DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

MISCELLANEOUS INVESTIGATIONS SERIES
MAP MF-2109
PAMPHLET

PRELIMINARY SURFICIAL GEOLOGIC MAP OF THE WASATCH FAULT ZONE, EASTERN PART OF UTAH VALLEY, UTAH COUNTY, AND PARTS OF SALT LAKE AND JUAB COUNTIES, UTAH

By

Michael N. Machette

INTRODUCTION

The Wasatch Front and, particularly, the Wasatch fault zone have been the subject of geologic investigations since the reconnaissance studies of G.K. Gilbert (1890, 1928) a century ago (Machette and Scott, 1988). In 1983, the U.S. Geological Survey (USGS) initiated a program to assess the hazards posed by the fault zone. This map, which is the second in a series funded by the National Earthquake Hazards Reduction Program, shows the surficial geology along part of the Wasatch fault zone (see index map) and provides basic geologic data needed to make reliable assessments of earthquake hazards.

This discussion describes the Quaternary geology along the fault zone and at fault-segment boundaries, including data on the age, size, and distribution of fault scarps, and summarizes the results of an extensive exploratory-trenching program conducted by the USGS and UGMS (Utah Geological and Mineral Survey). This information is part of the basis for Machette and others' (1987, 1989) recent assessments of the paleoseismic history of the Wasatch fault zone. Although the current understanding of the Wasatch fault zone is incomplete, this map should help identify key sites for further detailed studies of the fault's history.

The Wasatch fault zone in Utah Valley has been the subject of many geologic studies (for example, Hunt and others, 1953; Bissell, 1963, 1964), but Cluff and others' (1973) systematic approach of mapping the fault zone using low-sun-angle photographs initiated the modern investigation of the Wasatch fault zone. Further detailed studies by geologists (Swan and others, 1980; Schwartz and others, 1983; Schwartz and Coppersmith, 1984) focused on site-specific investigations of the history of the fault zone and provided the impetus to map the Wasatch fault zone for this series of maps (see index map).

Long normal and strike-slip fault zones are usually comprised of several seismically independent elements; that is, structural segments (see Doser, 1989). Initial work on segmentation along the length of the Wasatch fault zone, summarized by Schwartz and Coppersmith (1984), identified six fault segments, but recent work by a consortium of investigators suggests that the fault zone may be comprised of 10 or 11 segments (Machette and others, 1989). The concept of fault segmentation is critically important to the analysis of earthquake hazards, because the majority of surface rupturing during a major earthquake is restricted to a single fault segment, such as occurred in the 1983 Borah Peak, Idaho, earthquake (Crone and Machette, 1984; Scott and others, 1985; Crone and others, 1987).

Schwartz and Coppersmith (1984) defined the Provo segment as that part of the Wasatch fault zone that borders the eastern margin of the Utah Valley extending from the Traverse Mountains on the north to Payson Canyon in the Wasatch Range on the south. The Provo segment is 70 km long as measured along its surface trace and 59 km long from end-to-end (Machette and others, 1989). Following detailed mapping along the fault zone in Utah Valley, Machette and others (1986, 1987) suggested a subdivision of the original Provo segment into three shorter subsegments (fig. 1); from north to south they are the American Fork, the Provo (restricted sense), and the Spanish Fork.

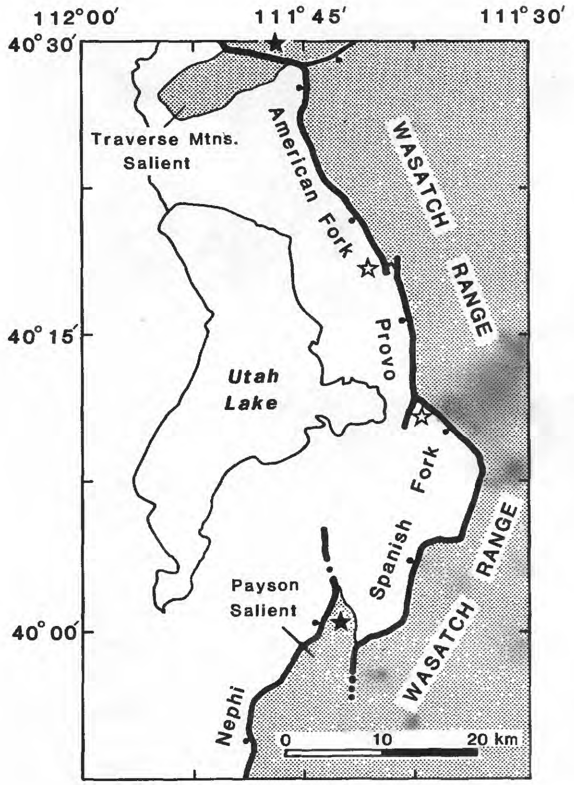

Figure 1.--Index map showing simplified trace of Wasatch fault zone in northern and central Utah. American Fork, Provo, and Spanish Fork subsegments (of the Provo segment) are from Machette and others (1987, 1989). Segment boundaries shown by solid stars, subsegment boundaries shown by hollow stars. Stippled area is Wasatch Range.

METHODS

Previously published maps show bedrock and surficial geology, faults, and types of soils at various scales for most of the map area, which for this study was restricted to the eastern part of Utah Valley. The surficial geologic maps by Hunt and others (1953), Bissell (1963), Miller (1982), and Davis (1983) proved useful for identifying the texture of materials and the geologic units in a stratigraphic framework that evolved over the past three decades. Cluff and others' (1973) 1:24,000-scale maps of the fault zone provided the most detailed trace of suspected surface ruptures along the Wasatch fault zone. However, I remapped most of the surficial geology and faults along the mountain front and adjacent basin terrain because existing maps were either not detailed enough or used outdated stratigraphic terminology and concepts. Differentiation and mapping of the Quaternary geologic units follows standard convention and relies heavily on age-dependent criteria such as geomorphic expression, preservation of original landforms, development of soils, and topographic and stratigraphic relations (see Birkeland, 1984, for a discussion of these techniques). However, the symbol Q (for Quaternary) has been omitted from all Quaternary map units, which does not follow standard practice.

Most mapping of the fault zone was done in the field on 1:12,000-scale low-sun-angle aerial photographs taken for the UGMS in 1970. These photographs were particularly useful for identifying fault scarps in surficial deposits. However, their poor tone and lack of contrast (because of low-angle illumination) made them inadequate for mapping the surficial geology. Black-and-white photographs from the Army Map Service taken in the 1950's at scales of 1:50,000-1:60,000 were used for that purpose. The Utah County Planning Department loaned me recent U.S. Department of Agriculture color photographs for selected areas along the Wasatch Range. The contacts between some lacustrine units were interpreted from the U.S. Soil Conservation Service soil maps of Utah County (Swenson and others, 1972).

Bedrock geology of the mountain blocks was compiled and simplified from maps published at a scale of 1:24,000 (see sources of geologic data) and from a 1:100,000-scale regional compilation by Davis (1983). Exposures of upper Cenozoic deposits were remapped (for this map and by B.H. Bryant, in press) in some areas to correct errors in previous mapping. In addition, an extensive program of exploratory trenching was undertaken by the USGS and UGMS starting in 1985 (see Machette and others, 1987). Within Utah Valley, results from five trenching sites have allowed Machette and others (1989) to decipher the movement history of the Wasatch fault zone. These data and interpretations are discussed in the following discussion.

The surficial and generalized bedrock geology shown on this map is supplemented by information on the size of fault scarps and the age of Quaternary deposits (see correlation chart), which are offset by the Wasatch fault zone. Fault-scarp characteristics can be used to estimate slip rates and average recurrence intervals at various sites along the Wasatch fault zone and to characterize the spatial and temporal variations in slip rates along the Wasatch fault zone. The scarp data were derived from traverse profiles of fault scarps made in the field using an Abney level and stadia rod; values of scarp height and surface offset were measured from computer plots of scarp profiles. Terminology used to describe fault-scarp morphology (fig. 2*A* and 2*B*) follows that established by Bucknam and Anderson (1979) for single-event scarps and Machette (1982) for multiple-event scarps.

