UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Surficial Geologic Map of an Area along the Wasatch Fault Zone in the Salt Lake Valley, Utah

by

William E. Scott[1] and Ralph R. Shroba[1]

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This map is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

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1 Denver Federal Center, Denver, CO 80225

INTRODUCTION

This map shows the surficial deposits and the faults that offset them along the Wasatch fault zone in the eastern part of the Salt Lake valley (Jordan valley), which is the site of Salt Lake City and its southern suburbs. About 600,000 people, or 40 percent of Utah's population, live in the valley, which is the main commercial and industrial center of Utah. Although the valley has not been the site of a major earthquake since its settlement in 1847, the geologic record of the past 20,000 yr contains abundant evidence that strong earthquakes have occurred here repeatedly in the past and will almost certainly occur in the future (Gilbert, 1890; Smith, 1972; Cluff and others, 1975; Arabasz and others, 1979; Swan and others, 1980; Schwartz and Coppersmith, 1984). The fault scarps produced during past earthquakes can be used as guides for estimating the most likely sites, amounts, and patterns of surface faulting that will accompany future earthquakes. In addition, the map units provide datums for estimating the ages of fault scarps, for determining the amount of surface displacement, and for assessing long-term rates of slip along faults. This information can help in planning both emergency responses to future earthquakes and long-term land use with regard to surface-faulting hazards.

The Wasatch fault zone, which extends for 370 km through central and northern Utah (Fig. 1), has abundant evidence of late Pleistocene (100-10 ka; ka, thousand years before present) and Holocene (past 10 ka) surface faulting along most of its length (Cluff and others, 1975). Schwartz and Coppersmith (1984) propose that the fault zone consists of 6 segments that range in length from 30-70 km. Only one or part of one segment is expected to rupture during a surface-faulting event. This map covers most of the Salt Lake City segment, which is marked by several discrete groups of scarps that define the Warm Springs, East Bench, and Wasatch faults. The scarps that define each fault occur as single scarps in narrow zones to complex networks of many scarps with grabens and back-tilted surfaces in zones of deformation that are as wide as 500 m.

The faults shown on the maps are compiled from several published sources in addition to this study. The faults north of Mt. Olympus are taken or modified from maps by Van Horn (1969, 1972b, 1982), Marsell and Threet (1960), and Kaliser (1976). The faults south of Mt. Olympus, most of which were noted by Cluff and others (1970) in a reconnaissance study, were mapped in the field on 1:12,000-scale aerial photographs taken in 1970 for the Utah Geological and Mineral Survey. The faults were transferred to the topographic base map using a photogrammetric plotter.

The surficial deposits represented on the map include sediments of ancient Lake Bonneville, as well as alluvial, glacial, colluvial, and windblown deposits. Our reinterpretation of mapping by Van Horn (1969, 1972a, 1979, 1982) provided most of the information for the northern map; the southern map includes much new mapping as well as reinterpretation of maps by Morrison (1965) and Richmond (1964). The reinterpretation of the previous mapping reflects revisions in the dating and correlation of some deposits and new views about the history of the fluctuations of Lake Bonneville. These revisions are based on studies of the glacial deposits at the mouths of Bells and Little Cottonwood Canyon by McCoy (1977) and Madsen and Currey (1979) and on studies of Lake Bonneville deposits by Currey (1980), Currey and others (1983), and Scott and others (1983). Some units from previous maps are combined into single units in order to simplify the map patterns and to help

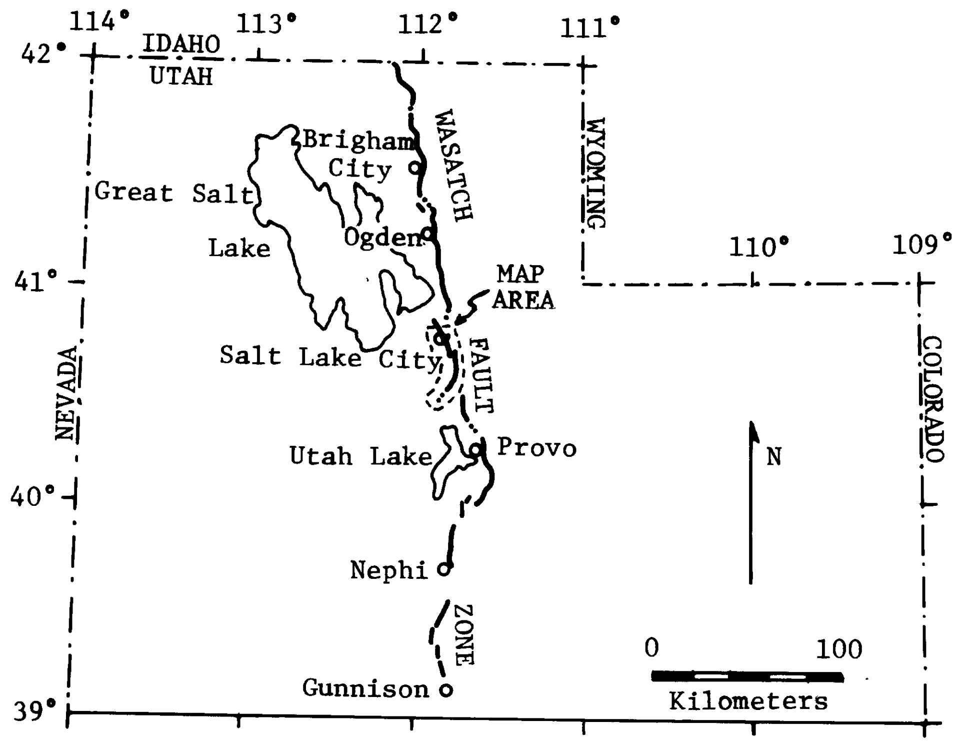

Figure 1. Map of northern Utah showing the Wasatch fault zone (from Swan and others, 1981) and the area of this map.

the faults stand out more clearly. The cited maps, especially those by Van Horn, should be consulted for detailed information about the physical characteristics of the deposits.

