLOW, FLUVIAL, AND COLLUVIAL DEPOSITS

4AU *Debris Flow (undifferentiated) — Cobbley sandy gravel: Pale brown (10YR 6/3); 20 percent cobbles and boulders (cobbles predominate), 50 percent gravel, 20 percent sand, 10 percent fines, maximum clast size 400 mm, angular to subrounded, most larger clasts angular; low to no plasticity; poorly stratified, some alignment of elongate clasts parallel to flow direction; thin, discontinuous $CaCO_3$ coatings on clasts, weakly cemented; post-penultimate event debris flow that contains a thin, well-sorted silty sand lens that either separates two debris flows of similar texture or was deposited penecontemporaneously by flood water between pulses of more viscous, coarse-grained material that now appear as a single debris flow.*

4A1 *Debris Flow (below thin sand lens) — Cobbley sandy gravel: Pale brown (10YR 6/3); 20 percent cobbles, 50 percent gravel, 20 percent sand, 10 percent fines, maximum clast size 300 mm, subangular to subrounded; low plasticity; nonstratified; thin, discontinuous $CaCO_3$ coatings on clasts, weakly cemented.*

4A2 *Debris Flow/Fluvial Deposit (thin sand lens) — Silty sand: Yellowish brown (10YR 5/4); 40 percent fines, 60 percent sand, maximum clast size approximately 4 mm (coarse sand), angular to subrounded; low to no plasticity; thinly stratified (beds 2-5 mm thick); thin, discontinuous $CaCO_3$ coatings on clasts, small nodules of caliche in matrix, weakly cemented; thin unit of limited horizontal extent either deposited penecontemporaneously within a complex debris flow or between two separate debris flows.*

4A3 *Debris Flow (above thin sand lens) — Cobbley sandy gravel: Pale brown (10YR 6/3); 20 percent cobbles and boulders (cobbles predominate), 50 percent gravel, 20 percent sand, 10 percent fines, maximum clast size 400 mm, angular to subrounded, most larger clasts angular; low to no plasticity; poorly stratified, some alignment of elongate clasts parallel to flow direction; thin, discontinuous $CaCO_3$ coatings on clasts, weakly cemented.*

4B *Fluvial Gravel — Sandy gravel: Brown/dark brown (10YR 4/3); 80 percent gravel, 20 percent sand, maximum clast size 50 mm, subangular to subrounded; nonplastic; stratified; thin, discontinuous $CaCO_3$ coatings on clasts and small caliche nodules in matrix, weakly cemented; distinctive, well-sorted stream gravel.*

4C *Fluvial Sand — Silty sand: Yellowish brown (10YR 5/4); 5 percent gravel, 70 percent sand, 25 percent fines, maximum clast size 20 mm, subangular to subrounded; low to no plasticity; poorly stratified; noncemented; thin unit of limited horizontal extent, possibly deposited within a graben resulting from the penultimate earthquake.*

4D *Fluvial Gravel — Sandy gravel: Pale brown (10YR 6/3); 60 percent gravel, 40 percent sand, maximum clast size 50 mm, subangular to subrounded; nonplastic; well bedded; thin, discontinuous $CaCO_3$ coatings on clasts, weakly cemented.*

4E *Debris Flow (matrix supported) — Silty sandy gravel/silty gravely sand: Brown/dark brown (10YR 4/3); 10 percent cobbles and boulders, 35 percent gravel, 35 percent sand, 20 percent fines, maximum clast size 350 mm, subangular with some subrounded clasts; low plasticity; poorly stratified, some alignment of elongate clasts parallel to flow direction; strong $CaCO_3$ coatings on clasts, weakly to moderately cemented; thick debris-flow unit with a distinctive "gray" color.*

4F *Debris Flow (clast supported) — Silty gravel with sand and cobbles: Brown (10YR 5/3); 10 percent cobbles, 60 percent gravel, 10 percent sand, 20 percent fines, maximum clast size 250 mm, subangular to subrounded; low to moderate plasticity; stratified, alignment of elongate clasts parallel to flow direction creates a strong imbrication fabric; continuous $CaCO_3$ coatings on clasts, weakly to moderately cemented; caliche coatings give a distinctive "silver" color to unit; contains charcoal which gave a calendar-calibrated radiocarbon date of 1290 (+130, -230) yr B.P.; locally eroded by unit 4I.*