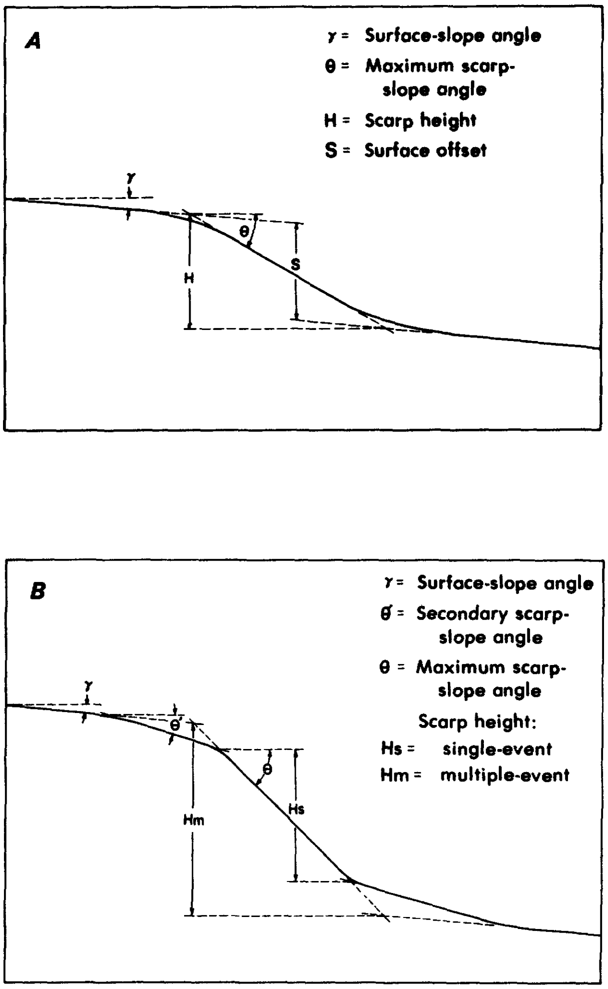

Figure 2.--Fault-scarp nomenclature as used in this report. *A*, single-event fault scarp (modified from Bucknam and Anderson, 1979, fig. 3). *B*, multiple-event fault scarp (from Machette, 1982, fig. 4).

QUATERNARY DEPOSITS AND DEPOSITIONAL HISTORY

In order to understand the stratigraphic framework used for this map, the following discussion of late Quaternary geology of the Wasatch Front has been summarized from pertinent articles by Scott and others (1983), Scott and Shroba (1985), Machette and others (1987), Machette and Scott (1988), and from a number of articles in the guidebook edited by Machette (1988a). Most of the surficial deposits along the Wasatch fault zone in and north of Utah Valley were deposited during the last pluvial lake cycle (known as the Bonneville lake cycle) between 32 and 10 ka (thousands of years ago) and in the subsequent interpluvial--the Holocene (<10 ka). Lake Bonneville began it's most recent expansion about 32 ka, rising with several fluctuations and pauses, until about 16 ka when it reached an external threshold (sill) at Red Rocks Pass, Idaho (1,552 m; 5,093 ft above sea level). After about 1,500 years at this highest Bonneville level (which may have included a major oscillation in lake level), overflow and downcutting of its sill caused the lake to drop about 108 m to the Provo level (altitude about 1,444 m; 4,737 ft). Jarrett and Malde (1987) estimated that most of the resulting Bonneville Flood (14.5 ka; Currey and Burr, 1988) occurred in about two months. The flood scoured deeply at Red Rocks Pass and deposited most of its debris along and within canyons of the Snake River Plain in Idaho (Gilbert, 1890; Malde, 1968). In Utah Valley, the rapid drop to the Provo level was accompanied by isostatic rebound and rapid erosion of Bonneville shoreline sand (unit lps) and gravel (unit lbg) and deltaic deposits (unit lbd) that filled the mouths of many canyons. This material was redeposited at lower levels as alluvial fan-delta complexes and terraces (units lpd and alp) graded to the newly established Provo shoreline. By 14.3 ka (Currey and others, 1983; Currey and Burr, 1988), the lake level began to drop below the Provo level in response to further downcutting of the Red Rocks threshold, isostatic rebound, and changing climate (warming or drying, or both). In the eastern Utah Valley, isostatic rebound and displacement along the Wasatch fault zone have uplifted the highest of the Bonneville shorelines as much as 34 m to altitudes of 1,553-1,587 m (5,095-5,205 ft; table 1); similarly, the highest Provo shoreline has been uplifted as much as 20 m to altitudes of 1,444-1,464 m (4,737-4,803 ft; table 1). The altitudes of these shorelines are a function of their position relative to the Wasatch fault zone (uplifted block versus down-dropped block) and the amount of local isostatic rebound (Crittenden, 1963).

By about 13 ka, Lake Bonneville had fallen to an altitude below 1,372 m (4,500 ft) and left Utah Lake near its present level, isolated from the evaporating main body of Lake Bonneville. Because Utah Lake was controlled by a natural threshold, after Lake Bonneville fell below an altitude of about 1,368 m (4,485 ft), subsequent expansions due to climatic variations (such as the Gilbert expansion of Currey and Oviatt, 1985) resulted in increased overflow from Utah Lake, rather than a rise in its level. As a result of this setting, none of the shorelines above about 1,372 m (4,500 ft) altitude in Utah Valley can be younger than about 13 ka. Some of the alluvial-fan complexes mapped as Holocene by Hunt and others (1953), Bissell (1963), and Miller (1982) have shorelines cut across their toes at altitudes of 1,378-1,390 m

(4,520-4,560 ft). The shorelines must be related to the lake's regression from Provo level and not to Holocene expansions of Utah Lake. Lake Bonneville reached the level of modern Great Salt Lake (1,282 m; 4,207 ft) about 11 ka and rose briefly to the Gilbert shoreline (1,295 m; 4,250 ft) about 10.3 ka. During the Holocene, Great Salt Lake has remained within about 10 m of its present level (Currey and others, 1984).

After Utah Lake became a fairly small and shallow body of water, eolian processes started to erode the desiccated lake beds of Utah Valley. These beds were the source of a widespread, thin mantle of calcareous loess that was deposited across the landscape. This phase of loess deposition (which occurred intermittently through the Quaternary) probably started about 12.5 ka in Utah Valley, but seems to have been most active during the early and middle Holocene (>8 ka; Machette and others, 1987), probably in response to changes in climate and vegetation.

After the drop to the Provo level, the larger streams downcut to maintain grade with local base level (Utah Lake), whereas local mountain-front drainages built small alluvial fans across a platform of shoreline and lake-bottom deposits. These fans consist mainly of coalesced debris-flow deposits (unit cd2) and alluvium (unit af2) of latest Pleistocene(?) to middle Holocene age. Textural analysis of the debris flows shows that their matrix (<2 mm fraction) was derived from the loess mantle, which now has been eroded from all but the most geomorphically stable landforms (such as fan-delta complexes and terraces). Trenching at the American Fork Canyon site (fig. 3 on map, see following discussion) exposed the loess and associated debris flows (Machette, 1988b). An age of 7,290±100 ^{14}C years was obtained from loess, whereas an age of 4,740±90 ^{14}C years was obtained from near the top of the overlying loess-derived debris. (These and other age determinations in this report are corrected for changes in atmospheric carbon on the basis of dated tree rings and are reported as calendar-corrected dates.) The above-mentioned radiocarbon ages yield calendar dates of 8,061 years B.P. and 5,518 years B.P. (the respective one sigma error limits are about 200 years). The radiocarbon ages at this site limit the debris-flow deposition and associated fan building episode to between 8.0 ka and about 5.5 ka--from the early Holocene to middle Holocene. Dating from other sites along the Wasatch Front (Machette and others, in press) support this time interval as a major fan-building episode.