QUATERNARY GEOLOGIC HISTORY

Most of the units shown on the map were deposited during either the last deep-lake cycle of Lake Bonneville or the last major glaciation of the Wasatch Range, both of which occurred between 30 and 10 ka, or during the Holocene epoch, which began 10 ka. The last cycle of Lake Bonneville is called the Bonneville lake cycle, and the last major glaciation in the Wasatch Range is called the Bells Canyon advance. The following brief geologic history of the time period from about 30 ka to the present is taken largely from Madsen and Currey (1979), Currey (1980), and Scott and others (1983).

Glaciers in Little Cottonwood and Bells Canyons advanced beyond the range front and into the eastern Salt Lake valley sometime prior to 22 ka while Lake Bonneville stood at a low to intermediate level in its rise that eventually reached the Bonneville shoreline. Till (gbt) deposited by these glaciers forms large end moraines that extend nearly 1 km into the valley. Meltwater from these glaciers and from glaciers in Big Cottonwood Canyon deposited gravelly outwash (gbo) fans along the range front and deltaic deposits in Lake Bonneville. Other streams in Wasatch valleys that were at altitudes too low to support glaciers, or contained only small glaciers, also deposited gravelly fans and deltas graded to the lake. The lake's rise, interrupted by pauses and minor fluctuations, culminated about 16 ka at the Bonneville shoreline (altitude 1573-1584 m, or 5160-5200 ft, in map area). Several thousand years earlier, the glaciers in Little Cottonwood and Bells Canyons had retreated some distance from their end moraines, which by 16 ka were partly submerged below the Bonneville shoreline. The outwash and alluvial fans along the mountain front were also largely inundated by the rising lake and, except for small areas near the canyon mouths that stood above the level of the lake, were covered by a veneer of lake sediment (lbg and lbc).

The lake remained at a high level for a period of 1000-2000 yr, after which the lake level fell rapidly about 100 m to the Provo shoreline when the outlet near Red Rock Pass, Idaho, was downcut catastrophically. This fall, which occurred sometime between 14 and 15 ka, initiated rapid stream erosion of unconsolidated sediments along former shoreline areas in the eastern Salt Lake valley. Much of the eroded material was deposited in deltas (lbpd) and bars and spits (lbp) at the Provo shoreline (altitude about 1463 m, or 4800 ft, in map area). As the lake level fell below the Provo shoreline, streams cut terraces into the higher deltas and deposited new deltas at successively lower altitudes. This fall in lake level was due to some combination of further downcutting of the outlet, isostatic uplift of shore areas in the eastern Salt Lake valley in relation to the outlet, and lowering of lake level below the outlet because evaporation exceeded input of water to the lake. Perhaps because of decreased sediment loads being carried by streams, deposition of gravel and sand deltas at the mouths of streams had ceased by the time the lake level reached an altitude of 1370-1400 m (4500-4600 ft). By 11 ka the lake had fallen to a level close to that of present Great Salt Lake (1283 m, about 4210 ft), and about 10.3 ka it rose briefly to the Gilbert shoreline (altitude about 1295 m, or 4250 ft, near map area). Since then the lake level has remained within about 10 m of the present level of Great Salt Lake.

During the time that the lake was receding from the Provo shoreline, streams were depositing gravelly alluvial fans (af2) along the mountain front, and the Jordan River and its tributaries were cutting into the former lake floor to establish their present courses. Also, several large hummocky debris-flow deposits (cd2) were emplaced at the mouths of several of the steep canyons along the range front.

During Holocene time, as climatic conditions became similar to those of the present, rates of alluvial-fan formation declined, and deposition of fan alluvium (af1) was restricted to areas close to canyon mouths. The mouths of steep canyons continued to be the sites of intermittent debris flows (cd1) and floods, as they are today. Away from the mountain front, reduced streamflows were not capable of transporting gravelly sediment, and streams developed flood plains of mostly sandy and muddy sediment (ay).

Surficial deposits older than the Bonneville lake cycle, which include deposits of the Little Valley lake cycle and glacial drift of the Dry Creek advance, are exposed locally in the map area. Till of the Dry Creek advance (gdt) of Madsen and Currey (1979) is exposed at the mouths of Little Cottonwood and Bells Canyons. Although undated, the degree of weathering of the till suggests that it may be about 150 ka. Outwash of probably the same age is exposed in gravel pits near the mouth of Big Cottonwood Canyon and along Dry Creek below the type Dimple Dell Soil of Morrison (1965). Deposits of the Little Valley lake cycle are known from a few localities in the map area, but are not exposed extensively enough to show at this scale. These deposits are found in an abandoned gravel pit near the Virginia Street fault (locality VSF), at several localities along the south side of Parleys Creek near I-215, and below outwash of Dry Creek age in a gravel pit north of the mouth of Big Cottonwood Creek (Scott, 1981; Scott and others, 1983). Based on stratigraphic, soil-morphologic, and amino-acid evidence, the Little Valley lake cycle appears to be about 150 ka (Scott and others, 1983). One small remnant of fan alluvium or outwash of middle Pleistocene age (af4) that lies south of Bells Canyon, and is thought to be equivalent in age to Dry Creek till, has a uranium-trend age of 250 ± 90 ka (J. N. Rosholt, written commun., 1984).

DESCRIPTION OF FAULTS AND SUSPECTED FAULTS

Following are short descriptions of the known and suspected latest Quaternary faults (those that have had surface displacement during the past 15,000-20,000 yr) in the eastern Salt Lake valley. Also discussed are faults that displace older Quaternary deposits, but not overlying deposits of the Bonneville lake cycle, as well as faults that were probably caused by slope failure rather than by tectonic faulting.

The ages of scarps formed by surface displacements along these faults are estimated by using both stratigraphic techniques and the morphology of the scarps. Limits on the ages of fault scarps are determined by the ages of stratigraphic units in which the scarps are formed and by younger units that cross the scarps but are not offset. The ages of stratigraphic units and geomorphic surfaces are estimated using soil-morphologic data (Fig. 2) and the relation of units to the relatively well dated deposits of the various phases of the Bonneville lake cycle (see Quaternary Geologic History).

