Woodward-Clyde Consultants

STUDY OF EARTHQUAKE RECURRENCE INTERVALS ON THE WASATCH FAULT, UTAH

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INTRODUCTION

Detailed geologic mapping, topographic profiling, and trenching are being conducted at selected sites along the Wasatch fault zone to measure the cumulative fault displacements in Quaternary strata of various ages and to obtain data regarding the amount of displacement per surface faulting event and the number and recurrence of faulting events that produced the cumulative displacement. These data are used to estimate the frequency of occurrence and magnitude of earthquakes associated with surface faulting along individual segments of the Wasatch fault zone. Investigations have been completed at three sites, the Kaysville, Hobble Creek, and Little Cottonwood Canyon sites (Figure 1). The results of the investigations at the Kaysville and Hobble Creek sites are discussed in our previous reports, which are listed in Appendix A. Detailed geologic investigations were conducted at the Little Cottonwood Canyon site during June, July, and October, 1979. This report presents our findings, interpretations, and preliminary conclusions based on our field investigations at the Little Cottonwood Canyon site.

LOCATION AND SETTING OF THE LITTLE COTTONWOOD CANYON SITE

The Little Cottonwood Canyon site is located at the mouths of Little Cottonwood and Bells canyons 20 km south-southeast of downtown Salt Lake City, Utah (Figures 1 and 2). Elevations in the study area at the base of the Wasatch Front range from approximately 1524 to 1829 m. Higher peaks in the Wasatch Range attain elevations of greater than 3354 m within 5 km of the base of the range. Little Cottonwood and Bells canyons are glacially carved valleys that are deeply incised into the range. Little Cottonwood Creek and Dry Creek (Bells Canyon) presently occupy these valleys and drain into Jordan Valley to

the west. Bedrock in the mountain front consists of late Precambrian clastics (mostly quartzite) intruded by quartz monzonite of the early Tertiary Little Cottonwood Stock (Granger and others, 1952).

During the late Pleistocene glacial maximum, numerous cirques and compound cirques supplied ice to major westward--flowing valley glaciers in both Little Cottonwood and Bells canyons. These glaciers extended as much as 1.7 km beyond the canyon mouths. Glacial outwash was deposited in a large compound delta, the Cottonwood delta, that formed at the mouths of Little Cottonwood and Big Cottonwood canyons and prograded into Lake Bonneville. The Bonneville shoreline, which marks the last major high stand of Lake Bonneville, occurs along the mountain front at elevations that vary from 1561 to 1567 m.

The Wasatch fault at this location is expressed as a zone up to 530 m wide that contains numerous subparallel and branching fault scarps. (Figure 3). Lateral moraines at the mouths of Little Cottonwood and Bells canyons are displaced by numerous east- and west-facing fault scarps that form a series of graben; the largest graben can be traced almost continuously for approximately 3 km north and 1 km south of Bells Canyon.

PREVIOUS INVESTIGATIONS

The relationships between the glacial and lacustrine deposits at the mouths of Little Cottonwood and Bells canyons have been studied by numerous investigators. These deposits were briefly noted during the Fortieth Parallel Survey of the 1870's (Hague and Emmons, 1877) and by King (1878), but were first studied in detail by Gilbert (1890). Atwood (1909), Blackwelder (1931), Marsell (1946), Ives (1950), and Eardley, Gvosdetsky, and Marsell (1957) also discussed shoreline and

moraine relations in this area. Additional data on Lake Bonneville stratigraphy and history in Jordan Valley are provided by studies of Jones and Marsell (1955) and Marsell and Jones (1955). The most comprehensive investigations of Quaternary deposits and history, including detailed mapping, were furnished by Richmond (1964), who studied the glacial deposits in Little Cottonwood and Bells canyons, and Morrison (1965a), who concurrently studied the Lake Bonneville stratigraphy of eastern Jordan Valley.

The Quaternary glacial sequence in the Little Cottonwood-Bells canyons area has recently been reevaluated by McCoy (1977) and Madsen and Currey (1979). Reassessment of the Lake Bonneville stratigraphy and history along the entire Wasatch fault is presently being conducted by Scott (1979a; 1979b; in press).

Gilbert (1890; 1928) made the first detailed study of the Wasatch fault zone. Other studies of the fault zone made prior to 1964 are summarized by Marsell (1964). Possible active traces of the Wasatch fault have been delineated by Cluff and others (1974) based on interpretation of 1:12,000 low-sun-angle black and white aerial photographs. Additional photogeologic interpretation and preliminary field reconnaissance along this segment of the fault were conducted by Gary A. Carver and John C. Young during an investigation for the U.S. Geological Survey, in which the Little Cottonwood Canyon site was selected for detailed investigation (Woodward-Clyde Consultants, 1975).

Seismicity data from the Intermountain seismic belt is presented by Arabasz and others (1979), Cook (1972), Cook and Smith (1967), and Smith and others (1978). The distribution of earthquakes within 10 km (epicentral distance) of the Wasatch fault zone during the period from July 1962 to June 1978 suggests that the Little Cottonwood Canyon site is near

the northern limit of a 70-km-long seismic gap (Arabasz and others, 1979).

METHODS OF STUDY

Geologic investigations at the Little Cottonwood Canyon site included:

1. Photointerpretation - Analysis of aerial photographs of the site was made to identify fault traces and to aid in selecting trench sites. The following imagery was used: a) 1970 1:12,000 low-sun-angle (morning and evening) black and white photographs; b) 1970 1:6000 low-sun-angle (morning and evening) black and white photographs; and c) 1958 1:10,000 and 1978 1:12,000 conventional, black and white photographs.

2. Topographic Profiling - Longitudinal topographic profiles across the main fault scarp, antithetic fault scarps, and adjacent geomorphic surfaces were measured using an Abney level, Brunton compass, and tape. The profiles, in conjunction with trench and map data, are used to assess cumulative displacement across the fault zone, examine the amount and extent of back-tilting, and examine the relationship between faulting and scarp morphology.

3. Trenching - Three trenches, totaling 109 m, were excavated and logged at a scale of 1:20 to assess the structural and stratigraphic relationships across the main fault and graben (Figures 2 and 4). A fourth trench was excavated into the base of the main fault scarp near the southern end of the graben but the fault could not be exposed and this trench was not logged in detail.

4. Radiocarbon Dating - Samples of detrital charcoal and carbonized wood were handpicked from the graben fill and colluvial deposits that were exposed in the trenches. The samples are too small to be dated by conventional radiocarbon beta counting techniques. The samples have been submitted to the Swiss Federal Institute of Technology's laboratory in Zurich, Switzerland, to determine if they can be dated by using an accelerator as a high energy mass spectrometer to measure the radioisotope concentrations. Results of these analyses are expected later this summer.

QUATERNARY STRATIGRAPHY

Interpretation of the geologic evidence for past surface faulting earthquakes depends on an understanding of the depositional and erosional history of the site. Despite the numerous studies of the late Quaternary stratigraphy that have been made during the past 25 years, there are still many unresolved questions regarding stratigraphic interpretations and ages assigned to the Quaternary deposits of the Bonneville basin. Stratigraphic studies and regional correlations by Morrison (1965a; 1965b; 1975) and Morrison and Frye (1965) and dating investigations by Broecker and Kaufman (1965) are presently the most cited sources on Lake Bonneville stratigraphy. However, the stratigraphic interpretations presented by these writers are presently being evaluated and revised by Scott (1979a; 1979b; in press). A correlation chart summarizing the glacial and pluvial history of the Little Cottonwood Canyon site is presented on Figure 5. The stratigraphy and chronology shown on this chart are based primarily on the current studies of Scott (1979a; 1979b; in press) and recent investigations of the glacial chronology of Little Cottonwood and Bells canyons by McCoy (1977) and Madsen and Currey 1979).

Although nearly all previous workers (Marsell, 1947; Eardley and others, 1957; Antevs, 1945) recognized two moraines at the mouth of Bells Canyon and interpreted them to be deposits of two separate glaciations, Richmond (1964) interpreted the moraines as representing two stades of the same glaciation. On the basis of stratigraphy, soils, and a qualitative comparison with glacial deposits of the Wind River Mountains of Wyoming, Richmond correlated this glaciation with the Bull Lake glaciation, which was considered at that time to be early Wisconsin in age. Recently, the glacial chronology of the Wind River Mountain sequence has been reevaluated, and the Bull Lake moraines at the type locality are now interpreted to be late Illinoian in age (Pierce and others, 1976). Because of the questions of correlation and age of the moraines at Little Cottonwood and Bells Canyon, the glacial sequence in this area has been reexamined by McCoy (1977) and Madsen and Currey (1979). Comparison of relative weathering characteristics on the moraine deposits at the mouth of Bells Canyon suggests that there is a significant difference in the age of the two moraines (McCoy, 1977). The younger moraine, mapped as late Bull Lake deposits by Richmond (1964), is probably correlative with early Pinedale moraines of late Wisconsin age elsewhere in the Rocky Mountains. The age of the older moraine is uncertain, but the extreme weathering suggests that it may represent a pre-Wisconsinan glacial advance (McCoy, 1977; Madsen and Currey, 1979). A correlation of nomenclature used by Richmond (1964) and Madsen and Currey (1979) for the glacial deposits of Little Cottonwood and Bells canyons is presented in Table 1.

A bulk soil sample from a mature paleosol (Majestic Canyon soil) developed on outwash overlying the Dry Creek till has yielded a radiocarbon date of 26,080 (+1200; -1100) y.b.p. (GX-4737) (Madsen and Currey, 1979). This mature soil is correlated with isotope stages 5 and 3 (Madsen and Currey,

1979). The radiocarbon date provides a maximum limiting age for the overlying younger till (Bells Canyon till).

Although climate-related indicators such as the marine record show that in mid-latitudes the Wisconsin epoch began about 75,000 years ago and, including fluctuations in intensity, lasted until about 12,000 to 10,000 years ago, deposits of earlier times of the Wisconsin (isotope stage 4) have not been recognized in the glacial sequence in this area. Whether this reflects non-deposition or burial by younger deposits is uncertain at this time.

The chronology of the Lake Bonneville sequence is also problematical. Based on stratigraphic studies of pluvial and interpluvial deposits and soils along the Wasatch Front in Jordan Valley and at Little Valley near Promontory Point, and studies of cores from deep boreholes (Saltair and Burmester cores), Morrison (1975) formulated a complex late Quaternary history of repeated fluctuations of pluvial lakes in the Bonneville basin. These chronologic/stratigraphic events are summarized in Table 2. Some aspects of this chronology have recently been questioned by Scott (1979a; 1979b; in press). Of particular significance to the estimates of recurrence and slip rate along the Wasatch fault zone are the definition, identification, and correlation of the Alpine and Bonneville formations (Scott, 1979b; in press). As defined by Morrison (1975), deposits of the most recent major lake cycle of Lake Bonneville are included in the Bonneville Formation; deposits of the second-most recent lake cycle are termed the Alpine Formation. At Little Valley, these formations are separated by a buried soil (Promontory Soil) and subaerial deposits (Morrison, 1965b). However, similar evidence of a major depositional break between deposits mapped as Alpine and Bonneville along the Wasatch Front is, at best, equivocal. In most places, the deposits of both formations appear to have

been deposited during the same lake cycle, the cycle in which the lake rose to the Bonneville shoreline. Limiting radiocarbon dates can only broadly place the age of the Bonneville shoreline between 20,000 and 12,000 years ago (Morrison, 1965b; Broecker and Kaufman, 1965; Scott, in press).

Evidence of a major unconformity beneath Bonneville lake deposits in the high-shore zone is well exposed in gravel pits north of the mouth of Big Cottonwood Canyon. In these exposures, Bonneville lake sediments bury a topographic surface having relief of at least 20 m to probably as much as 80 to 100 m (Scott, 1979b; in press). This unconformity is generally underlain by a strongly developed paleosol formed on pre-Bonneville cycle alluvium, which most likely is outwash from Big Cottonwood Creek. The paleosol probably represents weathering that culminated during the last interglacial period (isotope stage 5), and may be correlative with the Promontory Soil at the type locality.