The deposition of alluvial fans appears to have been rapid and extensive during the latest Pleistocene to middle Holocene in eastern Utah Valley. Along the mountain front, these alluvial fans (units af2 and af3) form a broad coalesced piedmont that is locally covered by upper Holocene fan alluvium (unit af1) and colluvium (unit cd1). Debris flows (unit cd1) are the most common upper Holocene deposit found at the mountain front, and they continued to be an important geologic hazard on the alluvial fans of the Wasatch Range (Kaliser and Slosson, 1988) during historic times, especially during the wet year of 1983. However, upper Holocene stream alluvium (units af1 and al1) is abundant along the major streams that drain into Utah Lake.

Although Quaternary deposits that predate the Bonneville lake cycle are present along the Wasatch fault zone, they generally are preserved as older alluvial fans (units af4 and af5) in uplifted blocks. The two largest remnants of old alluvium are north of Loafer Mountain (at the southeast end of Utah Valley) and in the foothills between American Fork Canyon and Provo Canyon. The deposits of unit af5 are probably several hundreds of thousands of years old as determined from comparisons of soil development, whereas the intermediate-age deposits (unit af4) have less well-developed soils and are thought to be about 100,000-200,000 years old (Machette, 1984). Glacial deposits of the Dry Creek advance (units gdco and gdct), which is equivalent to the Bull Lake glaciation of the Rocky Mountains, are only preserved at their type area along Dry Creek, northeast of Alpine, Utah (northern part of map area). These glacial deposits were probably deposited during the waning part of marine-isotope Stage 6 (Machette and Scott, 1988), which ended about 130-140 ka, and have soils similar to those found on alluvial fans (unit af4) related to the Little Valley lake cycle of Scott and others (1983; Machette and Scott, 1988). Although Hunt and others (1953) mapped extensive areas of the Alpine Formation that they considered to be deposited by pre-Bonneville lakes in Utah Valley, my studies do not support their conclusions. Most of the so-called Alpine Formation of Hunt and others (1953) appears to be offshore deposits (unit lbpm) of the Bonneville lake cycle (Scott and others, 1983; Machette and Scott, 1988; Machette, 1988b, 1988c).

THE WASATCH FAULT ZONE--SEGMENTATION AND BOUNDARIES

Schwartz and Coppersmith (1984) suggested that the 70-km-long section of the Wasatch fault zone from the Traverse Mountains south to Payson Canyon is a single segment, and they named it the Provo segment. As a result of my studies in the eastern part of Utah Valley, Machette and others (1986) tentatively subdivided the original Provo segment into three shorter subsegments: American Fork, Provo (restricted sense), and Spanish Fork (fig. 1). Since 1986, the USGS and UGMS have trenched three new sites (one on each of the proposed subsegments), and their dating of faulting events suggests that the subsegments have not behaved independently, at least during the last two events (see Machette and others, 1989). The Provo (restricted sense) subsegment is the subject of continued investigation as of March 1989. Although these subsegments are probably not independent structural entities, the three-fold subdivision of the Wasatch fault zone in Utah Valley provides a convenient format for the following discussion.

This section includes a brief description of the age, size, and distribution of fault scarps and trenching efforts on the American Fork, Provo, and Spanish Fork subsegments of the Wasatch fault zone. The discussion starts with the northern segment boundary at the Traverse Mountains, continues with descriptions of faulting along the three subsegments of the fault zone, and finishes with a description of the southern segment boundary near Payson, Utah.

BOUNDARY BETWEEN THE SALT LAKE CITY AND PROVO SEGMENTS

The west-trending Traverse Mountains form a major bedrock salient along the front of the Wasatch Range that separates the adjacent basin into two distinct and deep valleys. This salient is the structural boundary between the Salt Lake City (on the north) and Provo (on the south) segments of the Wasatch fault zone. The Traverse Mountains are one of four prominent salients that form structural barriers along the Wasatch fault zone (Wheeler and Krystinik, 1988).

Scott and Shroba (1985) traced the Salt Lake City segment from just north of Salt Lake City to Corner Canyon, which is the northwest-flowing drainage between the Traverse Mountains and the Wasatch Range (at the north edge of this map). There, the Wasatch fault zone forms a broad gouge zone into which Corner Canyon has eroded. Further south, the fault zone turns to the east and separates intrusive rocks of the middle Tertiary Little Cottonwood stock (unit Tpi) on the north from Neogene fanglomerate (unit Tn, Salt Lake Formation), middle Tertiary volcanic rocks (unit Tpv), and the underlying Paleozoic Oquirrh Formation (unit Pzm). My mapping in this area differs from the geologic compilation of Davis (1983), who showed the fanglomerate as Oquirrh Formation. The Wasatch fault zone can be traced continuously across the Traverse Range from Corner Canyon to the mouth of Dry Creek (northeast of Alpine) where uppermost Pleistocene glacial outwash (unit gbco) is displaced 3-5 m. Time-equivalent fan alluvium (unit af3) along the crest of the Traverse Mountains salient also is offset by the Wasatch fault zone, which indicates that the salient is being deformed, though at a slower rate than the segments to the north and south.

The Wasatch fault zone turns abruptly to the east as it crosses the Traverse Mountains. This section of the fault zone (the Fort Canyon fault of Bruhn and others, 1987, fig. 6) corresponds with the westward projection of the Deer Creek fault, which is a transverse structure (northern tear fault of the east-vergent Charleston-Nebo thrust fault). The Fort Canyon fault transfers motion along the Wasatch fault zone 8.5 km to the east, from the southern part of Salt Lake Valley to Utah Valley.

AMERICAN FORK SUBSEGMENT

The American Fork subsegment of the Wasatch fault zone bounds the northeastern margin of Utah Valley. It is about 22.5 km (14 mi) long along its north-south trace and, as such, is much shorter than the average length of segments along the fault zone (36.6 km; Machette and others, 1989, table 1). The Wasatch fault zone forms a left step at the Provo River, which transfers motion to the east about 2 km. This step is considered the southern boundary of the American Fork subsegment. Zoback's (1983) compilation of gravity for the region shows a prominent gravity saddle within Utah Valley and adjacent to Provo River Canyon, coincident with the step in the fault zone. The strong gravity lows to the north and south of the saddle probably reflect the bedrock floors of deep subbasins of Utah Valley.

The American Fork subsegment is marked by prominent scarps at the foot of the Wasatch Range, both north and south of American Fork Canyon. At American Fork Canyon, the fault cuts sediment of the Bonneville-level fan-delta complex and Holocene alluvial fans that overlie the delta (Machette and Lund, 1987). The fault scarps are typically 15-25 m high on lacustrine gravel (unit lbg), 7-8 m high on lower to middle Holocene fan alluvium (unit af2), and 1-3 m high on upper Holocene fan alluvium (unit af1). South of American Fork Canyon, the Manning Canyon Shale (stippled, upper part of unit Pzl) is exposed in the lower part of the Wasatch Range. The shale is particularly susceptible to landsliding, often carrying with it large blocks of bedrock (unit Pzm). Landslides of Holocene and Pleistocene to late Tertiary age are prominent along the Wasatch Front from American Fork Canyon to the vicinity of Provo. Most of the massive landslide deposits (unit clso) in the drainage of Hessetts Hollow (the first large canyon south of American Fork Canyon) are older than the Bonneville lake cycle, as evidenced by shorelines of Lake Bonneville etched across the toe of the landslide. The Wasatch fault zone extends through the landslide complex, but the scarps form a discontinuous, en echelon pattern that also includes landslide headscarps. South of Hessetts Hollow, the Wasatch fault zone again is represented by large, singular scarps or multiple, subparallel scarps in alluvial and lacustrine deposits. This pattern of discontinuous/continuous scarps is repeated several times to the south where the fault zone crosses landslide terrain at the foot of the range. Most of the large landslide complexes that I mapped in this region are shown on Davis' (1983) map as in place, but structurally down-dropped Manning Canyon Shale; however, exposures reveal chaotic to unbedded structure and large blocks of exotic material (unit Pzm).