Bucknam and Anderson (1979) and Machette (1982) explain fully the methods and assumptions involved in using morphologic parameters to estimate the ages of fault scarps. Briefly, fault scarps formed by faults like the Wasatch are initially nearly vertical. These so-called free faces collapse gravitationally over a period of time ranging from a few hundreds to, at most, a few thousand years to the angle of repose of the faulted materials (about 34-37°, Fig. 3; Wallace, 1977). Subsequently, the scarps degrade at slower rates as sheetwash and creep become the dominant degradational processes. The reduction in maximum scarp-slope angle is used as a measure of degradation. The maximum scarp-slope angle is also dependent on scarp height, which is the vertical distance from the crest to the base of the scarp. For scarps of the same age, the higher the scarp, the steeper will be the maximum scarp-slope angle. Therefore, the scarp-morphology data are plotted as maximum scarp-slope angle versus scarp height. Regression lines that show this relation for single scarps or groups of coeval scarps in Utah, whose ages are fairly well known, are plotted on Figure 3. An estimate of the age of a scarp whose age is not known can be made by comparing their morphology with that of the better-dated scarps.

Two values used in the following discussion that describe different types of vertical offset along a fault zone are fault-scarp height, which is

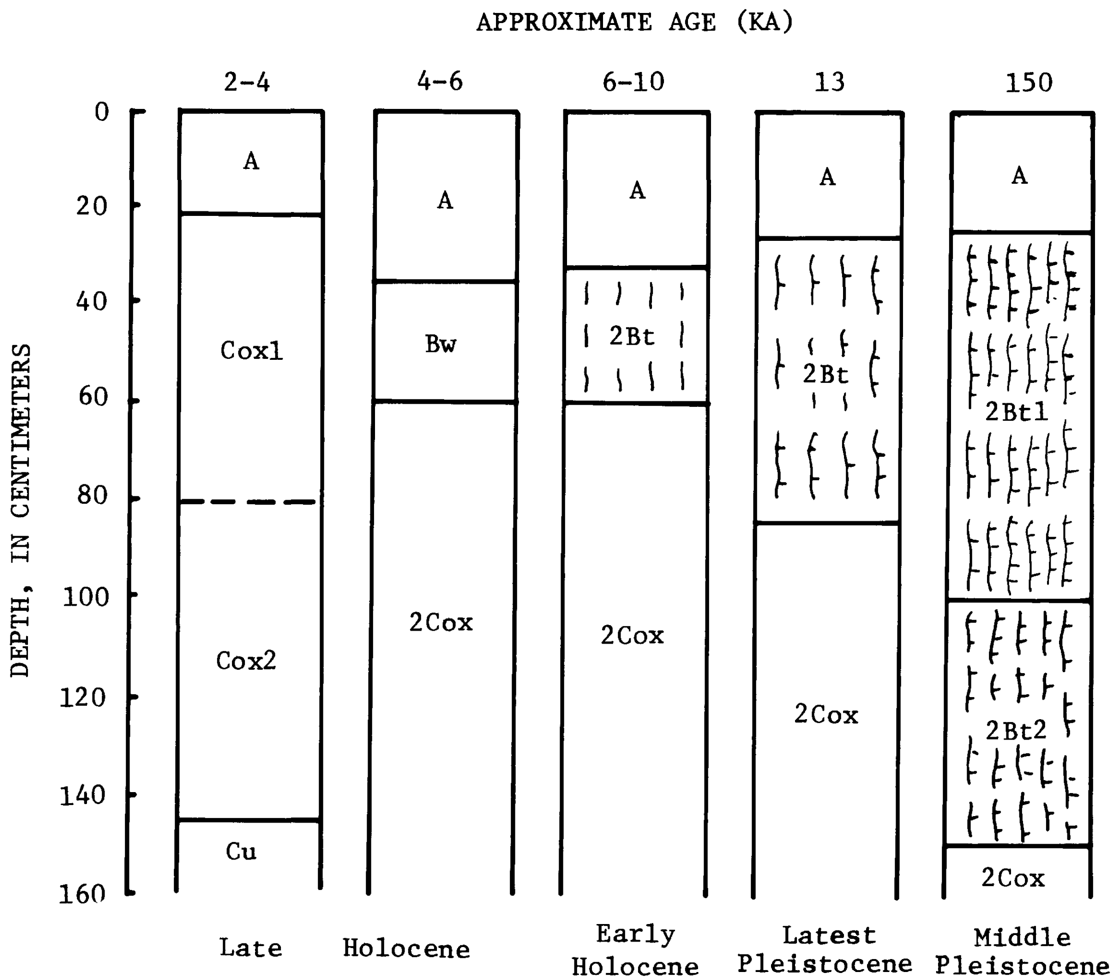

Figure 2. Generalized soil profiles developed in unconsolidated deposits of different ages (from Shroba, 1982, 1984). Soil-horizon nomenclature follows Birkeland (1984): Bw, cambic (color and (or) structural) B horizon; Bt, argillic (textural) B horizon; Cox, oxidized C horizon; Cu, unweathered C horizon. Arabic numerals preceding horizon designations indicate changes in the soil parent material. For all of the soils, except the youngest one, the upper parent material is loess (a silt-rich windblown sediment) that is mixed with sand and gravel from the underlying alluvium. By convention, the Arabic numeral 1 does not precede designations for horizon(s) formed in the upper parent material. The numeral 2 denotes alluvium that contains little or no admixed loess. The 2-4-ka soil is formed in a stony debris-flow deposit that lacks a mantle of loess. The relative density of the pattern in the Bt horizons corresponds to increased clay content, color, structure, and clay-skin development.

described above, and net vertical or surface displacement. As used here and by Bucknam and Anderson (1979), Swan and others (1980), and Machette (1982), surface displacement is the net vertical offset of a geomorphic surface across a fault zone. Surface displacement is typically less than scarp height because most of the scarps occur on sloping surfaces. Where the fault zone consists of a broad zone of deformation that includes fault scarps, grabens, and surfaces that are back-tilted toward the main scarp, the net vertical displacement may be as little as 20 percent of the height of the highest scarp in the zone.