Several authors (Bissell, 1963; Morrison, 1965a; Broecker and Kaufman, 1965) have postulated a rise of Lake Bonneville to, or nearly to, the Provo shoreline (elevation about 1455 m) about 10,000 years ago following a brief regression to a very low level. Deposits of this rise are included in the lower member of the Draper Formation of Morrison (1965a). However, radiocarbon dates from Danger Cave (elevation 1314 m) in western Utah suggest that from shortly before 10,000 to 11,000 years ago to the present the lake has stood within 40 m of the level of the present Great Salt Lake (Jennings, 1957). Evaluation of previously published and new information supports the interpretation of lake history based on the Danger Cave data (Scott, 1979a; in press). Along Dry Creek west of the Little Cottonwood Canyon site, the lower member of the type Draper Formation defined by Morrison (1965a) is probably alluvium and colluvium of Holocene age, rather than lacustrine deposits

representing a high stand of Lake Bonneville (Scott, 1979a; in press).

PHOTOGEOLOGIC INTERPRETATION

The distribution and pattern of faults and linear geomorphic features that may be faults in the Little Cottonwood Canyon site are shown on Figure 6. The zone of most recent faulting is conspicuous across the moraines at the mouths of Bells Canyon and Little Cottonwood Canyon. Here, the zone is up to 530 m wide and consists of as many as eleven north-trending, generally subparallel, fault scarps that face both to the west and to the east (Figures 3 and 6).

The fault crosses Little Cottonwood Canyon as a graben that displaces Provo- and younger-aged alluvium. Many of the fault scarps that occur to the south may have been eroded and/or buried by younger alluvium. Terraces located in the canyon upstream from the graben may be tectonic in origin, and could represent three or four episodes of faulting that resulted in entrenchment of the stream on the upthrown block. Similar terraces were not observed on the downthrown block. Numerous springs occur at the base of the main fault between Little Cottonwood Creek and the left lateral moraine in Little Cottonwood Canyon.

Immediately north of Little Cottonwood Canyon, the zone is defined by a prominent curvilinear west-facing scarp and a 200-m-wide zone of antithetic faulting developed in moraines; the heights of the antithetic scarps vary from less than 10 m to about 20 m. To the north, the main scarp, which is 25 to 40 m high, splays into three west-facing scarps having heights of 4 to 4.5 m, 2 m, and 3.5 m.

In addition to the fault-related features described above, several other scarps were identified. The most prominent of these trends northeast to north and is located immediately east of the municipal water treatment plant approximately 1 km northwest of the mouth of Little Cottonwood Canyon and 500 m west of the main fault zone (l_1, Figure 6). Morrison (1965a, p. 50) states that this scarp "displaces the Bonneville Member and apppears to date from the recession of the Bonneville-Provo lake cycle, after the Bonneville shoreline maximum, and probably shortly before or perhaps even during the Provo stillstand." Morrison (1965a, p. 50) also states that the contact between lacustrine sediments and the underlying lower till and outwash of the Bull Lake (Dry Creek till) stade in the scarp "appears to be dropped down at least 110 feet [134 m] below its position as projected from exposures in the scarp." However, this relationship cannot be verified from the present exposures. The scarp forms the southeastern edge of the terraces graded to the Provo and lower levels of Little Cottonwood Creek. The scarp may have been modified by lateral cutting of the creek during the Provo stillstand. If the scarp is a fault, there does not appear to have been appreciable displacement along it since the Provo level stillstand. The northern extension of the water plant scarp forms the western boundary of a horst-like ridge (l_2, Figure 6), which is bounded to the east by a more subdued scarp (l_3, Figure 6).

A north-facing scarp (l_4, Figure 6) south of Little Cottonwood Creek has been mapped previously as a continuation of the water plant scarp (Morrison, 1965). This scarp, which is more subdued and dissected, appears to be an erosional scarp produced during lateral cutting of Little Cottonwood Creek during the Provo stillstand. Two additional northwest-trending, down-to-the-southwest lineaments (l_5, Figure 6) were identified on the aerial photographs. These lineaments coincide with the margins of glacial outwash channels as mapped by Morrison (1965).

STRATIGRAPHY EXPOSED IN EXPLORATORY TRENCHES

Exploratory trenches LC-1, LC-2, and LC-3 were excavated across the main fault scarp and an antithetic scarp in a graben north of Little Cottonwood Canyon (Figures 2, 4, and 6). These trenches exposed Bonneville lake sediments, post-Bonneville alluvial fan and graben-fill deposits, Bells Canyon till, and scarp-derived colluvium. Stratigraphic and structural relationships exposed in these trenches are shown on Figures 6, 7, and 8.

Trenches LC-1 and LC-2

The oldest deposits exposed in trenches LC-1 (Figure 7b) and LC-2 (Figure 8) are lake sediments deposited during the last major high stand of Lake Bonneville. These deposits were exposed in the footwall in both trenches, and at a depth of 6 m in a test pit excavated in the floor of the graben on the downthrown side of the fault approximately 80 m west of the main fault scarp. The lake deposits consist of a coarse sequence of interbedded sand, gravelly sand, and pebble to cobble gravel that is overlain by thinly bedded silt and clayey silt. A weak to moderate calcic soil is developed on the Bonneville lake sediments. The soil profile, which has been truncated by erosion, consists of an approximately 20- to 30-cm-thick C_{ca} horizon (unit 1Sa) that is weakly to moderately indurated by calcium carbonate. This horizon is locally underlain by a zone (note n_1 on Figures 7b and 8) up to 1 m thick of lake sediments in which bedding has been disrupted by bioturbation.

The exact age of these deposits is not known. Based on radiocarbon dates of lake sediments deposited elsewhere in the Bonneville basin during the last high stand (see general

discussion of Quaternary stratigraphy), the deposits are between 12,000 and 20,000 years old. In both trenches, the Bonneville lake sediments are overlain by alluvial fan deposits (unit 2). They are in fault contact with graben-fill deposits (unit 3), and may be in fault contact with scarp-derived colluvium (unit 4).

The alluvial fan deposits (units 2a and 2b) in trench LC-1 consist of dark yellowish brown to dark brown, poorly sorted, unstratified silty fine sand and gravelly sand. Gravel clasts range in size from pebbles to cobbles and are generally subangular. In trench LC-2, the alluvial fan deposits are similar in color and texture to those exposed in trench LC-1 but are, in part, moderately to well bedded (unit 2a) and appear to have been deposited within a channel in the alluvial fan. Bedding gradually becomes less well defined in the upper part of the fan deposits (units 2b and 2c). In both trenches, the alluvial fan deposits have been displaced by faults on the upthrown block east of the main fault.

The graben-fill deposits (unit 3) consist of an interbedded sequence of sandy silt, gravelly sandy silt and silty sand, and minor discontinuous lenses of pebbly sand and gravel. The deposits generally coarsen and bedding becomes less well defined toward the main fault scarp. In places, poorly developed buried A horizons of soil (paleo-entisols) are preserved. The contacts between some of these soils and overlying sediments have been delineated on the log of trench LC-1 (Figure 7b) as marker horizons. The A horizon of the soil formed on the graben-fill deposits at the ground surface (unit 3S) is 50 to 100 cm thick and consists of very dark gray sandy silt having massive to weakly developed coarse blocky structure.

Adjacent to the main fault scarp, the graben-fill deposits may consist, in part, of scarp-derived colluvium. Within the graben, the deposits are chiefly derived from an alluvial fan, which has breached the fault scarp north of the trench site. The exact ages of the alluvial fan deposits on the upthrown block (unit 2) and within the graben (unit 3) are not known. Most, if not all, of unit 3 appears to be younger than unit 2, and both units postdate the recession of the lake from the Bonneville shoreline. These fans are included in a complex series of alluvial fans and fan segments that occur at the mouths of intermittent streams and gullies along the mountain front between Deaf Smith and Little Cottonwood canyons. Slip along the Wasatch fault has repeatedly beheaded many of these fans, producing fan segments of different ages.

Two samples of detrital charcoal were collected from the graben-fill deposits (unit 3) in trench LC-1. Sample number LC-1-1 is from unit 3e at station 33.4 and at a depth of 3.4 m (Figure 7b). Sample number LC-1-2 is from unit 3a and was collected between stations 3 and 4 (west of main fault) at a depth of 3 m. A third sample (LC-2-1) consisting of carbonized wood or burned root was collected from an organic-rich infilling that fills a fissure in the graben fill (Figure 8; unit 3; station 1.5 west; depth 2 m). All three samples are too small to be dated by conventional radiocarbon beta counting techniques.

Unit 4 consists mostly of dark, yellowish brown, gravelly silty sand derived primarily from alluvial fan deposits (unit 2) on the upthrown side of the fault. Fragments consisting of silt that is partially cemented by calcium carbonate occur within unit 4 and appear to have been derived from soil S1 in the upthrown block. On the north wall of trench LC-2 (not shown), unit 4 contained well-bedded sand and gravel that resemble the stratigraphy of unit 2. Unlike

unit 2, the sand and gravel beds in unit 4 dip steeply, suggesting that, in this exposure, most of unit 4 consists of an intact block of unit 2 that slumped off of the fault scarp. In trench LC-1, unit 4 is disturbed by numerous animal burrows.

The youngest colluvial unit on the main fault scarp (unit 5) grades laterally into the A horizon of the soil developed on the graben-fill deposits (unit 3). This unit overlies the main fault and is in depositional, rather than fault, contact with the underlying alluvial fan deposits (unit 2), scarp-derived colluvium (unit 4), and graben-fill deposits (unit 3). This unit was deposited immediately after the most recent surface faulting event.

Trench LC-3

Till of the younger lateral moraine at the mouth of Little Cottonwood Canyon is exposed in the footwall of the main antithetic fault in trench LC-3 (Figures 6 and 9). This till is correlated with the Bells Canyon till in the stratigraphic section measured by Madsen and Currey (1979) at Majestic Canyon Estates. The till is coeval with the Bonneville lake deposits exposed in trenches LC-1 and LC-2. Till interfingering with lake sediments was observed in exposures in the main fault scarp approximately 100 m south of LC-1. Till below elevations of 1566 m is veneered by Bonneville lake sediments, suggesting that the glacier began to recede before the lake reached this level (McCoy, 1977).

The till exposed in trench LC-3 is a yellowish brown, poorly sorted, compact mixture of sand, gravel, and silt. Gravel clasts are subangular and subrounded and range in size from pebbles to boulders up to 1 m in diameter. Quartz monzonite clasts within the till are fresh to partly grussified.

The till is displaced across several shears associated with the main antithetic fault and is in fault contact with scarp-derived colluvium (unit 3a). This colluvium consists of massive, poorly sorted dark yellowish brown, gravelly slightly silty sand that is derived primarily from the till (unit 1). It grades eastward from the scarp into finer graben-fill deposits (unit 3b) that consist of massive sandy silt containing less than ten percent pebbles and cobbles. The percentage and size of the gravel clasts decrease away from the fault scarp. The very dark grayish brown, organic-rich A1 horizon of a soil ($3S_1$) formed on the graben-fill deposits is 50 to 100 cm thick; the soil thickens adjacent to a shear zone approximately 10 m east of the main antithetic fault zone. The lower part of the soil profile (unit $3S_2$) is mottled in color and contains less organic material. These deposits are probably the same age as the graben-fill deposits (unit 3) in trench LC-1. A small sample of detrital charcoal (sample LC-3-1) was collected from unit 3b in this trench between stations 5.5 and 7.8 at a depth of 2 to 2.5 m.

An older graben-fill deposit was exposed in the lower part of trench LC-3 east of the fault zone at stations 12 to 17 (unit 2 on Figure 9). The deposit is a massive, poorly sorted slightly clayey gravelly silty sand that contains more gravel (10 to 20 percent) than the overlying younger graben fill. The age of this deposit is not known.

Trench LC-4

Trench LC-4 was excavated into the main fault scarp in an area where the most recent displacement along the main fault has occurred primarily along a single fault trace (Figure 6). Due to the height and steepness of the fault scarp and to the thickness of the bouldery colluvium on the scarp, it was not

possible to excavate far enough into the scarp to expose the main fault. The deposits exposed in this trench consisted of a sequence of three colluviums separated by organic soil horizons. The colluvial deposits were derived from moraine deposits exposed in the main fault scarp.