From Pleasant Grove south, the Wasatch fault zone forms a parallel series of large antithetic and synthetic scarps that are preserved on old alluvium, on landslides, and less commonly on sediment of the Bonneville lake cycle. These fault scarps can be traced along the mountain front through fairly dense oak brush or tree cover as far south as the Provo River fan-delta complex (unit alp). There, the surface trace of the fault zone is preserved as two parallel fault scarps that trend due south across Holocene alluvial-fan deposits (unit afy) and Provo-level alluvium (unit alp). The apparent surface offset of Provo-level alluvium is about 3 m, whereas the scarps are only 1-2 m high on the Holocene fans. Neither scarp can be traced south of Utah State Highway 52 or across the late Holocene floodplain of the Provo River. It is suspected that these faults extend to the south in the subsurface and are mostly coincident with the Provo shoreline, which lies at the base of uplifted Neogene fanglomerate (unit Tn) that crops out in the foothills of the Wasatch Range.

The American Fork Canyon trenching site

In 1986, W.R. Lund (UGMS) and I excavated three trenches across the Wasatch fault zone near American Fork Canyon. This is an area where I had previously mapped the Quaternary geology at a scale of 1:10,000 (fig. 3 on map). The American Fork Canyon trenching site is characterized by a large, well-preserved fan-delta complex constructed at the end of the transgressive phase of the Bonneville lake cycle (about 32-14.5 ka; Currey and Oviatt, 1985, fig. 2).

All three trenches at this site (AF-1, AF-2, and AF-3; fig. 3 on map) penetrated Holocene alluvial fans that are formed primarily by debris flows deposited before about 5.5 ka (Machette, 1988b). These deposits have been displaced 7-8 m (23-26 m) by the last three faulting events, although the trenches collectively revealed evidence for four events during the past 8 ka.

Trench AF-1, the deepest and longest of the trenches, crossed the main fault zone and penetrated a relatively thick section of scarp colluvium. The colluvium forms three discrete wedges, each of which was derived by erosion of the scarp's free face following faulting. The top of each wedge has a well-developed A horizon and a weakly developed calcareous A or C horizon. Trench AF-1 had evidence for the last three of the four faulting events recorded at the site. Trench AF-2 recorded the most recent and, probably, the second faulting events. Trench AF-3, which was on a splay of the main fault, had evidence for the second event and a fourth (oldest) event that was not recorded in the two other trenches.

The analysis of paleoseismicity at the American Fork Canyon trenching site (Machette, 1988b) relies on conventional- and accelerator-method radiocarbon dating of charcoal and organic carbon (AMRT), thermoluminescence (TL) analysis, and detailed mapping of soils and stratigraphic units both at the site and in the trenches. The first conclusion from the trenching was that the strength of development of soils on the colluvial wedges suggests faulting recurrence intervals that were long. Machette and Lund (1987) proposed that thousands, not hundreds, of years would have been required to develop the moderately thick A and Cca horizons found on each of the colluvial wedges.

The combination of radiocarbon (charcoal and AMRT) and thermoluminescence dating at the American Fork Canyon site indicate that three large-magnitude surface-faulting events occurred about 550±200 years, 2,650±300 years, and 5,300±300 years ago (Machette, 1988b; Forman and others, 1989). Timing of a fourth event is less well defined, occurring sometime between 5.5 ka and 8.0 ka. Two faulting events (the second and third) produced a total of 5-6 m of vertical displacement between 550 years ago and 5,300 years ago--an interval of 4,750 years; thus, the average recurrence interval is about 2,400 years. The resulting slip rate during the middle and late Holocene is 1.05-1.26 mm/year (5-6 m/4,750 years).

Repeated movement across the Wasatch fault zone has produced progressively more net displacement in older deposits; for example, in Holocene versus latest Pleistocene age (Bonneville lake cycle) versus late to middle Pleistocene age deposits. At the trench site, the fan-delta complex is the oldest material that records displacement across the fault zone. The fan-delta is capped by transgressive-beach and topset-delta gravel (about 15 ka) of the Bonneville lake cycle. South of American Fork Canyon, the gravel of the Bonneville shoreline is displaced 15-20 m across a wide graben that has formed along the fault zone. North of the canyon, lacustrine gravel at the same level is displaced as much as 26 m across the fault zone where there is minor backtilting, but no graben. If 15 m and 26 m are considered the minimum and maximum values for net displacement, the average slip rate over the past 15,000 years is 1.0-1.7 mm/year. These rates are similar to the rates documented for the past 5.3 ka from the trenching studies, and thus indicate a sustained and fairly high rate of slip since the culmination of the transgressive phase of the Bonneville lake cycle. In contrast, the long-term slip rates recorded by 130-250 ka alluvium along this and adjacent segments of the Wasatch fault zone have been only 0.1-0.2 mm/year (Machette, 1984). These values are almost an order of magnitude less than slip rates recorded since Lake Bonneville fell from its highest level and may indicate a causal relation between high slip rates and the most recent hydrologic cycle of Lake Bonneville (see Machette and others, 1987 and in press).

PROVO SUBSEGMENT

The Provo subsegment (restricted sense) extends from Provo Canyon south to Springville, Utah. The southern part of the subsegment includes the Springville fault, a basinward splay of the main Wasatch fault zone. As mapped, the Provo subsegment is 18.5 km long and is the shortest subsegment of the Wasatch fault zone. The southernmost (Fayette) segment of the Wasatch fault zone is about the same length, but it is pre-Holocene in age and has a low slip rate (Machette and others, 1987, 1989). South of Little Rock Canyon, which is 3.5 km south of Provo Canyon, the Wasatch fault zone is expressed primarily as scarps on surficial deposits at the base of the Wasatch Range.

Between Provo Canyon and Little Rock Canyon, the western front of the Wasatch Range is characterized by geologic relations that are unusual for the Wasatch fault zone of Utah Valley. Davis' (1983) compilation of the geology of this area shows large blocks of Paleozoic rock (Oquirrh Formation, unit Pzm) thrust eastward and uplifted in the Wasatch Range. My mapping indicates that much of the "Oquirrh-like" material is either a fanglomerate facies of the Salt Lake Formation (unit Tn) or large masses of Oquirrh Formation that have slid westward on the Manning Canyon Shale (unit Pzl, stippled part). Extensive areas of Quaternary landslide deposits (clso) that predate the Bonneville lake cycle also are present in this area. These deposits also are derived mostly from the Manning Canyon Shale.

The landslide deposits and Neogene fanglomerates south of Provo Canyon form a block that is bounded by the Provo subsegment in bedrock on the east and by a buried (concealed) southward extension of the American Fork subsegment on the west (see previous discussion). The result of this overlapping left-step in the Wasatch fault zone is to preserve locally derived, coarse-grained fanglomerate and landslide deposits at the surface; that is, at an intermediate structural level between the uplifted range and down-dropped basin. These deposits are rarely seen at the surface and are inferred to be deeply buried in the basins and eroded from the uplifted ranges. Although exposures of the Wasatch fault zone are relatively poor along this subsegment, two strands of the fault are exposed in the stream bank of Rock Canyon (northeast of Provo; see discussion of Rock Canyon trenching site).

The Provo subsegment is characterized by multiple parallel to branching fault strands that form a relatively narrow fault zone. Rarely is there a single fault strand on which most of the movement has taken place. For example, south of Rock Canyon the fault zone crosses a remnant of a Bonneville-level fan-delta complex. The fault zone is about 350 m wide and the most active traces are toward the basin along two down-to-the-west faults and a major down-to-the-east antithetic fault, which form a graben about 60-m wide and 10-m deep. Farther south, these three faults lose expression in easily eroded lacustrine sand (unit lbs). The easternmost splay of the zone bounds the mountain front at the same elevation as the highest Bonneville shoreline. The fault separates uplifted fan alluvium of pre-Bonneville age (unit afo), which lies on bedrock (unit Pzl), from younger lacustrine deposits. This fault does not have a continuous surface expression because of a lack of post-Bonneville movement, but instead terminates outliers of alluvium that predate the Bonneville lake cycle. About 1.5 km south of Rock Canyon this strand of the fault zone forms a scarp 5 to 8 m high on old alluvial-fan deposits (unit afo).