Warm Springs fault

The Warm Springs fault bounds the west end of the Salt Lake salient, the west-trending spur of the Wasatch Range that lies just north of Salt Lake City, and is named for the thermal springs that lie along the fault (Murphy and Gwynn, 1979). Gravel quarrying has locally exposed a spectacularly striated fault plane formed in bedrock (Pavlis and Smith, 1979), but has also removed much of the surficial deposits and with them the evidence for determining the age and the amount of latest Quaternary fault displacements. Also, urban development has obscured much of the fault south of Victory Road. The map attempts to show the geology of the area prior to quarrying and urbanization based partly on interpretation of old photographs and observations by G. K. Gilbert during the late 1800's. Gilbert (1928, p. 24) notes a steep fault scarp in bedrock, which coincides with the presently exposed striated fault plane, that lay below the more gently sloping front of the salient. He concludes that the scarp had formed during an episode of accelerated faulting that began prior to the last cycle of Lake Bonneville and has continued through post-Lake Bonneville time.

A photograph taken during Gilbert's study (Hunt, 1981, fig. 3D, p. 28) shows the fault in the vicinity of Becks Hot Spring (locality WS-1). South of the hot spring, the photograph shows a prominent fault scarp formed in two adjacent post-Lake Bonneville alluvial fans. Gilbert (Hunt, 1981, p. 27-29) describes the scarp as 10-14 m high and only narrowly breached by the fan-building streams. Locally there are two parallel scarps about 15 m apart. North of the spring, the scarp is clearly visible on the piedmont for several hundred meters after making a sharp bend toward the northeast at the spring. The northern extent of the scarp beyond the limit of the photograph is not known. However, the scarp probably died out not far north of the Davis County line as it is not seen on relatively undisturbed sections of the piedmont in southern Davis County. In contrast, Van Horn (1982) shows the Warm Springs fault trending north rather than northeast from the spring for several kilometers before joining a scarp in the basin that may be the Gilbert shoreline (Currey and others, 1984) rather than a fault scarp.

A shallow lake and marsh, now drained, formerly lay west of Becks Hot Spring (unit ly; Van Horn, 1982). Gilbert (Hunt, 1981, p. 27) notes that the low area occupied by the lake is anomalous in that it has not been filled by deposits of the Jordan River and suggests it is an area of local subsidence related to the Warm Springs fault. Recent tectonic back-tilting of this area toward the Warm Springs fault may have formed the low area. Alternatively, the low area may have formed behind a natural levee of the Jordan River and not be related to tectonism.

Gilbert (1890, plate 44, p. 348-349; field notes in Hunt, 1981, fig. 3.4) found evidence for three surface-faulting events on the post-Lake Bonneville fan of Jones Canyon (locality WS-2). Terraces cut by the stream of Jones Canyon in the footwall block were interpreted as being related to faulting.

The vertical separation between these strath terraces at the fault scarp, from uppermost to lowest, is 4.5, 1.5, and 3 m. This suggested to Gilbert that the 9-m-high fault scarp was formed by three events having offsets similar to the amount of terrace separation. A sketch of the site (plate 44) shows a possible free face on the mid-slope of the fault scarp just south of the fan. If a free face were present, it's preservation would suggest that the last event may be quite young, probably less than a few thousand years.

South of Victory Road (locality WS-3) the scarp decreases in height and appears to die out; however, urban development precludes determining how far the scarp extends south toward the center of Salt Lake City. Maps by Kaliser (1976) and Marsell and Threet (1960) show inferred faults (faults A and B, respectively) extending into the center of Salt Lake City; however, Gilbert's (1890, 1928) discussions suggest that post-Lake Bonneville fault scarps do not extend that far south. Gilbert could trace the scarps from the (then) northern suburbs of Salt Lake City near the warm springs (probably Wasatch Hot Spring near 900 North and 200 West) to some unstated distance north of Becks Hot Spring. Van Horn (1982) also shows the fault ending just south of Victory Road near 700 North. From this information it seems likely that significant surface faulting has probably not occurred south of 600 North in post-Lake Bonneville time.

Faults caused by lateral-spreading, ground failures in Salt Lake City

Excavations for the Hall of Justice (locality HJ; Osmond and Hewitt, 1965; Van Horn, 1982) and for several other buildings in an area several blocks to the northeast (Van Horn, 1969, 1982) revealed numerous faults and other evidence of deformation in deposits of the Bonneville lake cycle and older deposits. Little, if any, net vertical displacement is seen across deformed zones, individual faults are continuous along strike for only a few meters to a few tens of meters, and some high-angle faults flatten into detachment surfaces along lithologic contacts. These faults probably were caused by pre-historic, lateral-spreading, ground failures and are not related directly to tectonic faults. However, these failures may have been triggered by shaking during major earthquakes.

Fault at 11th Ave. and M St.

Everitt (1979) describes a fault striking N 5° E that was exposed in an excavation at 11th Ave. and M St. in northern Salt Lake City (location 11-M). Sufficient evidence did not exist at the site to determine if the faulting was tectonic or related to slope failure, or if any displacement had occurred along the fault in post-Lake Bonneville time.

Virginia Street fault

A striated fault plane in Tertiary bedrock (Pavlis and Smith, 1979) is exposed for about 100 m in an abandoned quarry just north of Virginia St. in northeast Salt Lake City (locality VSF). Locally, gravel that was probably deposited during the transgressive phase of the Bonneville lake cycle about 18 ka lies on narrow benches eroded into the fault plane. The unconsolidated deposits that lay against the fault plane have been removed by quarrying and with them the evidence for assessing the existence of faulting in post-Lake-Bonneville time. However, observations made in 1966 before the sediments had been removed showed evidence of probable faulting in Lake Bonneville sediments (R. Van Horn, written commun., 1985). Disrupted zones of pebbly silt as wide as 15 cm occurred in the well sorted lacustrine gravel that lay against the fault plane. These zones were close to and subparallel to the fault plane and were probably formed by faulting. No estimate of the total offset across the fault was made, but a marl bed was offset several centimeters. The lack of a conspicuous fault scarp along strike beyond the abandoned pit suggests that any vertical offset of deposits of the Bonneville lake cycle is probably small. The following evidence suggests also that the amount of late Pleistocene offset is small. Deposits of the Little Valley lake cycle, or an older lake cycle, are exposed in a shallow abandoned gravel pit just below the scarp (not shown at this scale). If there had been significant vertical offset along the fault since their deposition, which occurred at least 150 ka, they would be much more deeply buried.