FAULTING AND DEFORMATION OBSERVED IN EXPLORATORY TRENCHES

Faulting Associated with Main Fault Scarp. Trenches LC-1 and LC-2 (Figures 7b and 8) crossed the westernmost scarp of the main fault north of where it splays to form three subparallel traces (Figure 6). The faulting exposed in these trenches is described below.

Numerous minor faults that strike subparallel to the main fault and have small displacements (maximum of 6 cm) occur on the upthrown side of the fault in a zone extending for at least 6 m east from the main fault trace. The faults have normal displacement and form numerous horsts and graben in the Bonneville lake deposits. The upper parts of some of these faults have been obscured by soil forming processes and they cannot be traced into the post-Bonneville soil (unit 1S). Some of these minor faults displace the the 1S soil but not the overlying alluvial fan deposits (unit 2) and others displace both the soil and fan deposits.

The main fault strikes N15 to 45E and dips 60 to 70 degrees west. It juxtaposes the Bonneville lake deposits and the overlying alluvial fan deposits (units 1 and 2) against graben fill and colluvium (units 3 and 4). Young scarp colluvium (unit 5) overlies the fault and is not displaced. The cumulative vertical displacement on this fault appears to be greater than the height of the exposure (8 to 9 m). Based on the depth to the lake deposits near the center of the graben, the

post-Bonneville displacement may have been as much as 13 m on this fault. Alluvial fan deposits (unit 2) were not exposed on the downthrown side of the fault because they are too deep or they were eroded prior to deposition of the graben fill. Therefore, the amount of post-unit 2 displacement across the main fault is not known.

The graben-fill deposits, unit 3, occur only on the downthrown side of the fault; they were deposited against a preexisting scarp and have subsequently been faulted. Unit 4 is a colluvial unit that was derived from the fault scarp following the faulting that displaced unit 3 and soil 3S. In trench LC-1 and on the south wall of trench LC-2, this unit appears to be faulted, having a maximum down-to-the-west displacement of 40 cm. However, on the north wall of trench LC-2, this unit consists of bedded sand and gravel similar to the alluvial fan deposits (units 2a and 2b). The bedding is nearly vertical and the unit appears to be a slumped block of unit 2. The contact between this block and the fault scarp (that is, between unit 4 and units 1 and 2) may represent a slide plane along which the block failed and not post-unit 4 faulting.

Antithetic Faulting. Trench LC-1 crossed most of the graben and exposed numerous small antithetic faults (Figure 7b). Trench LC-3 was excavated across the main antithetic fault near the southern end of the graben (Figure 9).

The massive nature of the graben-fill deposits in trench LC-1 (unit 3) makes it difficult to detect faults having small displacement. However, more than 15 faults having displacements ranging from less than a centimeter to about 36 cm were observed. Where successively younger marker beds could be measured across the same fault, the amount of displacement was consistently the same, suggesting that these faults were all produced during one surface faulting event. The faults strike

N11E to N28E and dip steeply to both the east and west. Both down-to-the-east and down-to-the-west normal displacements were observed. Although many of these faults are associated with fissure infillings that involve the modern soil, most of them are not apparent at the ground surface. The only faults that clearly displace the ground surface are a zone of small faults 18 to 21 m west of the main fault that form a 2-m-wide complex graben having a net vertical displacement of 36 cm down to the west across the zone. The small west-facing scarp over this zone exhibits the same sense and amount of displacement.

Along most of its length, the main antithetic fault that bounds the graben on the west has been modified by a road (Figure 6). Trench LC-3 crossed the main antithetic fault scarp near the southern end of the graben where the road turns away from the fault. In this trench, Bells Canyon till (unit 1, Figure 9) is overlain by scarp-derived colluvium (unit 3a) that grades into the graben-fill deposit (unit 3b). Renewed movement along the fault has displaced the scarp-derived colluvium. In the older till deposits, the fault consists of a 30-cm-wide zone containing numerous anastomosing shears; there is a pronounced fabric with the long axes of the sand grains and pebbles oriented parallel to the fault plane. In the colluvium, the faults are difficult to detect and the fabric is poorly developed.

Cumulative Displacement Based on Topographic Profiles

Figure 10 is a topographic profile across the fault zone near trench LC-1. The steepness of the fans adjacent to the mountain front, the complexity of the fault zone, and differences in the ages of the surficial deposits make it difficult to determine the cumulative net tectonic displacement across

the zone at this location. Bonneville lake deposits crop out at the surface in road cuts on the west side of the graben and in the trenches excavated across the westernmost main fault scarp (station 0 on Figures 7 and 8). The difference in elevation between the top of the lake deposits in these exposures suggests that the cumulative post-Bonneville vertical displacement across the graben is 4 to 4.5 m. The displacement of the Holocene fan surface across the two fault scarps to the east is about 5.5 m. The amount of post-Bonneville displacement on these two faults must be at least this amount. This suggests that the post-Bonneville displacement across the entire zone is a minimum of 9.5 to 10 m.

Topographic profiles were measured along the crest of the prominent moraines that have been displaced across a 400-m-wide zone of faults at the mouths of Little Cottonwood and Bells canyons (Figure 11). Profile A-A' was measured along the crest of the left lateral moraine at the mouth of Little Cottonwood Canyon, and profile B-B' was measured along the right lateral moraine of Bells Canyon (Figures 3 and 6). Both of these moraines are underlain by Bells Canyon till (McCoy, 1977; Madsen and Currey, 1979).

The complexity of the fault zone and changes in the initial slope of the moraine crest across the zone make it difficult to measure the cumulative net vertical tectonic displacement across the fault zone. Measurements of the net displacement on the moraine at Bells Canyon (profile B-B', Figure 11) are further complicated by surface modifications resulting from the construction of dams. Based on the projection of the moraine surface across the fault zone, the net vertical tectonic displacement on the moraine in Little Cottonwood Canyon is estimated to be 14.5 (+10; -3) m. The amount varies depending upon the inferred location of the inflection between the crest and the nose of the moraine. Estimates for the net

displacement on the moraine in Bells Canyon range from a minimum of about 11 m to a maximum of about 24 m. A preferred value could not be selected because of the modification of this moraine. Madsen and Currey (1979) report a similar value (14 ± 3 m) for the net throw across the zone of normal and antithetic faults displacing the Bells Canyon till.

SLIP RATE

The late Pleistocene-Holocene slip rate along the segment of the Wasatch fault zone at the Little Cottonwood Canyon site is 0.9 (1.0; -0.3) mm per year based on the 14.5 (+10; -3) m cumulative net vertical tectonic displacement of the Bells Canyon age moraines, which are estimated to be 16,000 ± 3000 years old. Table 3 summarizes the available slip rate data for the Wasatch fault zone.

DISPLACEMENT PER EVENT AND EARTHQUAKE MAGNITUDE

The occurrence of multiple fault traces across a wide zone of deformation makes it difficult to determine the amount of displacement that occurred during individual faulting events. Data from a test pit and trenches LC-1 and LC-2 suggest that the top of the Bonneville lake deposits is displaced approximately 13 m down to the west across the main fault exposed in these trenches (Figure 10). This displacement was produced by a minimum of two or three surface faulting events. Evidence for the third event is equivocal; if it does represent a separate event, it produced a maximum of 0.4 m along this fault trace. This suggests that 12.6 m of vertical displacement may have been produced by two events on this trace, or 6.3 m per event. Data from the Kaysville and Hobble Creek sites indicate that the net cumulative tectonic displacement across the

fault zone at these sites is about half the cumulative displacement on the main fault scarp. This suggests that the net tectonic vertical displacement at Little Cottonwood Canyon may have been about 3.2 m per event.

On the west side of the graben, the top of the Bonneville lake deposits is displaced about 9 m down to the east across the main antithetic fault. The field relationships do not allow us to relate faulting events on the main antithetic fault directly to faulting on the main fault exposed in trenches LC-1 and LC-2. However, the age of the graben fill displaced along the main antithetic fault exposed in trench LC-3 indicates that displacement along this fault and the main fault in trenches LC-1 and LC-2 probably occurred simultaneously. Therefore, the true tectonic displacement across the graben (slip on main fault minus slip on antithetic fault) is about 4 m. If this displacement was produced by 2 or 3 events, the net vertical tectonic displacement was 1.3 to 2 m per event.

The available data suggest that the net tectonic displacement at the Little Cottonwood Canyon site may have ranged from 0.4 m per event to 3 m per event. However, factors that affect the accuracy of this estimate include the following:

1) There may have been more than two or three faulting events along the main fault trace exposed in trenches LC-1 and LC-2, which would decrease the average displacement per event. Evidence for other events may not have been preserved or could be buried too deep to have been exposed in the trenches.

2) East of trenches LC-1 and LC-2, there are two other splays of the main fault that have scarp heights of 2 and 3.5 m. More than one of these traces may have experienced displacement during a single event; this would increase the displacement per event.

3) The 2:1 ratio between displacement along the main fault and the net tectonic displacement observed at the Kaysville and Hobble Creek sites does not apply to all parts of the Wasatch fault zone and it may not be applicable to the segment of the fault at the Little Cottonwood Canyon site. The calculated values for the average displacement per event will vary depending upon this ratio.

Table 4 summarizes the available data on the amount of displacement per event on the Wasatch fault zone. Despite the uncertainties in the data for the Little Cottonwood Canyon site, the values for the net tectonic displacement per event are very similar to the values at the Kaysville and Hobble Creek sites.

Swan and others (in press) estimate the earthquake magnitudes associated with past surface faulting events at the Kaysville and Hobble Creek sites based on the empirical relation between the logarithm of maximum displacement and earthquake magnitude (Slemmons, 1977). The displacement data at these sites indicate that magnitude 6 1/2 to 7 1/2 earthquakes have occurred repeatedly along those segments of the fault zone. Although the data are not as well constrained at the Little Cottonwood Canyon site due to the complexity of the fault zone at this location, the available data on the amount of displacement per event suggest that earthquakes having comparable magnitudes have also occurred repeatedly along this segment of the fault zone.

RECURRENCE OF SURFACE FAULTING

Radiocarbon age dates on samples of detrital charcoal that were collected from the trenches are not yet available. These samples are too small to date using conventional beta counting

techniques. The samples have been submitted to the Labratorium fur Kernphysik at the Swiss Federal Institute of Technology for dating by determining the isotope concentrations by using an accelerator as a high energy spectrometer. If ages can be obtained on these samples, the dates will constrain the ages of the two most recent faulting events at the Little Cottonwood Canyon site.

Although individual faulting events have not been dated yet, the average recurrence interval for surface faulting events can be estimated based on the slip rate and displacement per event using the following equation:

$$\text{Recurrence Interval} = \frac{\text{Displacement Per Event}}{\text{Slip Rate}}$$

Using the preferred value of 0.9 mm per year for the slip rate and the range of 0.4 to 3 m for the displacement per event gives an average recurrence interval of approximately 450 and 3300 years for surface faulting events at the Little Cottonwood Canyon site. The average displacement per event is probably close to 2 m, which sugests that the recurrence interval may be closer to 2200 years. The factors affecting the estimated values for displacement per event also affect the accuracy of the calculated recurrence interval. Although the data are not well constrained, the available evidence suggests that the fault zone at the Little Cottonwood Canyon site has had a history of recent faulting that is similar to the history of faulting at the Hobble Creek site. Table 5 summarizes the estimated recurrence intervals at three locations along the Wasatch fault zone.

SUMMARY AND CONCLUSIONS

The Little Cottonwood Canyon site is 20 km south-southeast of Salt Lake City. At this location, the Wasatch fault is a zone up to 0.5 km wide that contains numerous discontinuous sub-parallel and branching fault traces. Seismicity data suggest that the Little Cottonwood Canyon site is located near the northern end of a 70-km-long seismic gap.

Late Pleistocene lateral moraines at the mouths of Little Cottonwood and Bells canyons are displaced by east- and west-facing scarps that form a series of graben. Individual scarps associated with these graben are up to 35 to 40 m high. The cumulative net tectonic displacement of the moraines, which are 16,000 ± 3000 years old, is 14.5 (+10.0; -3.0) m. The late Pleistocene (post-Bells Canyon till) slip rate is 0.9 (+1.0; -0.3) mm per year.