The pattern of ground rupture is even more complicated south of Slate Canyon (due east of Provo) where the Wasatch fault zone strikes across transgressive gravel of the Bonneville lake cycle and regressive gravel at and below the Provo level, both of which lie on steeply sloping alluvial-fan deposits that predate the Bonneville lake cycle. The history of faulting in this area is difficult to decipher for three reasons: (1) fault scarps predating the Bonneville lake cycle have been modified during the rise and fall of Lake Bonneville, (2) most of these faults were reactivated during the Holocene, and (3) much of the area has been disturbed by gravel mining or by regrading of abandoned gravel pits. The section of fault that is difficult to map extends south to the vicinity of Ironton.

The southern end of the Provo subsegment is considered to be the Springville fault, which is a basinward splay of the Wasatch fault zone that extends about 4 km into the southern part of Utah Valley. The boundary with the Spanish Fork subsegment is taken as the gap in faulting at the junction of the Springville fault and the trace of the main Wasatch fault zone subsegments to the east (fig. 1). The Springville fault extends from just east of the State Fish Hatchery southward to Utah State Highway 77, a distance of 3 km across the alluvial fan of Hobble Creek. Scarps along the Springville fault are 0.5 to <2 m high, but within Springville they have been extensively modified. Bissell's (1963) map shows a fault about 1 km south of Springville, which could be interpreted as an extension of the Springville fault. However, I agree with Miller (1982) and show this feature as the combined head scarp of a massive lateral spread (unit clsp) and a recessional (Provo) shoreline that is prominent at 1,378 m (4,520 ft) altitude in the eastern part of Utah Valley.

Rock Canyon trenching site

In 1986, M.N. Machette (USGS) and W.E. Mulvey (UGMS) mapped a natural stream exposure of the Wasatch fault zone at Rock Canyon and determined that there was about 2 m of net displacement in upper to middle(?) Holocene debris flows and alluvium. The displacement consisted of 1.5 m of tectonic displacement and 0.5 m of drag. The resulting scarp has been mostly eroded by stream flooding and buried by debris flows. Radiocarbon dating of organic matter in the fault-scarp colluvium yielded an AMRT date of 1,110±50 ^{14}C years B.P., which corrects to a calendar date of 1,005 years ago (Machette and others, 1987). This date is generally considered to constrain the maximum age of the most recent faulting event (about 1 ka) at Rock Creek.

Control on the minimum time of faulting at Rock Canyon was provided by a radiocarbon age from the soil that was buried by flood alluvium and debris-flow deposits that postdate the faulting. This soil is azonal and consists of a rich accumulation of organic matter (A horizon). The soil formed initially across the pre-fault surface, but after faulting it was locally buried by a wedge of scarp colluvium. Away from the scarp, the soil (which was dated) continued to form until it was buried by post-fault deposits. Organic carbon from the A horizon yielded an AMRT date of 455±35 ^{14}C years B.P., which corresponds to a calendar date of 512 years ago. These preliminary investigations suggested that the most recent faulting at Rock Creek occurred between 0.5 and 1 ka and that the resultant scarp was buried about 400 years ago.

In the spring of 1988, W.R. Lund (UGMS) and D.P. Schwartz (USGS) trenched the 4.5-m-high scarp formed on Holocene alluvium just north of the road that leads to Rock Canyon, about 100 m south of the stream exposure. In addition, they cleaned off the stream embankment and exposed a second splay of the fault; these two fault splays merge to the south and form a 4.5-m-high scarp.

Preliminary mapping of the trench (W.R. Lund and D.P. Schwartz, oral commun., 1988) revealed only one colluvial wedge and, thus, only one faulting event for the 4.5-m-high scarp. Although the size of this scarp had suggested two to three faulting events (Machette and others, 1987), Lund and Schwartz found that backtilting and graben formation account for the 2-m difference between stratigraphic offset (about 2.5 m) and scarp height. Although no charcoal was found in the trench, they sampled several organic soil samples for bulk (AMRT) radiocarbon dating. At the new exposure along the stream channel, future dating of charcoal found both above and below the colluvial wedge should allow them to limit the time of most recent faulting more precisely. Because of the pervasive backtilting at this site, Lund and Schwartz's trenching did not penetrate deposits old enough to record previous faulting events. Additional trenching of fault scarps caused by multiple events will be needed to determine the timing of penultimate faulting events and recurrence intervals along this subsegment of the fault zone so that meaningful comparisons can be made with the American Fork and Spanish Fork subsegments.

SPANISH FORK SUBSEGMENT

The Spanish Fork subsegment (Machette and others, 1986) is restricted to the range-bounding Wasatch fault zone between Springville and Payson Canyon. It is the southernmost of three subsegments that comprise Schwartz and Coppersmith's (1984) original Provo segment. The lack of a prominent bedrock spur or salient between the Provo (restricted sense) and Spanish Fork subsegments indicates that this boundary probably is not a persistent structural feature; that is, one that controls the ends of surface ruptures (Wheeler and Krystinik, 1987).

The Spanish Fork subsegment forms a major concave-to-the-west bend in the Wasatch fault zone, the only such prominent bend along the entire fault zone. In detail, this bend consists of two prominent arcs; on the north, a large southwesterly facing scallop and, on the south, a smaller westerly facing scallop. The northern end of the Spanish Fork subsegment is marked by a relatively complexly faulted area between the Springville fault and the abrupt clockwise bend at the north end of the subsegment. This triangular area (centered on the border between Sections 27 and 28, T. 7 S., and R. 3 E.) is characterized by discontinuous faulting both at the bedrock/alluvium contact and on the piedmont. The south end of the Spanish Fork subsegment forms the east side of the Payson salient, which is a persistent structural barrier (see following discussion).

The central part of the Spanish Fork subsegment is less complicated than the ends. For most of its length, the fault forms a single scarp or narrow zone of subparallel scarps on Bonneville or Provo shoreline deposits or across local alluvial fans that were deposited at the base of the Wasatch Range. Due east of Springville, the fault cuts through an area of young landslides, some of which have been active recently enough to obscure the trace of the fault. South from Springville the fault zone strikes approximately southeast for 4.5 km (3 mi) to the north bank of Hobble Creek. At this point it turns abruptly south and crosses a series of Holocene to latest Pleistocene fluvial terraces (fig. 4 on map), which provide reliable surfaces for net tectonic displacement across the fault zone (see following discussion).

From Hobble Creek south to the mouth of Spanish Fork Canyon, the fault zone lies at the base of a spectacular set of triangular faceted bedrock spurs, which were first recognized as tectonic landforms by Gilbert (1890). These spurs are the erosional signature of a long and repeated history of movement on the fault zone. South from Hobble Creek, the late Pleistocene record of fault movement is recorded by an uplifted platform of lacustrine sand and gravel of the Bonneville shoreline that was probably last occupied about 14.5-16 ka. Scarps on these deposits are commonly 50 m high, but much of the apparent offset is caused by back rotation and antithetic faulting. Steeply sloping stream drainages along this part of the Wasatch Range have cut narrow slots in the shoreline platform and deposited thick alluvial fans (unit afy) that are underlain mainly by Holocene debris flows. Repeated faulting of the fans has formed scarps that commonly have slopes of >33°-38° and heights of 8-14 m. The youngest of the debris flows (unit cd1), which are too small to map at 1:10,000 scale, were displaced 2-3 m by the most recent faulting event.

Just east of the mouth of Spanish Fork Canyon, the trace of the Spanish Fork subsegment makes a 100° clockwise bend, from a north-south trend to an east-west trend (fig. 5 on map). Several prominent antithetic faults cross the fault bend in a southwesterly trend. Although this geometry and marked change in trend could suggest a segment boundary, figure 5 (on map) shows that surface faulting is continuous around the bend. The displacement along the main fault, which is recorded in high-level deposits of the Bonneville lake cycle, decreases at the bend in comparison to sites both to the north and west. This local decrease is probably caused by drag of the down-dropped block, which is constrained by the fault's bend and downdip geometry.