University Hospital fault

Excavations for an addition to the University of Utah Hospital (locality UHF) exposed faulted alluvium lying below unfaulted deposits of the Bonneville lake cycle (Everitt, 1979). The throw on most of the faults is less than 1 m; however, the throw on a few of the faults exceeds 2.5 m. The net displacement across the zone is down to the west. The extent of faulting along strike beyond the excavations is not known. Because the overlying transgressive deposits of the Bonneville lake cycle, which at this altitude cannot be older than 18 ka, are not offset, the last movement on the fault must have occurred before that time.

Fault at the mouth of Parleys Canyon

Van Horn (1972a) shows a short fault just south of the mouth of Parleys Canyon that displaces deposits of the last cycle of Lake Bonneville as well as alluvium of post-Lake Bonneville age. We have not found evidence of offset along the fault in deposits of the Bonneville lake cycle; however, evenly bedded fine sand, silt, and clay of the Little Valley lake cycle east of the fault (not shown at this scale) dip about 30° to the southwest. Because the dip is too steep to be an original bedding attitude for sediment this fine grained, the deposits probably were tilted following their deposition. This tiliting may be related to faulting that occurred between the Little Valley and Bonneville lake cycles.

East Bench fault

Marsell (1969) showed that a branch of the Wasatch fault zone that was active during the Quaternary diverges from the range front near Mt. Olympus to form the East Bench fault. This fault trends north-northwest parallel to and 3 to 5 km west of the range front in the eastern part of Salt Lake City before rejoining the range front at Dry Creek, north of the University of Utah. Numerous springs lie along the fault, which is marked by a pronounced scarp as high as 50 m. The evidence for faulting at the base of the range at the University Hospital and at the mouth of Parleys Canyon discussed above suggests that some faulting has occurred along the range front as well as along the East Bench fault during Quaternary time. However, the two following lines of evidence suggest that the East Bench fault probably has been more active than the fault along the range front in middle to late Quaternary time. (1) Bedrock lies at shallow depths on the piedmont slope between the East Bench fault and the front of the Wasatch Range (Marsell, 1969). If there had been a great amount of vertical offset along the fault at the range front during Quaternary time, the bedrock surface on the downthrown block would likely be buried by a substantial amount of sediment derived from the upthrown block. (2) The front of the range east of the East Bench fault is less strikingly faceted and less steeply sloping than the range front farther south, where the Wasatch fault zone lies in a narrow belt at the base of the range. These physiographic differences may reflect a lower rate of slip during Quaternary time on the range-front fault east of the East Bench fault than on the Wasatch fault zone south of the East Bench fault. This pattern is consistent with much of the displacement between the range and basin blocks in the northern part of the valley being concentrated along the East Bench fault rather than at the base of the range.

Marsell (1969) recognized that the scarps along the East Bench fault between 400 South and 2100 South are higher and more degraded than the scarps between 2100 South and 3300 South. Studies by Van Horn (1969, 1972a, 1972b, 1972c) show that the lower scarps of the East Bench fault between 2100 South and 3300 South are formed in deposits of the Bonneville lake cycle and alluvium of post-Lake Bonneville age. Scarp heights are as great as 11 m; however, in some localities, as near 1000 East and 2840 South, scarp heights are less than one-half the throw measured on stratigraphic units (Van Horn, 1972c). This suggests that the bases of some scarps have been partly buried by post-faulting deposits. Similarly, the occurrence of broad, coalescing alluvial fans on the west side of the high scarps of the East Bench fault north of 2100 South suggests that there may be substantial burial of the downthrown block in this area also.

How much of the 50-m scarp height along the East Bench fault north of 2100 South is due to post-Lake Bonneville faulting and how much is due to older faulting is not known. Marsell (1969) describes one exposure of the East Bench fault in a foundation excavation (locality E-1), but does not discuss the amount of displacement or the age of the faulted beds. Although the scarps have been modified by urban development, some estimate of their age can be obtained from their morphology by using the method described earlier. Fault scarps 20-40 m high that are of post-Lake Bonneville age and have not been artificially modified have typical maximum scarp-slope angles of about 35°, which is approximately the angle of repose for these materials (Fig. 3). Maximum scarp-slope angles cannot be measured on the high scarps of the East Bench fault because of urbanization; however, mean slope angles (the angle measured between the crest and base of the scarp) can be measured and used for comparison. These mean scarp-slope angles are less than the maximum scarp-slope angles. The pre-urbanization, mean scarp-slope angles of the 50-m-high scarps north of 2100 S were probably no more than $10-15^{\circ}$. In contrast, the mean scarp-slope angles of latest Quaternary scarps are much greater than $10-15^{\circ}$. For instance, mean slope angles of scarps 10-25 m high in the southern part of the valley are $25-30^{\circ}$, or more. This suggests that the 50-m-high scarps along the East Bench fault cannot have formed entirely in latest Quaternary time, and that only part of their height could be due to latest Quaternary faulting. Perhaps the latest Quaternary, 11-m-high scarps along the East Bench fault south of 2100 South are typical of the amount of post-Lake Bonneville movement that has contributed to the 50-m-high scarps of the East Bench fault farther north.

South of Mill Creek, scarps along the East Bench fault increase in height to nearly 40 m and have low mean slope angles that are similar to those of scarps north of 2100 South. Again, probably only part of the total 40-m scarp height is due to post-Lake Bonneville faulting. To the south-southeast, scarps decrease in height and become inconspicuous a few blocks south of 4500 South, near Holladay. The latest Quaternary scarps along the Wasatch fault zone west of Mt. Olympus lie about 2.5 km east of the south end of the East Bench fault.

Wasatch fault zone between Mt. Olympus and Corner Canyon

From Mt. Olympus to Corner Canyon, the Wasatch fault zone is marked by a complex system of anastomosing fault scarps of post-Lake Bonneville age that lie mostly within 0.5 km of the front of the Wasatch Range. Various aspects of the fault zone will be discussed beginning with scarps near Mt. Olympus and proceeding south.