The cumulative displacement was produced by multiple surface faulting events. Data from trenches excavated across a graben north of Little Cottonwood Canyon that displaces Holocene alluvial fan deposits indicate that the graben was produced by a minimum of two or three surface faulting events. The average vertical tectonic displacement per event is estimated to be between 0.4 and 3 m for these events; the preferred average value is estimated to be about 2 m per event. This estimate may represent minimum values because of the presence of sub-parallel fault traces. The recurrence interval for surface faulting events at the Little Cottonwood Canyon site is estimated to be between 450 and 3300 years; the preferred interval is approximately 2200 years. The available data suggest that the history of recent faulting at the Little Cottonwood Canyon site is similar to the history of faulting 50 km to the south at the Hobble Creek site, which is located along the same seismic gap. The displacement data indicate that earthquakes

having magnitudes of 6 1/2 to 7 1/2 have occurred repeatedly along this segment of the fault zone.

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APPENDIX A

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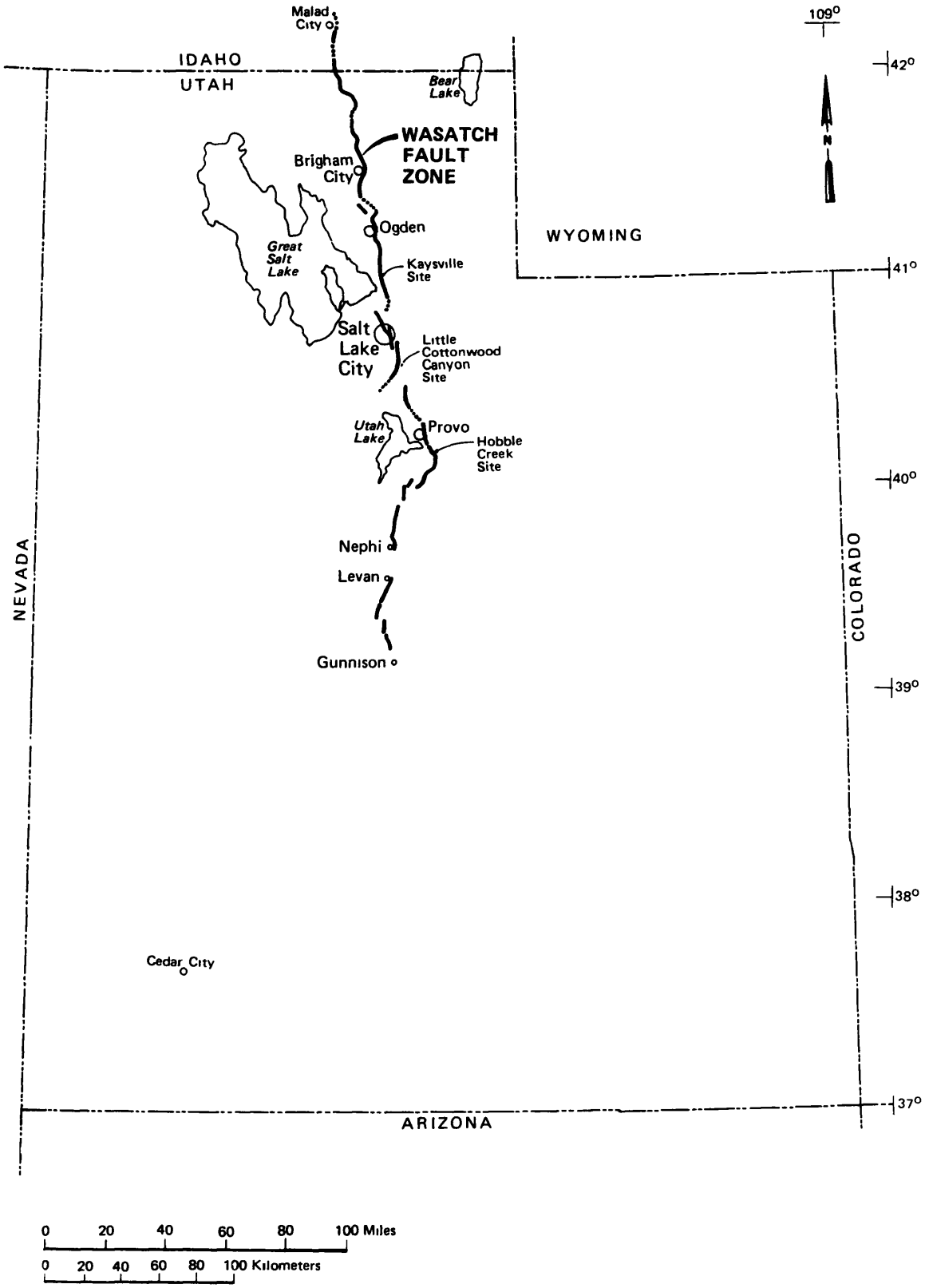
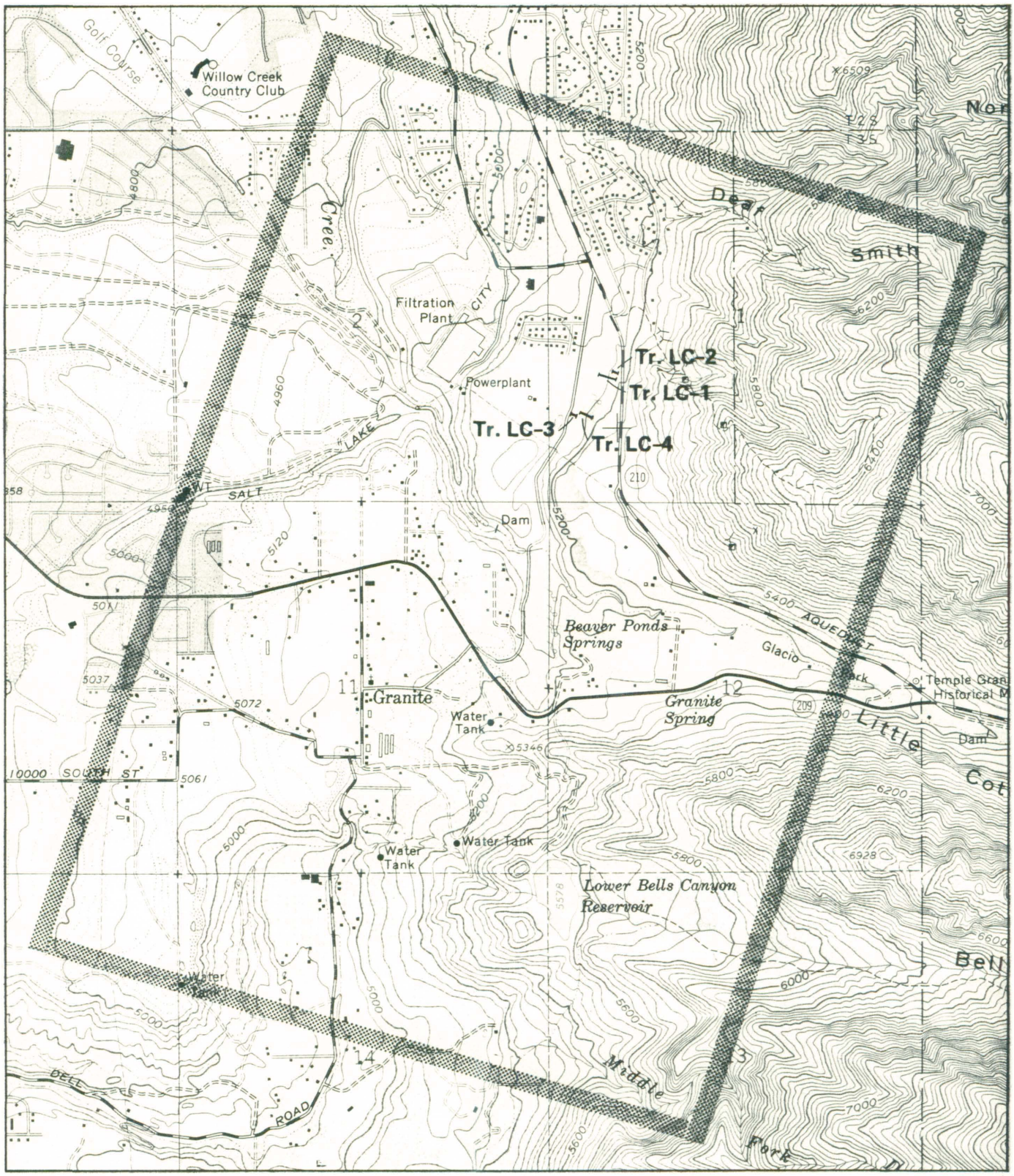


Project No. 14093B	USGS Contract No. 14-08-0001-16827	MAP OF WASATCH FAULT ZONE	Figure 1
Woodward-Clyde Consultants			



0 ½ 1 mile

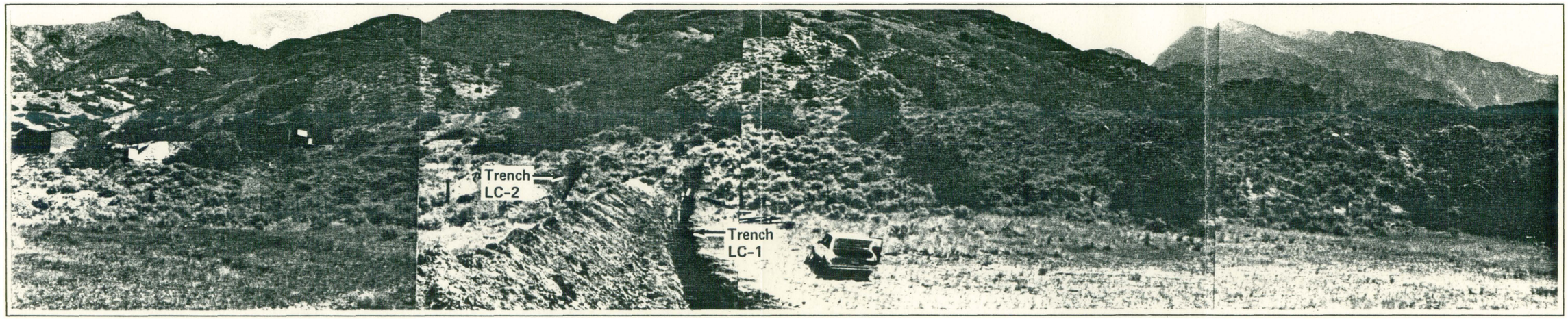
0 0.5 1 kilometer

Area of detailed map of Wasatch Fault (Figure 6)

Project No. 14093B	USGS Contract No. 14-08-0001-16827	LOCATION MAP OF LITTLE COTTONWOOD CANYON SITE	Figure 2
Woodward-Clyde Consultants			