The fault zone strikes west from Spanish Fork Canyon along the base of Provo- and Bonneville-level shoreline escarpments. This relation continues as far west as the north bank of Water Canyon, where broad Holocene alluvial fans bury the highest Bonneville shoreline. Southward from there, the fault zone bounds bedrock of the Wasatch Range and forms scarps on colluvial and alluvial-fan deposits of Holocene to middle(?) Pleistocene age. As the fault approaches Peteetneet Creek (and Payson Canyon), it enters old landslide deposits (unit clso); from here it appears to turn due south into Payson Canyon. The recent faulting probably continues 2-3 km up Payson Canyon, but extensive landsliding of Tertiary and Cretaceous rocks (unit TpK) obscures all such (inferred) fault scarps.

TRENCH STUDIES ON THE SPANISH FORK SUBSEGMENT

The Spanish Fork subsegment has been the focus of detailed trench investigations and mapping for the past 10 years, which culminated in the investigation of two major sites (Mapleton and Water Canyon) during 1987. Four geographically separate sites have been investigated; three on the main Wasatch fault zone and one on a splay of the Wasatch fault zone.

Hobble Creek/Deadmans Hollow site

The first evidence of repeated Holocene movement on this subsegment of the Wasatch fault zone came from Swan and others' (1980) study of tectonic, stratigraphic, and geomorphic relations at Hobble Creek (fig. 4 on map), coupled with trenching at the Deadmans Hollow site (fig. 4 on map). They found evidence for as many as six or seven surface-faulting events that produced 11.5-13.5 m of net vertical tectonic displacement since formation of the Provo fan-delta surface of Hobble Creek about 13.5 ka. An age of about 14.3±0.2 ka is now preferred for this surface on the basis of recent stratigraphic studies (see discussion of Quaternary deposits). Three young events are defined on the basis of colluvial stratigraphy observed in trenches across a faulted Holocene alluvial-fan complex at Deadmans Hollow. Three or four older events are inferred from tectonic strath terraces preserved along Hobble Creek, upstream from the fault zone. The inference of six or seven post-Provo surface-faulting events is probably reasonable, but the absence of organic material in the terraces and trenches prevented dating faulting events and calculation of individual recurrence intervals. The average interval between faulting events is 1,700-2,600 years (as revised by Schwartz and Coppersmith, 1984). They thought that the recent faulting event occurred >1,000 years ago on the basis of the degree of preservation of fault scarps (however, no systematic study of fault-scarp morphology was made). Individual displacements during the post-Provo faulting are unknown, but the average value ranges from 1.6 to 2.3 m for six or seven events.

Scarps on transgressive Bonneville-lake-cycle sediment (units lbg and lbs) just south of Hobble Creek are large and quite steep (33°-40°). However, the true net displacement is difficult to determine because of extensive backtilting, graben formation, and a general lack of marker beds that can be traced across the fault zone. Swan and others (1980, table 1) preferred a value of 30±0.5 m displacement since 17±2 ka, whereas Machette and others (1987) estimated 40-45 m of displacement on the basis of a geometry similar to that seen in the well-preserved, but deformed Provo-level terraces of Hobble Creek. If the faulted sediment is 17±2 ka, then the resulting average slip rate at Hobble Creek is between 1.8 mm/year (Swan and others, 1980, table 1) and 2.5 mm/year (this report). Because there may be as much as two to three times more net displacement in transgressive deposits than regressive deposits, but only a slight difference in age, it appears that faulting occurred at a very high rate (perhaps as much as 10 mm/year) at this site during and after the catastrophic fall of Lake Bonneville (Machette and others, 1987).

Mapleton trenching sites

In June 1987, W.R. Lund (UGMS) and D.P. Schwartz (USGS) dug six exploratory trenches at two sites east and south of Mapleton, Utah, to determine recurrence intervals and further refine the time of the most recent faulting along this subsegment of the Wasatch fault zone. The trenching sites (MN, Mapleton North; MS, Mapleton South) are 4 and 5.5 km south of the Hobble Creek site. Mapping of the three most productive trenches at the two sites was completed in October 1987, and the preliminary radiocarbon and TL dating was completed in September 1988. Their investigations indicate two surface-faulting events in the past 3,000 years, and the most recent event is limited by radiocarbon ages on charcoal of 445±75 and 770±100 ^{14}C years B.P. (these dates correspond to calendar dates of 512 and 689 years ago, respectively). Thus, the most recent faulting event at Mapleton probably occurred about 600±100 years ago and, thus, could well be the same event recorded at the American Fork Canyon site. In addition, they obtained a preliminary TL age estimate of 3,200±300 years and a radiocarbon date of 2,810±95 years B.P. (which yields possible calendar dates of 2,893, 2,904, and 2,934 years ago) from the soil buried by two colluvial wedges (Schwartz and others, 1988). The TL and radiocarbon dates suggest that the second event occurred about 3,000±200 years ago (D.P. Schwartz, oral commun,. 1989), or about 2,400 years before the most recent faulting. The timing of the second event is similar to the 2,650±300 year estimate from the American Fork Canyon site. The coincidence in dating from these two sites almost demands that the Spanish Fork and American Fork subsegments are part of a master (Provo) segment that commonly ruptures in its entirety. Additional dating control at the Mapleton sites may come from radiocarbon analyses of detrital charcoal from abundant burn layers and from organic carbon in buried A horizons.

Woodland Hills and Water Canyon trenching sites

The southern part of the Spanish Fork segment has been the subject of recent investigation by both the USGS and by the U.S. Bureau of Reclamation (USBR) as part of their Central Utah (Water Diversion) Project. Before making a detailed study of the Water Canyon (WC) site, which is about 14 km southwest of Hobble Creek, the Bureau excavated two trenches across a fault scarp that crossed the planned alignment of the project's pipeline. This scarp is 1.5 to 3 m in height and trends away from the main Wasatch fault zone, parallel to and above the highest Bonneville shoreline (altitude 1,553 m, 5,095 ft; table 1) at the southeast end of Utah Valley. This scarp is formed by the Woodland Hills (WH) fault, which is defined herein as a splay of the Spanish Fork subsegment. The trenches are about 1.5 km southwest of Water Canyon. The larger, western trench was mapped by R.M. Robison (Utah County

Geologist), C.V. Nelson (Salt Lake County Geologist), Rod Weisser (USBR), James McCalpin (Utah State University), and myself in November 1986. The surface rupturing along the Woodland Hills fault is relatively short and infrequent compared to that observed on other earthquake-producing faults (Machette and others, 1989), such as the Wasatch fault zone. Thus, motion on this fault probably occurs as a splay of the main trace of the Wasatch fault zone.

The relations exposed in the trench suggest only three or four surface-faulting events and about 3 m of net vertical displacement since the end of the middle Pleistocene (about 130 ka). This age estimate is based on the correlation of soils on the faulted alluvial-fan deposits with those on old alluvium (unit af4) in nearby areas. Although this history results in very long recurrence intervals (about 40,000-65,000 years), the most recent movement was quite recent. AMRT dates of 1,190±50 ^{14}C years B.P. and 1,380±60 ^{14}C years B.P. were obtained from a block of soil (A horizon) that had collapsed from the fault free face and was buried in the scarp colluvium. The dates, which represent the minimum time since burial (and faulting), correspond to calendar dates of 1,102 and 1,306 years (respectively), have error limits of about 80-130 years, and are concordant at 1,200±100 years. From this 1,200-year estimate, 200 years is subtracted to compensate for the inferred AMRT age of the soil at the time of burial. Thus, it is suspected that the most recent faulting occurred about 1,000±300 years ago at this site, and thus may be correlative with the most recent event at the Mapleton site (600±100 years ago).