Previous maps show approximately located or concealed faults that follow the northeast trend of the embayment on the north side of Mt. Olympus (Marsell and Threet, 1960; Crittenden, 1965; Van Horn, 1972b). From our field investigations and study of aerial photographs taken prior to urbanization, post-Lake Bonneville fault scarps are probably not present on the north side of Mt. Olympus, but extend southward from just north of Casto Springs, which lies west of Mt. Olympus. The scarp between Casto Springs and 5060 South (locality W-1) is delineated by several springs. The scarp is only 1-2 m high and has been greatly modified and obscured by urban development. Near the alluvial fan at the mouth of Tolcats Canyon, this scarp is joined by one and possibly two (the dashed fault near Cottonwood School is either a fault scarp or a fluvial scarp) fault scarps and increases in height to 16.5 m. From here south to Corner Canyon, fault scarps form a conspicuous physiographic feature along the base of the range.

From the fan of Tolcats Canyon south to Big Cottonwood Canyon, the fault zone is as wide as 300 m and is composed of a complex system of fault scarps. The scarps along this part of the fault zone are formed in deposits of the Bonneville lake cycle, outwash of Bells Canyon age, and fan alluvium of early Holocene age. The highest scarp measured reliably is 24 m, although in an artificially disturbed area one scarp may be 28 m high. These scarps have morphologic characteristics intermediate between those of scarps thought to be of late and early Holocene age (Fig. 3). However, most of the scarps in the Tolcats-Heughs area plotted on Figure 3 have maximum scarp-slope angles at or near the angle of repose for the faulted materials. This suggests that the scarps are geologically young, but because scarps of a variety of heights all have the same scarp-slope angle, the data doesn't provide an interpretable scarp-height/slope-angle relationship. Furthermore, except for one data point, all of the Tolcats-Heughs scarps are more than 6 m high and probably are compound scarps formed by multiple surface-faulting events, whereas the regression lines plotted on Figure 3 are for scarps formed by single events. Machette (1982) shows that ages of compound scarps based on their morphology may be significantly older than the age of the last surface-faulting event that occurred on the scarp. Therefore, the scarp-morphology data, while offering little definitive information, suggest that the last surface-faulting event in the Tolcats-Heughs area is younger than early Holocene, and may be as young as late Holocene.

Gravel quarrying just north of the mouth of Big Cottonwood Canyon exposes several faults, but these faults cannot be traced through the area owing to extensive disturbance (locality W-2). Four faults across a zone about 500 m wide offset deposits of the Bonneville lake cycle a total of about 8 m. Glacial and lacustrine deposits about 150 ka are offset about 40 m across part of this zone, but their total offset across the zone cannot be determined (Scott, 1981). However, if this 40 m is the total offset, it implies that the latest Quaternary slip rate (8 m/15,000 yr=0.5 mm/yr) is more than twice the slip rate for the preceding time interval (40-8 m/135,000 yr=0.2 mm/yr).