4G *Debris Flow/Debris Flood (clast supported) — Sandy gravel: 5 percent cobbles, 65 percent gravel, 20 percent sand, 10 percent fines, maximum clast size 150 mm, subangular to subrounded; nonplastic; alignment of elongate clasts parallel to flow direction creates a strong imbrication fabric; continuous $CaCO_3$ coatings on clasts, weakly cemented; caliche gives unit a distinctive "silver" color. This unit was displaced during the MRE, but could not be recognized with certainty in the main fault zone. It is probably represented in the main fault zone by unit 4U, which is also coarse grained, but too badly disturbed by faulting to be positively correlated with a unit 4 deposit outside of the fault zone.*

4Gs *Soil A-Horizon Developed On Unit 4G — Silty sand with gravel: Dark grayish brown (10YR 4/2); 5 percent cobbles, 10 percent gravel, 50 percent sand, 35 percent fines, maximum clast size 100 mm, subangular to subrounded; low plasticity; nonstratified; thin, discontinuous $CaCO_3$ coatings on clasts and caliche filaments in matrix, weakly cemented; not recognized in the main fault zone.*

4H *Slope Colluvium — Sandy silt: Brown (10YR 5/3); 5 percent cobbles, 35 percent sand, 60 percent fines, maximum clast size 150 mm, subangular to subrounded; low to no plasticity; nonstratified; some $CaCO_3$ filaments, weakly cemented.*

4I *Fluvial Gravel — Sandy clayey gravel: Brown (10YR 5/3); 60 percent gravel, 20 percent sand, 20 percent fines, maximum clast size 50 mm, subangular to subrounded; low to moderate plasticity; stratified; continuous CaCO3 coatings on clasts, weakly cemented; clay adheres to gravel clasts; locally erodes lower units.*

4J *Slope Colluvium — Clayey sand: Dark grayish brown (10YR 3/2); 5 percent cobbles, 5 percent gravel, 50 percent sand, 40 percent fines, maximum clast size 150 mm, subangular to subrounded; moderate plasticity; nonstratified; noncemented.*

4U *Unit 4 Undifferentiated — Sandy gravel: Brown (10YR 5/3); faulted material related to unit 4, but not identifiable as to subunit.*

MOST RECENT SURFACE-FAULTING EARTHQUAKE

Unit 5 MOST RECENT EVENT FAULT-SCARP COLLUVIUM

MAIN FAULT ZONE

5A *Fault-Scarp Colluvium Derived From Lake Bonneville Shoreline Sediments (unit 1A) — Cobbley gravelly sand: Very pale brown (10YR 7/4), but with numerous large clasts of other colors; 20 percent cobbles, 20 percent gravel, 50 percent sand, 10 percent fines, maximum clast size 200 mm, subrounded to rounded; nonplastic; nonstratified; noncemented; loose material derived from unit 1A that accumulated quickly at the base of the main scarp following the most recent surface-faulting earthquake.*

5B *Fault-Scarp Colluvium Derived From Lake Bonneville Deep-Water Sediments (unit 1B) — Silty sand: Very pale brown (10YR 7/3); 5 percent gravel and cobbles, 65 percent sand, 30 percent fines, maximum clast size 100 mm, subangular to subrounded; nonplastic; nonstratified; $CaCO_3$ disseminated throughout unit, probably relict, weakly cemented.*

5C *Rotated Blocks Derived From Unit 1B and/or 3E — Silty sand/sandy silt: Very pale brown (10YR 7/3); 50 percent sand, 50 percent fines, maximum particle size approximately 0.5 mm (fine sand), subrounded to rounded; nonplastic; nonstratified; nodules and filaments of $CaCO_3$ present, weakly cemented; blocks are at various orientations.*

5D *Fault-Scarp Colluvium — Sandy clayey gravel: Brown (10YR 5/3); 5 percent cobbles, 40 percent gravel, 25 percent sand, 30 percent fines, maximum clast size 150 mm, subangular; moderate plasticity; nonstratified; relict coatings of $CaCO_3$ on clasts, noncemented; probably derived from alluvial-fan (debris-flow) deposits on the upthrown block.*

5E *Rotated Blocks Derived From Units 2 and 4 — Silty sandy gravel to silty gravelly sand: Pale brown (10YR 6/3); 10 percent cobbles, 20-40 percent gravel, 20-40 percent sand, 20 percent fines, maximum clast size 200 mm, subangular to subrounded; low to moderate plasticity; parallel alignment of elongate clasts shows relict flow bedding, now inclined at various orientations; relict $CaCO_3$ coatings, weakly cemented.*