This study was expanded by the USBR to the main fault zone in 1987 with excavation of three trenches at Water Canyon by Dean Ostenna and his associates from the USBR. Two trenches were excavated in Holocene fan-head terraces at the mouth of the canyon and a third trench in slope colluvium at a proposed tunnel-portal site south of Water Canyon. Although final analysis of the trenching investigations awaits the completion of accelerator-method radiocarbon dating of charcoal samples, Dean Ostenna (oral and written commun., 1987) suspects three or possibly four faulting events since 6-8 ka, with two of these in the past 1,000 years. If Ostenna's estimate of the number of events and time range is correct, there would be a conflict between the fault chronology determined here and at Mapleton, 14 km to the northeast. Part of the conflict may be due to the proximity of the Water Canyon site to the boundary between the Spanish Fork segment and Nephi segment. This site may be recording some or all of the events from both segments, because of their spatial overlap.

BOUNDARY BETWEEN THE PROVO AND NEPHI SEGMENTS

The boundary between the Provo segment and the Nephi segment, which extends from Payson south to Nephi, is an echelon, overlapping right step in the Wasatch fault zone (fig. 1). Wheeler and Krystinik (1988) named the north-trending bedrock spur between these two segments the Payson salient. The Payson salient consists of Precambrian to Paleozoic rocks exposed on Dry Mountain and Tithing Mountain and volcanic rocks (unit Tpv) exposed on Little Mountain. Little Mountain, which extends into Utah Valley at Payson, is mantled by lacustrine gravel below the highest shoreline of Lake Bonneville, and is bounded by faults on three sides. The western side has several down-to-the-west faults that form scarps on shoreline gravel of the Bonneville lake cycle (unit lbg). The southern end is terminated by a west-striking normal fault (possibly low angle) that places volcanic rocks (unit Tpv) against the Oquirrh Formation (unit Pzu). This relation is similar to that at Spanish Fork Canyon, where Tertiary and Cretaceous rocks (unit TpK) are down-dropped between Paleozoic rocks (unit Pzm) and the Wasatch fault zone. I suspect these two faults and similar mapped ones along the Wasatch Front (Davis, 1983) are the soles of large-scale, gravity-slide blocks that have slid into Utah Valley during uplift of the Wasatch Range.

The Nephi segment and its northern extension--the Benjamin fault--form the west side of the Payson salient. Although it appears that the Benjamin and Springville faults could connect in the subsurface beneath Utah Valley, Zoback's (1983) gravity map shows that the deep part of the basin extends, uninterrupted, from east of Spanish Fork northwest under Utah Lake. Thus, the Springville and Benjamin faults must die out (lose structural throw) as they extend into Utah Valley.

OTHER FAULTS WITHIN UTAH VALLEY

As previously mentioned, three splays of the Wasatch fault zone extend into Utah Valley: the Springville fault of the Provo subsegment, the Woodland Hills fault of the Spanish Fork subsegment, and the Benjamin fault of the Nephi segment. The Benjamin fault is associated with a line of hot springs that extend toward Utah Lake for about 5 km from the Benjamin Cemetery (Hintze, 1973, p. 10), which is on a small hill underlain by Tertiary basin-fill sediment (unit Tn, Salt Lake Formation). In addition, I found that lake-bottom sediment (unit lpm) of the Provo phase of the Bonneville lake cycle is offset as much as 2 m (down-to-the-west) along this fault. The resulting scarp is subdued because of the type of material it is formed on, but can be traced along the west side of the hill for 2 km toward Payson. If this hill represents the northern extension of the Payson salient as exposed 5 km south at Little Mountain, then it is probably bounded on the east by another major fault.

There are a large number of suspected faults under Utah Lake and several other suspected faults on land in Utah Valley that merit discussion. Utah Lake is a shallow but permanent body of water, nowhere more than 4 m deep. Brimhall and others (1976) conducted a reconnaissance study of the lake bottom using an acoustical-sounding device. Although their acoustical profiles only penetrate at most the upper 15-20 m of sediment beneath the lake, many of the records clearly show fault-displaced reflectors that must be clayey beds (units lpm and lbm) of the Bonneville lake cycle. For example, Brimhall and others (1976, fig. 9; Brimhall and Merritt, 1981, fig. 8) show about 5 m of offset on lacustrine clay (probably unit lpm), which is buried by partially deformed younger lacustrine sediment (unit ly).

The faults shown within Utah Lake are from Brimhall and Merritt (1981; fig. 9). The location of individual faults on this map is suspect because of possible errors in navigation during their acoustical survey and to the wide spacing of their transects. For the part of Utah Lake included on this map, they had eight north-northwest-trending traverses 1.2-5 km apart and five northeast-trending traverses 2-5 km apart. Although the acoustical-profile traverses yield point locations for the faults, the repeated presence of faulted sediment in adjacent survey lines is compelling evidence of through-going faults in Utah Lake.

Brimhall and Merritt (1981) infer several continuous faults within the area of this map, and of these the Bird Island fault, Pelican Point graben, and East and West Jumbers Point faults are discussed in their paper. The maximum throw observed on these faults is 5 m, but values of <2 m are more typical. If the persistent marker on their records is, in fact, a lake-bottom clay (unit lpm) of the Provo phase of the Bonneville lake cycle, then most of the faults mapped under Utah Lake have moved more recently than 13 ka.

Two other areas of suspected faulting are shown on the map of eastern Utah Valley. The first area is in the NW 1/4 of section 32 (T. 4 S., R. 1 E.) where faults were exposed during excavation for a new aqueduct that extends from the Provo River to Salt Lake Valley parallel to the Provo Reservoir Canal. Tim Sullivan (USBR, oral and written commun., 1987) reports that silt and sand of the Bonneville lake cycle (probably units lpm and lps) are offset by two closely spaced south-striking faults. These faults are coincident with a small south-trending stream drainage that has cut into geomorphic surfaces of different elevation on its east and west sides. If the adjacent surfaces were once concordant and are of the same age, then these relations suggest about 2-3 m of down-to-the-east movement, which is consistent with the exposures of faulted sediment in the new aqueduct. To the south of Utah State Highway 80, there is no scarp on lake-bottom sediment of the Provo phase of the Bonneville lake cycle (unit lpm), which suggests that faulting may have occurred between about 14.5 ka (end of Bonneville phase) and 13 ka (end of Provo phase in Utah Valley).

The second suspected fault is just east of the intersection of Utah State Highways 74 and 80, about 2.6 km west of the American Fork Canyon trenching site. This fault forms a scarp that is 1.5-3-m high on the Provo-level fan-delta complex of the American Fork River. The scarp is almost parallel to the topographic contours of the fan-delta complex, thus it might possibly be a shoreline of Lake Bonneville. However, the stratigraphic relations argue for a tectonic rather than erosional origin. The scarp is on a Provo-level fan-delta surface; thus it must be related to the recessional phase of Lake Bonneville. Hydrologic-modelling studies by Jarrett and Malde (1987) show that the fall from the Bonneville to the Provo level, which was the cause of the catastrophic Bonneville Flood, may have been completed in as little as eight weeks. If this time frame is even close, the lake could not have stayed at any altitude between the Bonneville and Provo thresholds long enough to form a regressive shoreline. Thus, a tectonic origin for the scarp best explains the observed relations. Although the scarp crosses the high, broad fan-delta complex, there is no scarp on slightly lower, inset terraces which grade to recessional lake levels below the highest Provo shoreline. These terraces are slightly younger than the fan-delta complex (about 14.5-14.3 ka), which suggest that the faulting occurred between about 14-14.5 ka.

The evidence for timing of movement on some of the subsidiary faults in Utah Valley, from one gravel pit in northern Utah Valley (Machette, 1988c) and from evidence collected at other sites along the main fault zone (such as at Hobble Creek), suggest that some faulting in Utah Valley could have been associated with the rapid crustal rebound that occurred during and after the geologically rapid fall and subsequent desiccation of Lake Bonneville (Machette and others, 1987 and in press).

SUMMARY AND UNANSWERED QUESTIONS

This map and report are based on detailed mapping of Quaternary surficial deposits and some bedrock units in Utah Valley, coupled with measurements of fault scarps in deposits of various ages and exploratory trenching at selected sites along the Wasatch fault zone. The combination of research efforts by scientists at a variety of organizations has helped identify some of the paleoseismic characteristics of the Wasatch fault zone and subsidiary faults in Utah Valley.