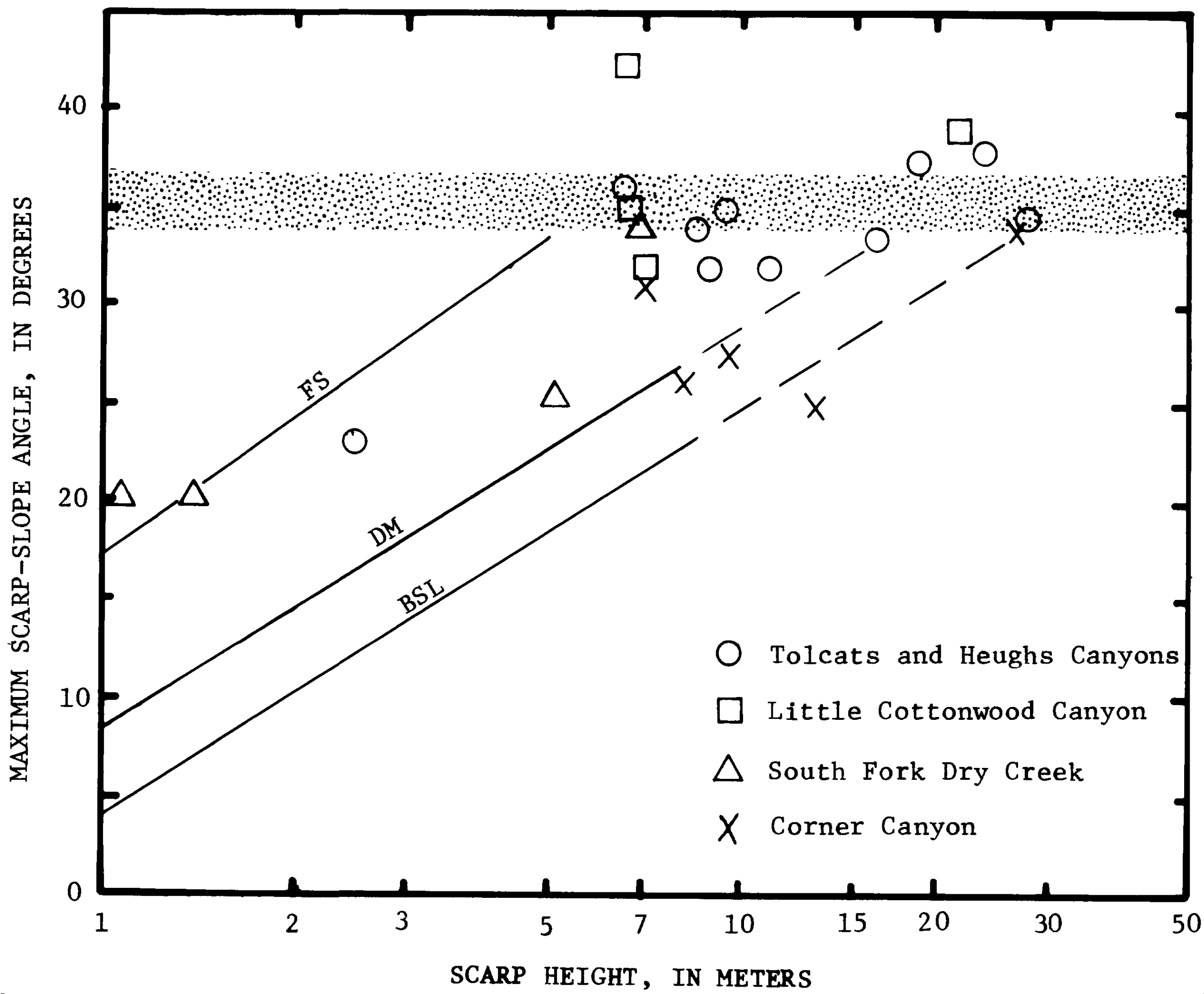

Figure 3. Plots of maximum scarp-slope angle versus height for scarps in several areas in the eastern Salt Lake valley (data from Petersen, 1981; Rebecca Dodge, written communication, 1981; this study). Also shown for comparison are regression lines from Bucknam and Anderson (1979) of scarps of the few-thousand-yr-old Fish Springs fault scarps of western Utah (FS), the early Holocene (Crone, 1983) Drum Mountains fault scarps of west-central Utah (DM), and the 14-to 15-ka, wave-cut Bonneville shoreline scarps (BSL). Stippled pattern between 34 and 37° indicates approximate angle of repose (Wallace, 1977) for materials in which most of the scarps are formed. The Corner Canyon scarps are developed largely in lacustrine sand, whose angle of repose is probably less than 34°.

Between Big Cottonwood and Bells Canyons (locality W-3), the fault zone is marked by well developed grabens from 100 to more than 200 m wide that, in detail, consist of many fault-bounded blocks. Faulted deposits range in age from late Holocene to late Pleistocene. Faulting has back-tilted the gently west-sloping depositional surface of the fan-delta of Big Cottonwood Creek so that for 200-300 m west of the fault the fan-delta surface now slopes gently eastward. Extensive back-tilting and formation of grabens along this portion of the fault zone has led to development of scarps tens of meters high, even though the net offset across the zone of deformation probably nowhere exceeds 15 m. The highest scarp (40 m) of latest Quaternary age in the map area, which lies just north of Little Cottonwood Creek, is formed in till and has a free face (Gilbert, 1928, plate 14B). The presence of a free face on scarps several meters high in unconsolidated material is thought to reflect an age of less than a few hundred to a few thousand years (Wallace, 1977). However, we hesitate to apply this relation in interpreting the significance of a free face on a 40-m-high scarp formed in compact till, because of the differences in scarp height and materials.

Reports by Woodward-Clyde Consultants of detailed investigations at the mouth of Little Cottonwood Canyon show that several surface-faulting events occurred along this part of the fault since about 19 ka, and that at least one event, and probably more, occurred since 8 ka (Swan and others, 1981; Schwartz and Coppersmith, 1984). This is consistent with limited scarp-morphology data (Fig. 3); however, further interpretation is hampered by the compound nature of the scarps and by their maximum scarp-slope angles lying at or near the angle of repose.

Morrison (1965) mapped several faults along scarps to the west of the fault zone shown on this map. Swan and others (1981) and we interpret these scarps as erosional in origin. We find no evidence of faulting related to these scarps, which are probably alluvial scarps cut by streams graded to the Provo shoreline.

A complex fault zone continues from Bells Canyon to Little Willow Creek (locality W-4) and has evidence of multiple surface offsets in post-Lake Bonneville time that yielded net displacements of 10-14 m. Trenching of one scarp between South Fork Dry Creek and Dry Gulch revealed evidence that a 7-m-high scarp formed in two surface-faulting events (Kaliser and Lund, 1979). Just north of Little Willow Creek, the fault zone is a complex graben and back-tilted surface from 100-400 m wide with many scarps; the main west-facing scarp is about 30 m high.

Just south of Bells Canyon, a small remnant of an alluvial fan (af4) is preserved on the upthrown side of the fault. The soil formed in the fan deposit is shown schematically in Figure 2 and is thought to represent at least 150,000 yr of soil development. In addition, a uranium-trend date of 250 ± 90 ka (J. N. Rosholt, written commun., 1984) suggests that the deposit may be older than 150 ka. At the fault scarp, this alluvial surface lies only several meters higher than an alluvial surface estimated to be 12-15 ka (af2), which lies about 12 m above the streams that breach the scarp. Although many tectonic and geomorphic factors govern the position of successive alluvial surfaces along faulted range fronts, the relatively low topographic position of this remnant of fan alluvium 4 in relation to fan alluvium 2, suggests that rates of fault slip have been greater since the deposition of fan alluvium 2 than in the time interval between the deposition of fan alluviums 2 and 4.

Near South Fork Dry Creek, several debris-flow deposits of late Holocene age are offset 1-3 m, probably during the last surface-faulting event along this section of the fault zone. The degree of soil development in the debris-flow deposits suggests they are 2-4 ka (Fig. 2) and that the last surface-faulting event occurred less than 2-4 ka. In addition, the morphology of the fault scarps is similar to that of the Fish Springs fault scarp in western Utah, which is thought to be a few thousand years old (Fig. 3; Bucknam and Anderson, 1979).

South of Little Willow Creek, the fault zone consists mostly of one scarp or two nearly parallel scarps that decrease in surface offset from 10-14 m near Little Willow Creek to about 6 m near Corner Canyon (locality W-5). Morphologically the compound scarps between Bear Canyon and Corner Canyon are similar to the early Holocene and latest Pleistocene scarps plotted in Figure 3. However, the age of the last event along the scarps between Bear and Corner Canyon is probably younger than early Holocene if the compound nature of the scarps is considered. Also, most of these compound scarps are formed in loose, sandy lake deposits that probably degrade faster than the materials in which the other scarps are formed. Thus, the scarp-morphology data can probably provide only a maximum estimate of the age of the last event on the scarps near Corner Canyon. Latest Quaternary scarps along the Wasatch fault zone die out at the mouth of Corner Canyon, beyond which the Wasatch fault zone separates Tertiary intrusive rocks of the Little Cottonwood stock from Tertiary volcanic rocks of the Traverse Mountains (Marsell and Threet, 1960). No geomorphic evidence has been recognized for post-Lake Bonneville surface ruptures along the section of the Wasatch fault zone between the Travese Mountains and Little Cottonwood stock.