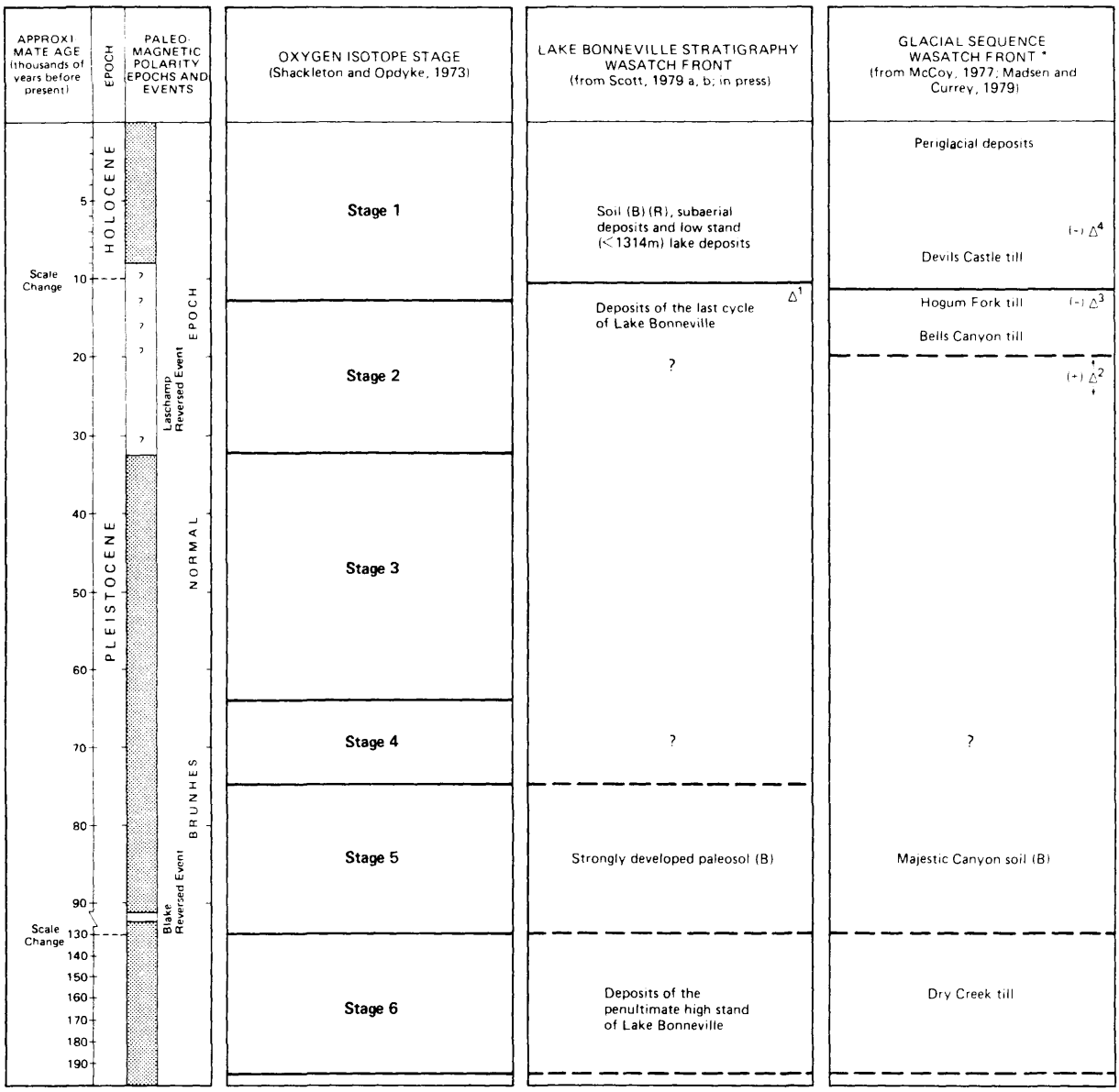
Oblique aerial photograph of the Wasatch fault zone at the mouths of Little Cottonwood and Bells canyons. View is east.

Project No. 14093B	USGS Contract No. 14-08-0001-16827	PHOTOGRAPH SHOWING THE WASATCH FAULT ZONE Little Cottonwood Canyon Site	Figure 3
Woodward-Clyde Consultants			



Trenches LC-1 and LC-2 were excavated across the westernmost splay of the main fault. View is east from center of graben.

Project No. 14093B	USGS Contract No. 14-08-0001-16827	PHOTOGRAPH OF TRENCHED FAULT SCARP Little Cottonwood Canyon Site	Figure 4
Woodward-Clyde Consultants			



EXPLANATION:

- Δ^3 — Radiocarbon date. Number refers to note listed below; arrows indicate statistical limits of error where space permits.
- (+) — Radiometric data indicate that this is the maximum age for the overlying unit.
- (-) — Radiometric data indicate that this is the minimum age for the underlying unit.
- Soil — Soil, either buried (B) or relict (R)
- ——— Boundary of stratigraphic unit; close chronological control.
- — — — Approximate boundary between stratigraphic units; close chronological control is lacking.

NOTES:

* See Table 1 for comparison with glacial stratigraphy proposed by Richmond (1964).

1. 10,000 ± 700 ^{14}C yr. b.p. (M-119) on twigs (Crane, 1956), 11,000 ± 700 ^{14}C yr. b.p. (M-118) on dung (Crane, 1956), 11,150 ± 570 ^{14}C yr. b.p. (C-610) on wood (Libby, 1955); from Danger Cave (Jennings, 1957).
2. 26,080 (+1200 -1100) ^{14}C yr. b.p. (GX-4737) bulk soil sample; Madsen and Currey (1979).
3. 12,300 ± 330 ^{14}C yr. b.p. (GX-3481) on woody forest litter at till-bog-interface, Madsen and Currey (1979).
4. 7515 ± 180 ^{14}C yr. b.p. (GX-4644) on humic colluvium; Madsen and Currey (1979).

Project No. 14093B	USGS Contract No. 14-08-0001-16827	CORRELATION CHART	Figure 5
Woodward-Clyde Consultants			

EXPLANATION:

Fault; dashed where inferred; dotted where buried; ball and bar on downthrown side

Linear break in slope; dashed where less distinct; circle and bar on lower side

ℓ2 Lineament identification number

Tr. LC-1 Trench location

A' A Topographic profile

0 0.5 1 kilometer

Project No. 14093B	USGS Contract No. 14-08-0001-16827	MAP OF FAULT TRACES AND LINEAMENTS Little Cottonwood Canyon Site	Figure 6
Woodward-Clyde Consultants			

UNIT DESCRIPTIONS:

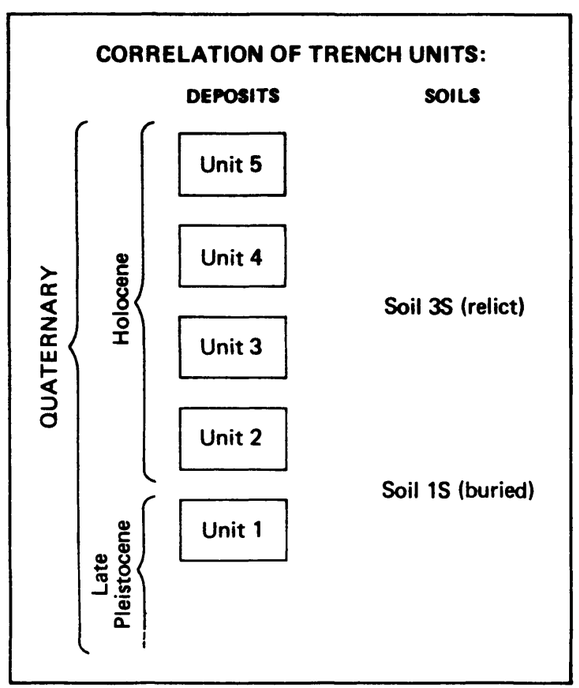
Unit 1 BONNEVILLE LAKE DEPOSITS

(1S) **Post-Bonneville soil** — light brownish gray to light yellowish brown (2.5 YR 6/3, moist) silt; massive; calcareous.

(1a) Interbedded fine to coarse sand, gravelly sand and sandy gravel; light gray to light brownish gray (10 YR 6.5/2, dry) brown and dark grayish brown (10 YR 5/3 and 10 YR 4/2, moist); well stratified and bedded; beds range in thickness from less than 1 cm to 10 cm; gravel clasts are subrounded and rounded; gravel clasts are generally less than 2 cm, pebbles up to 3 to 4 cm common; fine-grained horizons are weakly cemented by calcium carbonate; gravel horizons are generally loose.

(1b) Grayish brown (2.5 YR 5/2, moist) and light olive brown (2.5 YR 5/4, moist) silt; finely laminated, individual lamina are generally less than 1 mm thick.

(1c) Silty clay; finely laminated; bedding disrupted, in places, and tilted 5 degrees to the west; calcareous.



Unit 2 ALLUVIAL FAN DEPOSITS

(2a) Yellowish brown to dark yellowish brown (10 YR 4.5/4, moist) silty fine sand and minor clay; upper 10 to 20 cm contains approximately 10 percent pebbles and cobbles, maximum size 10 cm; massive; upper 15 cm contains some organic material and is dark brown (10 YR 3.5/3, moist) in color.

(2b) Dark brown (10 YR 3/3, moist) gravelly sand; poorly sorted, unstratified; contains 5 to 20 percent subangular and some subrounded pebbles and cobbles, mode less than 2 cm, maximum size 20 cm; massive.

Unit 3 GRABEN-FILL DEPOSITS

Interbedded sequence of sandy silt, gravelly sandy silt, and silty sand; contains minor discontinuous lenses of pebbly sand and gravel. These deposits are subdivided into the following units:

A horizon of soil developed on unit 3
(formed on upper 50 to 100 cm of unit 3, not shown everywhere) —

(3S) Very dark gray (10 YR 3/1, moist) pebbly sandy silt; massive to weakly developed coarse blocky structure; numerous fine roots: upper 20 to 30 cm may be disturbed by plowing; gradational lower soil boundary.

(3a) Dark brown (10 YR 3/3, moist) pebbly fine sandy silt, silty fine sand, coarse sand, and pebble to cobble sand; massive; unstratified, lenticular bedding poorly developed in places. Upper 1.5 m contains 5 to 10 percent subangular pebble- to cobble-size clasts; mode less than 2 cm, maximum size 10 cm; gravel content decreases to less than 2 percent towards bottom of unit. Minor disseminated charcoal fragments occur in the lower part of the unit.

(3b) Interbedded sequence of brown to dark yellowish brown (10 YR 4/3.5, moist) silty fine sand, pebbly medium to coarse sand, and pebble to cobble gravel; gravel clasts are generally subrounded to subangular; bedding is poorly to well developed. In places poorly developed buried A horizons of soils are preserved; some of which can be followed laterally for several meters (see markers mh_3 and mh_4).

(3c) Dark brown (10 YR 3/3, moist) gravelly sandy silt; contains 5 to 10 percent subangular and a few subrounded pebbles, maximum size 10 cm, mode less than 1 cm, 2 to 3 cm clasts common; some fine rootlets in upper part of unit.

(3d) Dark brown (10 YR 3/3, moist) interbedded sandy silt, silty sand, pebbly sand, and pebble-cobble gravel; generally coarsens to east; lenticular bedding, moderate to well bedded bedded; beds vary in thickness from 2 to 20 cm.

(3e) Dark yellowish brown (10 YR 4/4, moist) clayey silt and minor coarse sand; locally contains discontinuous sandy silt lenses; massive.

(3f) Interbedded silty fine sand, pebbly sand, and sandy fine gravel; beds are generally discontinuous and less than 5 cm thick.

(3g) Similar to 3c, except contains less pebbles (approximately 1 to 2 percent) and less organic material; pebble content increases slightly to the east.

(3h) Dark brown (10 YR 3/3, moist) fine sandy silt; minor small pebbles, coarse sand, and discontinuous pebbly sand lenses; pebbles generally less than 2 to 5 mm in diameter; less than 1 percent $CaCO_3$ occurs along root tubules; some fine rootlets.

(3i) Very dark gray (10 YR 3/1, moist) pebbly sandy silt; contains 5 to 10 percent subangular to subrounded pebbles; maximum size 1 cm; mode less than 3 mm; micaceous; massive; organic staining; fine rootlets, some animal burrows.

Unit 4 SCARP-DERIVED COLLUVIUM

Dark brown to dark yellowish brown (10 YR 4/3.5, moist) pebbly silty sand derived primarily from units 2a and 2b; contains 15 to 20 percent small (less than 1 cm) subangular to angular clasts and a few pebbles up to 4 cm; massive, poorly sorted.

(4a) **Disturbed zone between units 4 and 5** — zone of mixing; consists primarily of unit 4; numerous burrows; organic material in upper part.

Unit 5 YOUNG SCARP COLLUVIUM

Very dark gray (10 YR 3/1, moist) and very dark grayish brown (10 YR 3/2, moist) pebbly sandy silt; contains 5 percent angular to subangular pebbles; very weakly defined stratification, subparallel to slope where developed; disturbed by numerous animal burrows; some roots and rootlets.

Project No. 14093B	USGS Contract No. 14-08-0001-16827	UNIT DESCRIPTIONS TRENCH LC–1 Little Cottonwood Canyon Site	Figure 7a
Woodward-Clyde Consultants			

EXPLANATION:

Lithologic contacts; dashed where less distinct; dotted where approximate or gradational.

Soil boundary; clear, transition zone between 2.5 and 6 cm thick.

Soil boundary; gradual, transition zone between 6 and 12.5 cm thick.

N45E,60SW — Fault: solid line where well defined; dashed where less distinct; dotted where inferred; bold numbers indicate strike and dip of the fault plane; small numbers indicate stratigraphic separation in cm; arrows indicate sense of displacement.

mh_5 — Marker horizon

(b) — Animal burrow

LC-1-2 — Location and number of C^{14} sample.