5F *Fault-Scarp Colluvium — Silty gravelly sand to silty sandy gravel: Pale brown (10YR 6/3); 10-20 percent cobbles, 20-40 percent gravel, 20-40 percent sand, 20-40 percent fines, maximum clast size 200 mm, subangular to subrounded; low to no plasticity; nonstratified to locally thinly bedded (5-15 mm thick); relict $CaCO_3$ coatings on many clasts, noncemented; loose sand and gravel filling spaces between scarp-derived blocks of material.*

5G *Fault-Scarp Colluvium — Clayey sand with gravel: Brown (10YR 5/3); 10 percent gravel, 50 percent sand, 40 percent clay, maximum clast size 50 mm, subangular; moderate plasticity; nonstratified; noncemented; dark color makes this unit distinctive, possibly derived from unit 4J.*

5H *Blocks of Soil A-Horizon Material — Clayey sand/sandy clay: Dark grayish brown (10YR 4/2); 10 percent gravel, 45 percent sand, 45 percent fines, maximum clast size 100 mm, subangular; low to moderate plasticity; nonstratified; noncemented; very dark color, highly organic material.*

5I *Fault-Scarp Colluvium — Silty gravelly sand: Yellowish brown (10YR 3/3); 5 percent cobbles, 30 percent gravel, 40 percent sand, 25 percent fines, maximum clast size 150 mm, subangular; low to moderate plasticity; some alignment of elongate clasts parallel to scarp slope; relict $CaCO_3$ coatings, noncemented; possibly derived from unit 4J.*

5J *Fault-Scarp Colluvium — Silty sand: Brown (10YR 5/3); 5 percent gravel and cobbles, 60 percent sand, 35 percent fines, maximum clast size 100 mm, subangular to subrounded; low to no plasticity; nonstratified; relict $CaCO_3$ coatings on clasts and caliche filaments, noncemented.*

5K *Fault-Scarp Colluvium — Sand with silt: Pale brown (10YR 6/3); 90 percent sand, 10 percent fines, maximum particle size approximately 2 mm (medium sand), subangular to subrounded; nonplastic; nonstratified; relict nodules and filaments of caliche, noncemented; probably derived from units 1B and/or 3E.*

5L *Fault-Scarp Colluvium — Gravelly silty sand: Yellowish brown (10YR 5/4); 5 percent cobbles, 30 percent gravel, 35 percent sand, 30 percent fines, maximum clast size 150 mm, subangular; low plasticity; alignment of elongate clasts parallel to scarp slope; continuous $CaCO_3$ coatings on clasts, weakly cemented; slope-wash facies of scarp-derived colluvium deposited as the fault scarp began to re-establish a smooth profile.*

5M *Fault-Scarp Colluvium — Silty sand with gravel and cobbles: Brown/dark brown (10YR 4/3); 5 percent cobbles, 10 percent gravel, 50 percent sand, 35 percent fines, maximum clast size 250 mm, subangular; low plasticity, alignment of elongate clasts parallel to scarp slope; continuous, thick $CaCO_3$ coatings on clasts, weakly cemented; slope-wash facies.*

5N *Graben-Fill Colluvium in Small Antithetic Fault Zone — Gravelly silty sand: Dark grayish brown (10YR 3/2); 5 percent cobbles, 25 percent gravel, 40 percent sand, 30 percent fines, maximum clast size 150 mm, subangular; low plasticity; poorly stratified; noncemented.*

WEST FAULT ZONE

5O *Fault-Scarp Colluvium — Sandy silty gravel: Brown/dark brown (10YR 3/2); 5 percent cobbles, 50 percent gravel, 25 percent sand, 20 percent fines, maximum clast size 150 mm, subangular to subrounded; low plasticity; poorly stratified, some alignment of clasts parallel to scarp slope; thin, discontinuous coatings of $CaCO_3$ on clasts, weakly cemented.*

5P *Fault-Scarp Colluvium — Silty sandy gravel grading to silty gravelly sand: Brown/dark brown (10YR 4/3); 10 percent cobbles, 30-60 percent gravel, 30-60 percent sand, 30 percent fines, maximum clast size 150 mm, subangular; low plasticity; alignment of clasts parallel to scarp slope; noncemented; slope-wash facies that becomes finer grained to the west.*

Unit 6 POST-FAULTING SLOPE COLLUVIUM — *Gravelly silty sand to silty sandy gravel: Dark grayish brown (10YR 4/2); 10 percent cobbles, 20-40 percent gravel, 20-40 percent sand, 20-40 percent silt, subangular to subrounded; low to moderate plasticity; alignment of elongate clasts parallel to slope; noncemented; variable texture, finer grained to the west (downslope).*