Gravity data suggests that the northwestern flank of the Traverse Mountains is probably bounded by faults (Cook and Berg, 1961); however, there is no evidence that surface faulting occurred along any of them in post-Lake Bonneville time. We interpret numerous scarps on the piedmont as shorelines of Lake Bonneville, because they are horizontal and no faults have been observed in outcrops of Lake Bonneville or post-Lake Bonneville deposits exposed along the scarps. Because bedrock crops out in the basin as far as 1.5 km west of the front of the Traverse Mountains, a broad pediment may flank the mountain front. The relatively stable tectonic conditions necessary for a pediment to form further suggest that little uplift has occurred on the range front faults in late Quaternary time. The high, steep slope along the northwest face of the Traverse Mountains (Steep Mountain) is not related to young faulting, but rather is a wave-cut cliff fronted by a wave-cut bench. The bench and the cliff are cut in highly fractured bedrock.

SURFACE FAULTING DURING LATEST QUATERNARY TIME

Surface faulting has displaced deposits of latest Quaternary age throughout almost the entire length of the eastern Salt Lake valley. Systems of fault scarps ranging in height from less than 1 to 40 m define a fault zone that is locally as wide as 500 m. In addition, on large fan-deltas of the Bonneville lake cycle at the mouths of Big Cottonwood and Little Willow Canyons, a zone of back-tilting extends hundreds of meters west of the fault zone. After removing the effects of back-tilting and graben formation, the amount of latest Quaternary, net vertical displacement along most of the Wasatch fault zone in the area south of Mt. Olympus ranges from about 12-15 m. The amounts of net vertical displacement along the Warm Springs and East Bench faults are more difficult to estimate because of quarrying, urban development, burial of the bases of scarps by sediments, and other problems. However, latest Quaternary displacements on these faults probably do not exceed those on the Wasatch fault zone south of Mt. Olympus.

Because net vertical displacements during numerous past surface-faulting events along the Wasatch fault zone range from 1.5-2.5 m (Schwartz and Coppersmith, 1984), the net displacements of 12-15 m along much of the Wasatch fault zone in the Salt Lake valley were probably formed by numerous events, perhaps 4-10.

Some information about the temporal distribution of latest Quaternary surface-faulting events in the Salt Lake valley can be obtained from the amount of surface offset in stratigraphic units of various ages. However, this information is limited by the lack of widespread units that are younger than about 10 ka, which is due to two factors. (1) After 10 ka, the areas of active alluviation at the mouths of canyons were small compared with those of latest Pleistocene time. Thus widespread depositional surfaces have not formed since 10 ka. (2) Fault scarps, once formed, become incised by streams, and subsequent alluvial deposition is shifted to areas basinward of the scarp. Therefore, younger surface-faulting events along the scarp will generally leave either a very limited or no record in the younger deposits.

In spite of the above limitations, we have some information about the temporal distribution of surface-faulting events along the Wasatch fault zone in the southern part of the Salt Lake valley. Near the mouths of Little Cottonwood and Bells Canyons, the net vertical displacement of Bells Canyon till, which in this area is no younger than about 18-20 ka, is difficult to measure because of assumptions that have to made about the gradient of the surface of the till prior to faulting. However, Petersen (1981) estimates a displacement of about 14 m. Similar amounts of displacement occur in deposits of the Bonneville lake cycle that lie near the Bonneville shoreline and are about 14-18 ka, as well as in alluvial and debris-flow deposits that post-date the fall of Lake Bonneville from the Bonneville to the Provo shoreline, which occurred about 14-15 ka. Based on the degree of soil development in some of the post-Provo deposits (Fig. 2), they may be as young as 10-12 ka. These relations suggest that deposits that vary in age by at least 50 percent are displaced similar amounts, which argues that the surface-faulting events along this part of the fault have not been spaced uniformly in latest Quaternary time. This is consistent with other studies (e.g., Wallace, 1985) that show that grouping of surface-faulting events in space and time is probably an appropriate model of activity for faults in the Basin and Range Province.

Because of the problems discussed above, we cannot say much more about the temporal distribution of surface displacements in latest Quaternary time, except that the last surface-faulting event along at least parts of the Wasatch fault zone in the Salt Lake valley occurred in late Holocene time. This conclusion is supported by stratigraphic and scarp-morphology data from near South Fork Dry Creek and scarp-morphology data from the Heughs-Tolcat area that were discussed earlier. We do not know if the offsets in these two areas repesent one or two events.

Evidence exists also for grouping of surface-faulting events along the Salt Lake segment of the Wasatch fault zone from a longer time perspective than latest Quaternary time. Slip rates estimated from the net vertical displacements of latest Quaternary stratigraphic units and geomorphic surfaces whose ages are relatively well known are on the order of 0.7 to more than 1.0 mm/yr. This range is based on values of 0.76 mm/yr (Schwartz and Coppersmith, 1984); 0.7 mm/yr from the 14 m offset of moraines at the mouths of Little Cottonwood and Bells Canyons (Petersen, 1981), whose age is estimated to be about 18-20 ka; and more that 1.0 mm/yr from the 13 m offset of the alluvial fan of Heughs Canyon, which is estimated to be 10-12 ka on the basis of soil development. In contrast, as mentioned earlier, deposits exposed north of the mouth of Big Cottonwood Canyon and just south of Bells Canyon have displacements or topographic positions that indicate slip rates much less than latest Quaternary rates. Machette (1985) and Personius (1985) discuss similar patterns for other segments of the Wasatch fault zone, along which slip rates estimated over a 10^5-yr interval are 0.15 mm/yr. Furthermore, the segment of the Wasatch fault zone near Ogden has a mean late Cenozoic slip rate of 0.4 mm/yr (Naeser and others, 1983). These data suggest that the latest Quaternary slip rates may not be representative of mean slip rates over a long time period. Grouping of events during latest Quaternary time is one method of explaining the higher slip rates in latest Quaternary compared with longer time periods.

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