NOTES:

n_1 Disturbed zone; fine sandy silt to silty sand; contains small (generally less than 1 cm, some up to 7 cm) randomly oriented fragments of laminated lake sediments (unit 1); calcareous, grades into soil 1S.

n_2 Infilled zone; organic-rich.

n_3 Dark brown to dark yellowish brown (9 YR 4/4, moist) pebbly clayey sandy silt; contains 20 percent small (less than 3 cm) subangular pebbles; massive, no strong fabric developed; effervescence using HCl increases towards fault.

n_4 Disturbed zone

n_5 Disturbed zone; not organic-rich.

MARKER HORIZONS:

mh_1 Fine sandy silt; well stratified; iron-oxide stained; 5 cm thick.

mh_2 Contact between pebble to cobble gravelly sand and sandy gravel, and underlying massive fine sandy silt.

mh_3 Contact between poorly stratified and poorly sorted sand, which contains 20 to 30 percent pebbles to boulders, and underlying buried A soil horizon of a soil developed on pebbly silty sand; soil varies in thickness from 20 to 35 cm.

mh_4 Contact between moderately bedded coarse sand and pebbly sand unit and underlying silty fine sand (very weakly developed soil?).

mh_5 Silty fine sand bed

mh_6 Sandy pebble gravel

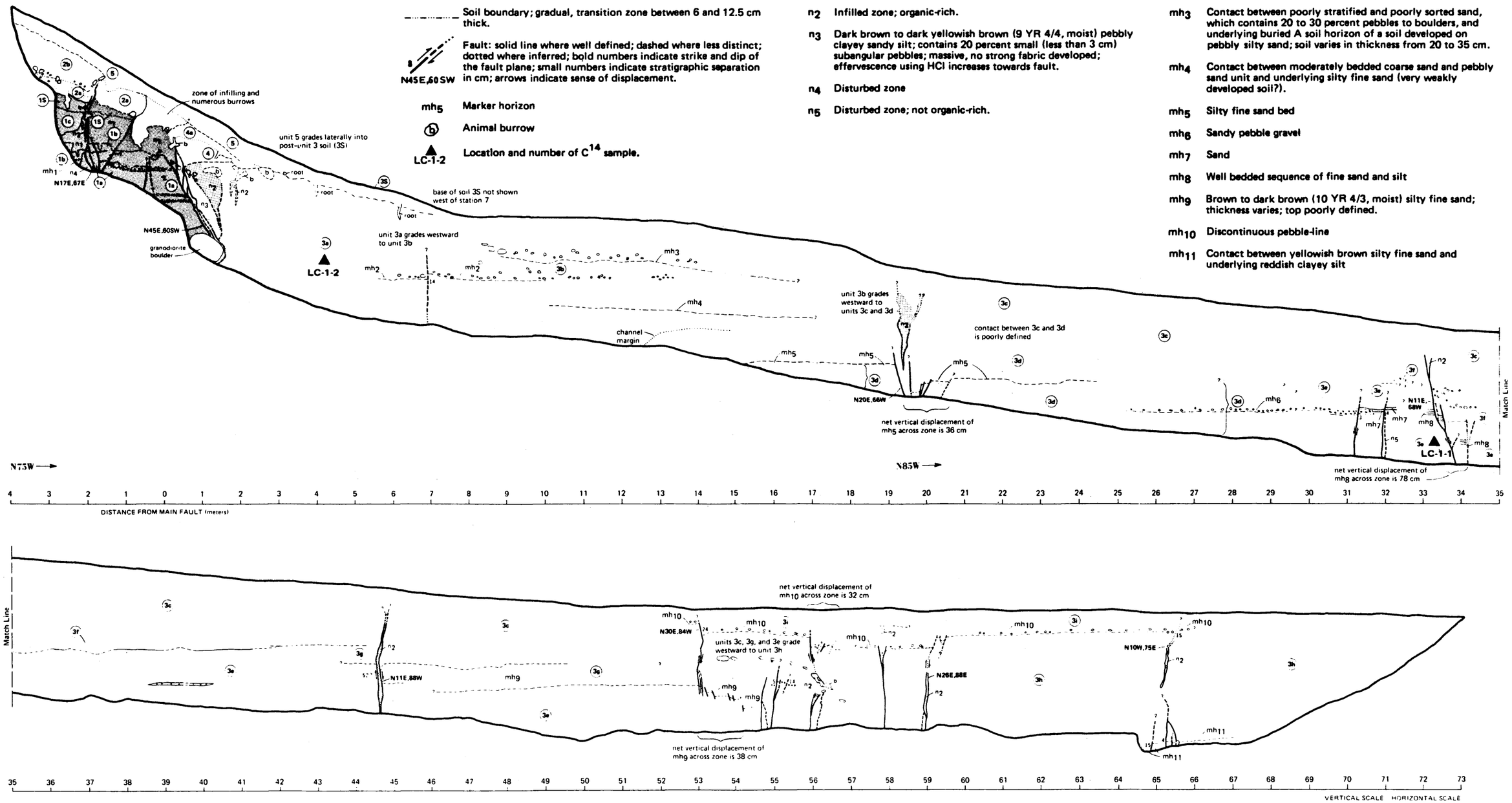
mh_7 Sand

mh_8 Well bedded sequence of fine sand and silt

mh_9 Brown to dark brown (10 YR 4/3, moist) silty fine sand; thickness varies; top poorly defined.

mh_{10} Discontinuous pebble-line

mh_{11} Contact between yellowish brown silty fine sand and underlying reddish clayey silt



Project No. 14093B	USGS Contract No. 14-08-0001-16827	LOG OF TRENCH LC-1 Little Cottonwood Canyon Site	Figure-7b
Woodward-Clyde Consultants			

UNIT DESCRIPTIONS:

Unit 1 BONNEVILLE LAKE DEPOSITS

Post-Bonneville soil –

(1S) Brown (10 YR 5/3, moist) and grayish brown (10 YR 5/2, moist) silty fine sand; vesicular; weakly cemented by calcium carbonate; locally, upper 10 to 15 cm is noncalcareous and darker (10 YR 4.5/4, moist).

Coarse-grained lake sediments –

(1a) Interbedded coarse sand, pebble to cobble gravel, and minor fine to medium sand; gravel clasts are subrounded to rounded, maximum size 12 cm, mode less than 1 cm, 2 to 5 cm pebbles are common; well bedded, gravel beds range in thickness from 3 to 20 cm, individual beds are moderately to well sorted; loose; weakly cemented by calcium carbonate in places.

Silty lake sediments –

(1b) Grayish brown (2.5 YR 5/2, moist) to light olive brown (2.5 YR 5/3, moist) and dark yellowish brown (10 YR 4/6, moist) finely laminated clayey silt and silt; laminae are generally less than 1 to 2 mm thick; iron-staining occurs along many laminae.

Clayey lake sediments –

(1c) Light yellowish brown (2.5 YR 6/4, moist), light brownish gray (2.5 YR 6/2, moist), grayish brown (2.5 YR 5/2, moist), and dark grayish brown (2.5 YR 4/2, moist) silty clay and minor silt; finely laminated; contains some calcium carbonate concretions.

Unit 2 ALLUVIAL FAN DEPOSITS

Basal alluvium –

(2a) Dark yellowish brown (10 YR 4/4, moist) and dark brown (10 YR 4/3, moist) interbedded silty sand and gravelly sand to sandy gravel; contains subangular pebble-size clasts ranging in size from less than 1 cm to approximately 5 cm; moderately to well bedded; weakly cemented by calcium carbonate.

Stratified alluvium –

(2b) Dark brown to dark yellowish brown (10 YR 4/3.5, moist) gravelly silty sand; contains up to 20 to 30 percent pebble gravel, locally finer grained; weakly stratified; poorly sorted; moderately hard when dry.

Massive alluvium –

(2c) Similar to units 3a and 3b, except bedding is less well defined, particularly in the upper part of the unit; contains some coarse cobble gravelly sand having clasts up to 20 cm.

Unit 3 GRABEN-FILL DEPOSITS

A horizon of post-unit 3 soil –

(3S) Similar to unit 3; except very dark grayish brown (10 YR 3/2, moist); organic-rich; gradational lower soil boundary.

Graben-fill deposits –

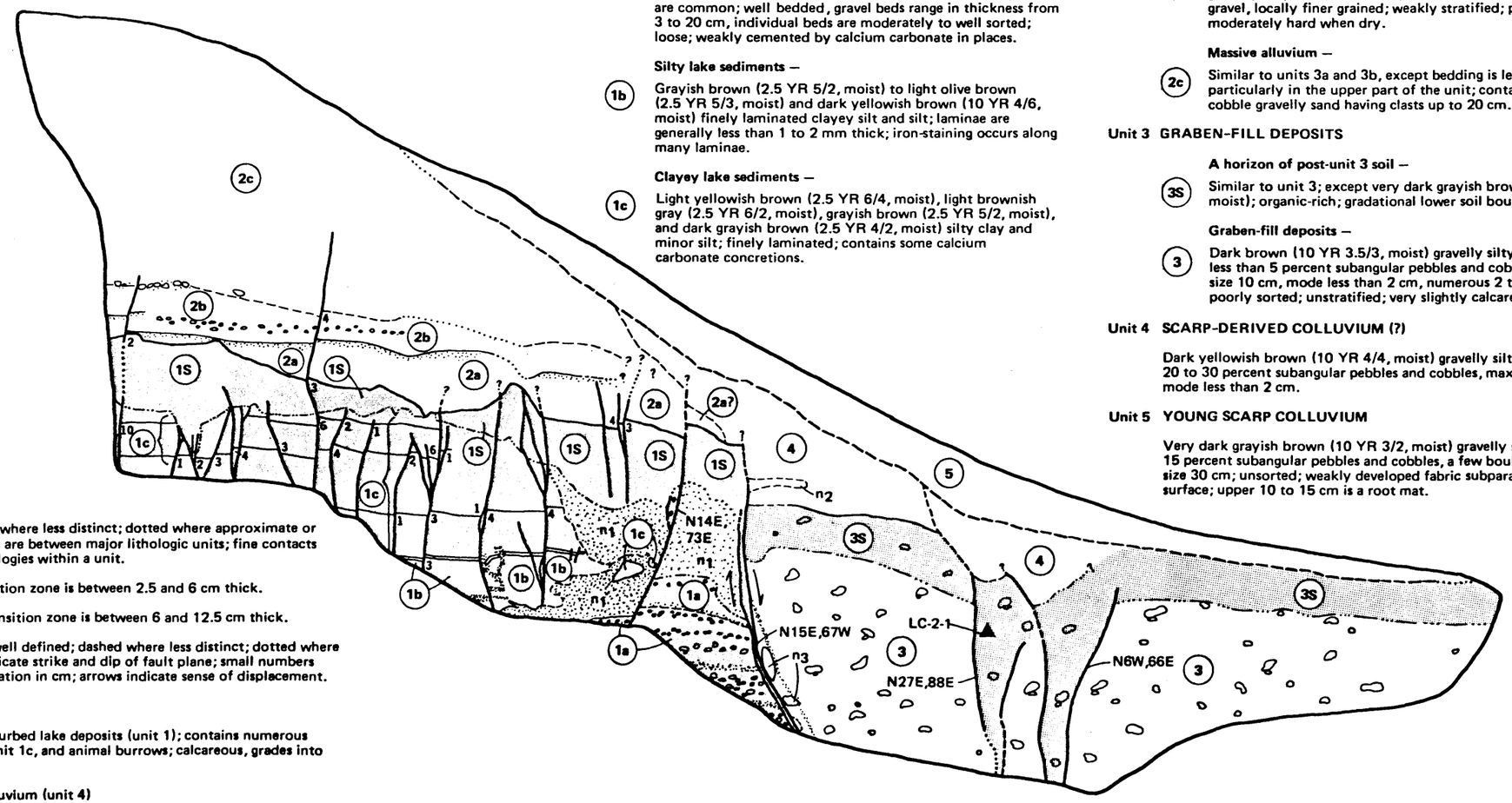
(3) Dark brown (10 YR 3.5/3, moist) gravelly silty sand, contains less than 5 percent subangular pebbles and cobbles; maximum size 10 cm, mode less than 2 cm, numerous 2 to 7 mm clasts; poorly sorted; unstratified; very slightly calcareous.

Unit 4 SCARP-DERIVED COLLUVIUM (?)

Dark yellowish brown (10 YR 4/4, moist) gravelly silty sand; contains 20 to 30 percent subangular pebbles and cobbles, maximum size 10 cm; mode less than 2 cm.

Unit 5 YOUNG SCARP COLLUVIUM

Very dark grayish brown (10 YR 3/2, moist) gravelly silty sand, contains 15 percent subangular pebbles and cobbles, a few boulders; maximum size 30 cm; unsorted; weakly developed fabric subparallels ground surface; upper 10 to 15 cm is a root mat.



EXPLANATION:

Lithologic contact; dashed where less distinct; dotted where approximate or gradational; heavy contacts are between major lithologic units; fine contacts are between different lithologies within a unit.

Soil boundary; clear, transition zone is between 2.5 and 6 cm thick.

Soil boundary; gradual, transition zone is between 6 and 12.5 cm thick.

N14E,73E — FAULT: solid line where well defined; dashed where less distinct; dotted where inferred; bold numbers indicate strike and dip of fault plane; small numbers indicate stratigraphic separation in cm; arrows indicate sense of displacement.

NOTES:

n_1 Zone of deformed and disturbed lake deposits (unit 1); contains numerous shears, rotated blocks of unit 1c, and animal burrows; calcareous, grades into soil 1S.

n_2 Fragment of soil 1S in colluvium (unit 4)

n_3 Pods of calcium-carbonate cemented fan deposits along fault.

LC-2-1 Location and number of C^{14} sample

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Woodward-Clyde Consultants			

EXPLANATION:

Lithologic contacts; dashed where less distinct.

Soil boundary; clear, transition zone is between 2.5 and 6 cm thick.

Soil boundary; gradual to diffuse; transition zone is greater than 6 cm thick.

N29E,90 — Fault: solid line where well defined; dashed where less distinct; numbers indicate strike and dip of the fault plane; arrows indicate sense of displacement.

LC-3-1 — Location and number of C^{14} sample.

UNIT DESCRIPTIONS:

Unit 1 BELLS CANYON TILL

(1) Yellowish brown (10 YR 5/5, moist) poorly sorted, compact mixture of sand, gravel, and some silt; contains 10 to 30 percent subangular and subrounded pebbles, cobbles, and boulders, maximum size 1 m; contains some thin (1 to 6 cm) sand beds; very weakly developed subhorizontal bedding; numerous quartz monzonite clasts are partly grussified (easily broken with pick); some roots in upper 1 to 2 m.

Unit 2 GRABEN-FILL DEPOSITS (OLDER)

(2) Dark yellowish brown (10 YR 3.5/4, moist) slightly clayey gravelly silty sand; contains 10 to 20 percent angular and subangular pebbles, cobbles, and boulders, boulders up to 30 cm common, mode less than 10 cm; poorly sorted, nonstratified; massive.

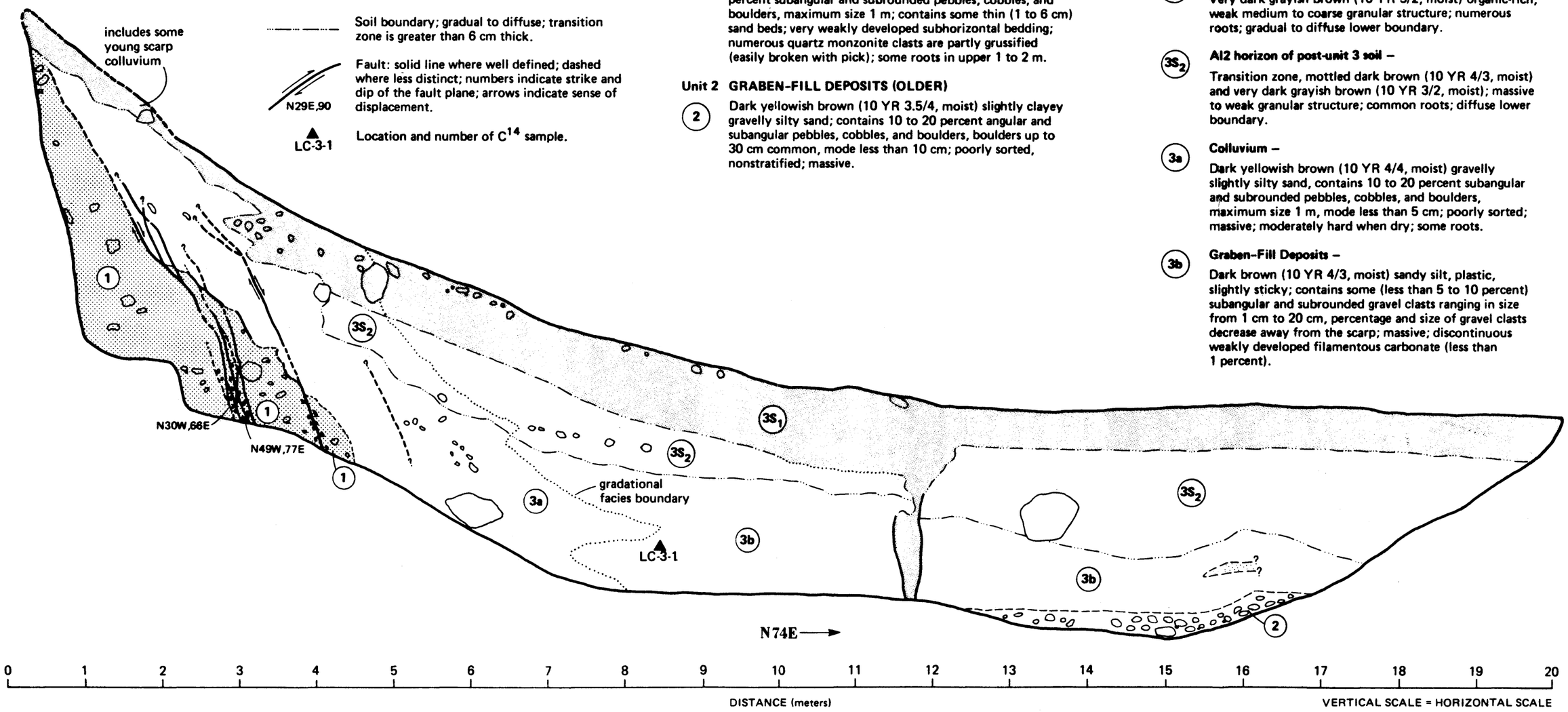
Unit 3 COLLUVIUM AND GRABEN-FILL DEPOSITS

($3S_1$) **A11 horizon of post-unit 3 soil –**
Very dark grayish brown (10 YR 3/2, moist) organic-rich, weak medium to coarse granular structure; numerous roots; gradual to diffuse lower boundary.

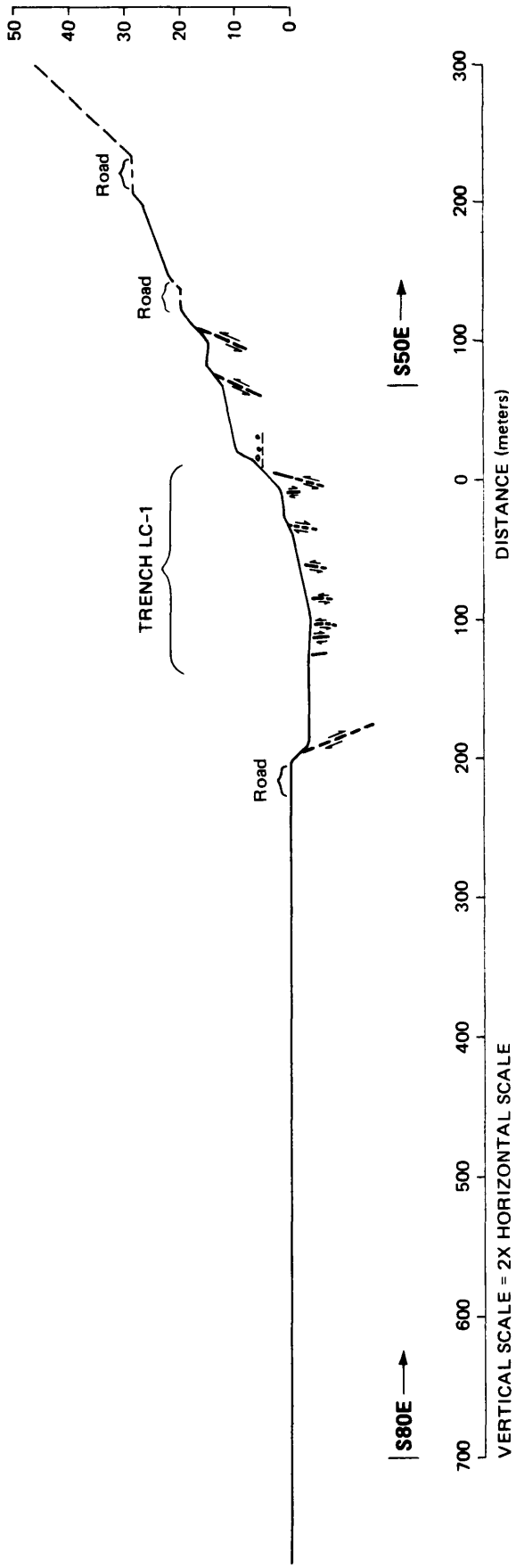
($3S_2$) **A12 horizon of post-unit 3 soil –**
Transition zone, mottled dark brown (10 YR 4/3, moist) and very dark grayish brown (10 YR 3/2, moist); massive to weak granular structure; common roots; diffuse lower boundary.

(3a) **Colluvium –**
Dark yellowish brown (10 YR 4/4, moist) gravelly slightly silty sand, contains 10 to 20 percent subangular and subrounded pebbles, cobbles, and boulders, maximum size 1 m, mode less than 5 cm; poorly sorted; massive; moderately hard when dry; some roots.

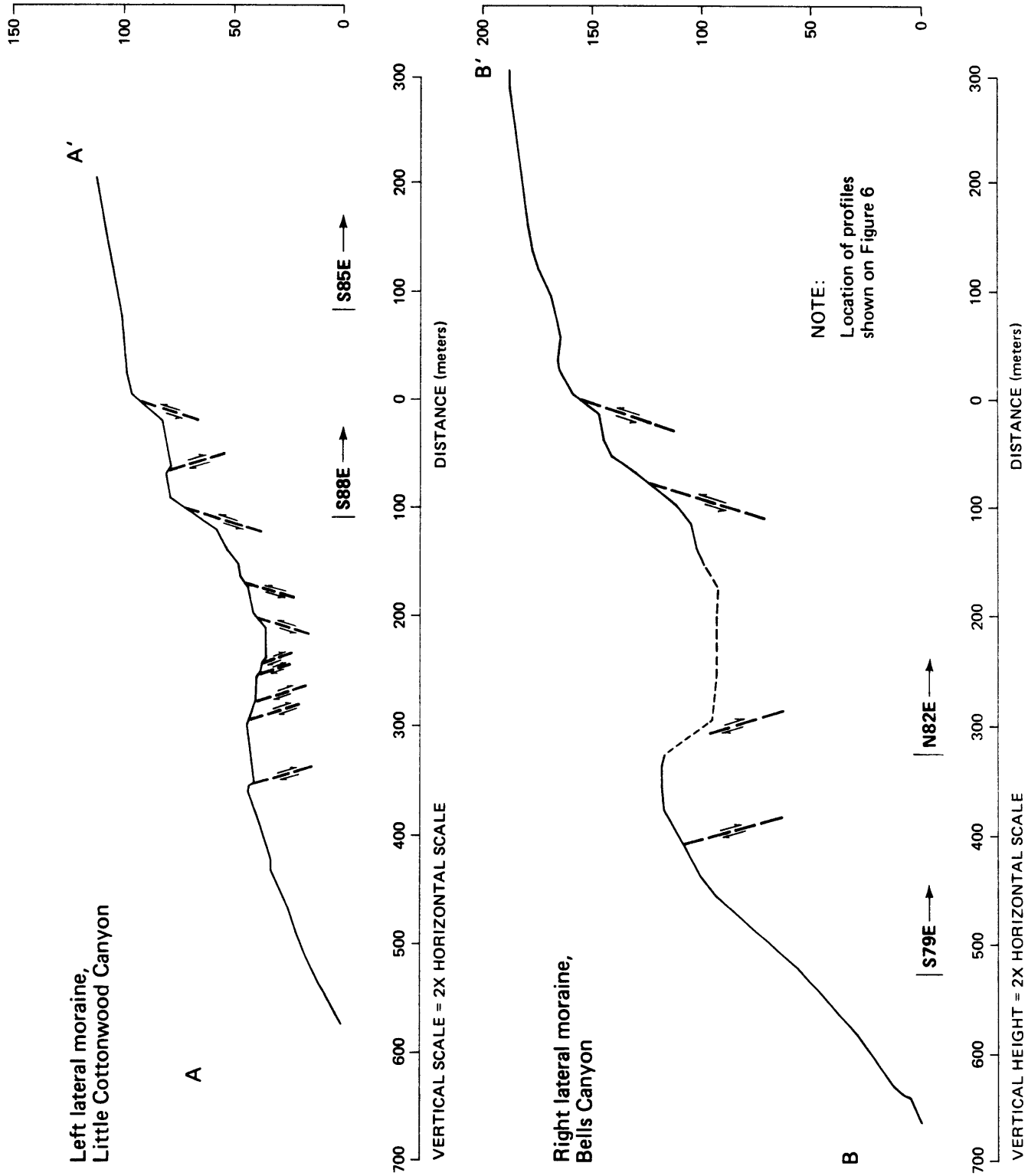
(3b) **Graben-Fill Deposits –**
Dark brown (10 YR 4/3, moist) sandy silt, plastic, slightly sticky; contains some (less than 5 to 10 percent) subangular and subrounded gravel clasts ranging in size from 1 cm to 20 cm, percentage and size of gravel clasts decrease away from the scarp; massive; discontinuous weakly developed filamentous carbonate (less than 1 percent).



Project No. 14093B	USGS Contract No. 14-08-0001-16827	LOG OF TRENCH LC-3 Little Cottonwood Canyon Site	Figure 9
Woodward-Clyde Consultants			



Project No. 14093B	USGS Contract No. 14-08-0001-16827	TOPOGRAPHIC PROFILE IN VICINITY OF TRENCH LC-1 Little Cottonwood Canyon Site	Figure 10
Woodward-Clyde Consultants			



Project No. 14093B	USGS Contract No. 14-08-0001-16827	TOPOGRAPHIC PROFILES OF DISPLACED MORAINES Little Cottonwood Canyon Site	Figure 11
Woodward-Clyde Consultants			

TABLE 1

Summary of Nomenclature Applied to the Glacial Deposits of Little Cottonwood and Bells Canyons

Richmond (1964)		McCoy (1977); Madsen and Currey (1979)
Rock glaciers of historic stade		Cirque deposits of Neoglacial age
Azonal soil		
Rock glacier or moraine of Temple Lake stade		Devils Castle till
Immature zonal soil		
Till of Pinedale Glaciation	Upper till	
	Erosion	
	Middle till	Hogum Fork till
	Erosion	
	Lower till	Hogum Fork till
Till of Bull Lake Glaciation	Upper till	Bells Canyon till
	Erosion	Majestic Canyon soil
	Lower till	Dry Creek till
Very mature zonal soil		
Till of a pre-Bull Lake glaciation		

TABLE 2

History of Lake Bonneville
Proposed by Morrison (1975)

Oxygen Isotope Stratigraphy (Shackleton and Opdyke, 1973)	Suggested Chrono-Stratigraphic Correlation (modified from Morrison, 1975)	Main Pre-Holocene Events
		9) One or more minor lake maxima (Draper Formation)
Stages 2,3,4	Wisconsinan	8) Graniteville Soil
		7) Deposits of 3 deep lake maxima (Bonneville Formation)
Stage 5	Sangamonian	6) Promontory Soil
	Illinoian (Bull Lake Glaciation)	5) Deposits of 5 moderate to deep lake maxima (Alpine Formation)
		4) Dimple Dell Soil
		3) Deposits of 3 or more lake maxima
	Yarmouthian	2) 4 soils with intervening minor lake maxima
Stage 16		Pearlette "O" Ash
Stage 19		Bishop Ash
		1) Deposits of 3 deep lake maxima

TABLE 3

Summary of Data on Slip Rates
Along the Wasatch Fault Zone

Location	Slip Rate (mm/year)	Interval	Source
1) west flank of Wellsville Mountains	~0.2	post ~150,000	Scott (1980)
2) "	~0	post Bonneville	"
3) Bountiful to Ogden	0.4	post 10 m.y.	Naesser & others (1979)
4) Kaysville Site	1.8 (+1.0; -0.6)	late Holocene	Swan & others (in press)
5) Big Cottonwood Canyon	>0.1	next to last major L. cycle (~150,000)	Scott (1980)
6) "	>0.5	post Bonneville	"
7) Little Cottonwood Canyon Site	0.9 (+1.0; -0.3)	late Pleistocene-Holocene	this report
8) Hobble Creek Site	1.0 (±0.1)	Holocene (post Provo)	Swan & others (in press)

TABLE 4

Summary of Data on Displacement
Per Event on the Wasatch Fault Zone

Location	Vertical Displacement Per Event on Main Fault Scarp (m)	Net Vertical Tectonic Displacement Per Event Across Fault Zone (m)	Source
Kaysville Site	4 - 8	>1.7 to ≤3.7	Swan & others (in press)
Hobble Creek Site	1.6 to 5.6	0.8 to 2.8	Swan & others (in press)
Little Cottonwood Canyon Site	0.4 to 6.5	≥0.4 to ≥3	this report

TABLE 5

Recurrence Intervals at Selected Sites Along the Wasatch Fault Zone

Location	Recurrence Interval* (years)	Source
Kaysville Site	500 - 1000 (1000)	Swan & others (in press)
Little Cotonwood Canyon Site	450 - 3300 (2200)	this report
Hobble Creek Site	1500 - 2600 (2000)	Swan & others (in press)

*preferred value shown in parentheses

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Office of Earthquake Studies

SUMMARIES OF TECHNICAL REPORTS, VOLUME X

Prepared by participants in

NATIONAL EARTHQUAKE HAZARDS REDUCTION PROGRAM

June 1980

OPEN-FILE REPORT 80-842

This report is preliminary and has not been edited or reviewed for conformity with Geological Survey standards and nomenclature

Menlo Park, California

1980

STUDY OF EARTHQUAKE RECURRENCE INTERVALS ON THE WASATCH FAULT ZONE, UTAH

14-08-0001-16827

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Investigations

Detailed geologic studies that include mapping of the late Quaternary deposits, topographic profiling of displaced geomorphic surfaces, and trenching have been completed at three locations along the Wasatch fault zone. Data on the cumulative displacement of late Quaternary deposits, the number of surface faulting events, and the amount of displacement per event have been collected at these sites to estimate the magnitude and frequency of past surface faulting on the Wasatch fault zone.

The results of the investigations at the Kaysville and Hobble Creek sites, 32 km north and 46 km south of Salt Lake City respectively, are described in our earlier reports (see list of selected reports). The results of our investigations at the Little Cottonwood Canyon site are summarized below. Two additional sites, one north of Ogden and one near Nephi, will be investigated during fiscal year 1980.

Results

The Little Cottonwood Canyon site is 20 km south-southeast of downtown Salt Lake City. At this location, the Wasatch fault is a zone up to 0.5 km wide that lies a few hundred meters west of the range and generally trends parallel to the mountain front. Seismicity data compiled by the University of Utah (16 years of record) suggest that the Little Cottonwood site is located near the northern end of a 70-km-long seismic gap (Arabasz and others, 1979). The Hobble Creek site is located near the southern end of this seismic gap.

Late Pleistocene lateral moraines at the mouths of Little Cottonwood and Bells canyons are displaced by numerous east- and west-facing scarps that form a series of graben. Individual scarps within these graben are up to 35 to 40 m

high. The cumulative net tectonic displacement across the zone is estimated to be 14.5 (+10.0; -3.0) m on the basis of topographic profiles of the displaced moraines, which are 16,000 ± 3000 years old. The late Pleistocene (post-Bells Canyon till) slip rate is 1.0 (+0.9; -0.4) mm per year.

The cumulative displacement was produced by multiple surface faulting events. Data from trenches excavated across a graben north of Little Cottonwood Canyon that displaces Holocene alluvial fan deposits indicate that the graben was produced by a minimum of two or three surface faulting events. Recurrent displacement is also suggested by three or four terraces on the upthrown side of the fault in glacial outwash deposits in Little Cottonwood Creek. Due to the complexity of the fault zone and to suburban development of the area, it was not possible to determine if the graben and the terraces were produced by different faulting events. Although a unique sequence of faulting events cannot be reconstructed for the Little Cottonwood Canyon site, the available data suggest that the history of faulting at the site is probably similar to the history of faulting 50 km to the south at the Hobble Creek site.

Selected Reports

Cluff, L. S., Swan, F. H., III, Schwartz, D. P., Hanson, K. L., and Knuepfer, P. L., 1978, Study of earthquake recurrence intervals on the Wasatch fault, Utah: U.S. Geological Survey, National Earthquake Hazards Reduction Program, Summaries of Technical Reports, v. VII, p. 115-117.

Cluff, L. S., Patwardhan, A. S., and Coppersmith, K. J., 1979, Estimating the probability of occurrence of surface faulting earthquakes on the Wasatch fault zone, Utah: to be published in the Proceedings of Conference on Earthquake Hazards Along the Wasatch Front and in the Reno-Carson City Area (U.S. Geological Survey Open-File Report).

Cluff, L. S., Patwardhan, A. S., and Coppersmith, K. J., in press, Estimating the probability of occurrence of surface faulting earthquakes on the Wasatch fault zone, Utah: Bulletin of the Seismological Society of America, v. 70, no. 5, October, 1980.

Schwartz, D. P., Swan, F. H., III, Knuepfer, P. L., Hanson, K. L., and Cluff, L. S., 1979, Surface deformation along the Wasatch fault, Utah: Geological Society of America Abstracts with Programs, v. 11, no. 3, p. 127.

Schwartz, D. P., Swan, F. H., III, Hanson, K. L., Knuepfer, P. L., and Cluff, L. S., 1979, Recurrence of surface faulting and large magnitude earthquakes along the Wasatch fault zone near Provo, Utah: Geological Society of America Abstracts with Programs, v. 11, no. 6, p. 301.

Swan, F. H., III, Schwartz, D. P., Hanson, K. L., Knuepfer, P. L., and Cluff, L. S., 1978, Recurrence of surface faulting and large magnitude earthquakes along the Wasatch fault, Utah: American Geophysical Union Transactions (EOS), v. 59, no. 12, p. 1126.

Swan, F. H., III, Schwartz, D. P., Hanson, K. L., Knuepfer, P. L., and Cluff, L. S., 1979, Recurrence of surface faulting and large magnitude earthquakes along the Wasatch fault zone, Utah: Geological Society of America Abstracts with Programs, v. 11, no. 3, p. 131.

Swan, F. H., Schwartz, D. P., and Cluff, L. S., 1979, Recurrence of surface faulting and moderate to large magnitude earthquakes on the Wasatch fault zone at the Kaysville and Hobble Creek sites, Utah: to be published in Proceedings of Conference on Earthquake Hazards Along the Wasatch Front and in the Reno-Carson City Area (U.S. Geological Survey Open-File Report).

Swan, F. H., Schwartz, D. P., Cluff, L. S., Hanson, K. L., and Knuepfer, P. L., in press, Study of earthquake recurrence intervals on the Wasatch fault at the Hobble Creek site, Utah: U.S. Geological Survey Open-File Report, 40 p.

Swan, F. H., Schwartz, D. P., Hanson, K. L., Knuepfer, P. L., and Cluff, L. S., in press, Study of earthquake recurrence intervals on the Wasatch fault at the Kaysville site, Utah: U.S. Geological Survey, Open-File Report, 33 p.

Swan, F. H., Schwartz, D. P., and Cluff, L. S., in press, Recurrence of moderate to large magnitude earthquakes produced by surface faulting on the Wasatch fault, Utah: Bulletin of the Seismological Society of America, v. 70, no. 5, October, 1980.