The entire length of the Wasatch fault zone within Utah Valley has been demonstrated to be repeatedly active in the Holocene. Estimates of the timing of fault movement come from a series of exploratory trenches excavated during the past 10 years at American Fork Canyon, Rock Canyon, Deadmans Hollow/Hobble Creek, Mapleton, and Water Canyon. Collectively, these studies have shown that there have been three or four surface-faulting events in the past 8,000 years and they suggest that the most recent event was about 500-700 years ago. The average time between faulting events at any one site along this part of the Wasatch fault zone is on the order of 2,300-2,400 years.

The height of scarps along the Wasatch fault zone mostly reflect the age of the material that is faulted; older deposits commonly have larger scarps because they record a longer time of faulting. Differences in scarp slope and height also reflect whether movements on the fault zone have been along single or multiple faults. However, the net slip in deposits of a specific age (for example, the Provo phase of the Bonneville lake cycle) appears fairly uniform at many points along the mountain front in Utah Valley, suggesting that the entire length of the fault has been continually active in the late Quaternary. In addition, 4- to 7-m-high scarps on lower and middle Holocene alluvium along the fault zone attest to multiple surface-faulting events associated with large-magnitude (M > 7) earthquakes during the Holocene.

In 1986, I tentatively subdivided the Utah Valley part of the Wasatch fault zone (Provo segment of Schwartz and Coppersmith, 1984) into the American Fork, Provo, and Spanish Fork segments, primarily on the basis of fault geometry and apparent recency of movement as deciphered from scarp morphology studies. The results of trenching studies conducted since then suggest that this subdivision was not justified and, as such, the American Fork, Provo (restricted), and Spanish Fork are considered as subsegments of a master Provo segment. The surface trace of the Provo segment is nearly 70 km long. Its boundaries with the adjacent Salt Lake City and Nephi segments are at the Traverse Range (on the north) and Dry Mountain/Tithing Mountain (on the south). Each of these boundaries coincides with bedrock salients that appear to be long-term (persistent) structural barriers to the propagation of surface ruptures.

The probability of nonsynchronous (independent) fault rupturing on three subsegments of the Wasatch fault zone in Utah Valley seems questionable now as a result of recent dating at the Rock Canyon site by W.R. Lund (UGMS) and D.P. Schwartz (USGS). Although the subsegment boundaries show some characteristics common to segment boundaries, such as changes in fault trend and complexity and gaps in faulting, the two boundaries between the three subsegments of the Provo segment do not appear to have impeded the propagation of major surface ruptures during the two most recent faulting events in Utah Valley. The large error limits (commonly 200-300 years) in the timing of faulting events allow a remote possibility that the three fault subsegments in Utah Valley may rupture independently, particularly during earthquakes that are less than the maximum credible magnitude. However, if the Wasatch fault zone in Utah Valley is a single 70-km-long segment, then earthquakes that nucleated on the fault zone could have been (and may be) as large as M = 7.5, rather than about M = 7 as would have been expected for segments having lengths of 20-30 km.

Table 1. *Altitudes of prominent shorelines in Utah Valley*

[Altitudes after rebound of the Bonneville basin. The altitude of the Bonneville shoreline threshold was 1,552 m (5,192 ft) and the Provo shoreline threshold was 1,444 m (4,737 ft) (Currey and Oviatt, 1985). Shoreline features along deep margins of ancient Lake Bonneville show proportionately more rebound that those shorelines along shallow margins of the lake. See Crittenden (1963) and Currey (1982) for discussions of isostatic rebound of Lake Bonneville. Abbreviations: WFZ, Wasatch fault zone; Bnv., Bonneville; SL, shoreline(s); n.d., not determined; n.a., not applicable]

Area	Highest Provo (meter/feet)	Highest Bonneville (meter/feet)	Remarks
South of Salem	1,449/ [1]4,755	1,553/ [2]5,095	Both SL below WFZ.
Rocky Ridge at Payson	1,446/ [2]4,744	n.d. n.d.	On spur between WFZ segments.
Spanish Fork Canyon	n.a. n.a.	1,564/ [2]5,131	Bnv. SL above WFZ. Provo SL below WFZ.
Pleasant Grove (near Lindon)	1,444/ [2,3]4,737	1,561/ [1]5,120	Bnv. SL above WFZ. Provo SL below WFZ.
Provo Canyon	n.a. n.a.	1,562/ [1]5,125	On bedrock between WFZ segments.
American Fork Canyon	n.a. n.a.	1,587/ [1]5,205	Bnv. SL above WFZ. Provo SL below WFZ.
North of Alpine	n.a. n.a.	1,574/ [2]5,164	Both SL below WFZ.
Point of the Mountain	1,464/ [2]4,803	1,573/ [2]5,161	On Traverse Mountains.
West Mountain	1,454/ [2]4,770	1,562/ [2]5,125	South of Utah Lake.

[1]Data from interpretation of geologic and topographic mapping, 1:24,000 scale. Accuracy is probably from ±3 to ±6 m (±10 to ±20 ft).

[2]Data from Currey, 1982. Accuracy is probably from ±1 to ±2 m (±3 to ±6 ft).

[3]I map the highest Provo shoreline (which is subdued) at about 1,448 m (4,760 ft) altitude, 1.6 km east of Lindon.

DESCRIPTION OF MAP UNITS

[These descriptions are arranged by genesis (mode of formation) and by increasing age (units designated by numerals 1-5). In some areas, temporary exposures or natural exposures too small to show on the map reveal the nature of the underlying unit. In these areas, the underlying unit is shown as a denominator (for example, alp/lpd). Genetic divisions include lacustrine, alluvial, glacial, eolian, colluvial, and artificial (man made). For this series of maps, many of the age categories are based on climatic cycles; that is, mainly on the basis of correlation of alluvial and glacial units with lacustrine materials deposited during major pluvial lake cycles in the Bonneville basin (see discussion of Quaternary geology). Soils are a major criteria for establishing the age of the surficial materials in Utah Valley. The following soil-horizon designations (profiles) are from Shroba (1982, 1984) and this study and are considered typical for the age of materials on which they are formed. Soil-horizon designations follow the usage described by Birkeland (1984)]

Age of unit	Soil profiles
Late Holocene (1).	A/Cox or A/Bw/Cox.
Mid to early Holocene (2).	A/Bw/Cox or A/Bt(weak)/Cox.
Late Pleistocene (3) (Provo phase).	A/Bw/Bk(or Cox) to A/Bt(weak)/Bk(or Cox). Clay in Bt is derived mainly from loess.
Late Pleistocene (3) (Bonneville phase).	A/Bt/Bk(or Cox). Clay in Bt is derived mainly from loess.
Late middle Pleistocene(4).	A/Bt(moderate)/Bk(stage II-III)/Cox. Clay in Bt is derived mainly from loess; calcium carbonate in Bk is derived from airborne sources.
Middle Pleistocene (5).	A/Bt(strong)/Bk(stage II-III)/K(stageII)/Cox. Clay in Bt is derived mainly from loess; calcium carbonate in Bk and K is derived from airborne sources.

LACUSTRINE DEPOSITS

[These deposits consist of gravel, sand, silt, and clay deposited in response to major rises and falls (cycles) in the level of the last deep lake (the Bonneville lake cycle) in the Bonneville basin and its Holocene successor--Great Salt Lake. Lacustrine deposits in the map area are divided by age into four groups: (1) deposits that postdate the Bonneville lake cycle (<10 ka); (2) deposits associated with the Provo shoreline and regressive phase of the lake cycle (14.5-10 ka); (3) deposits associated with the Bonneville shoreline and the transgressive phase of the lake cycle (32-14.5 ka); and (4) undivided Bonneville-lake-cycle sediment deposited below the Provo shoreline that cannot be assigned to either phase of the Bonneville lake cycle (32-10 ka). The altitudes of Provo and Bonneville shorelines in the Utah Valley are shown in table 1. Contrary to the interpretations of Hunt and others (1953), I have not found sediment of the two pre-Bonneville lake cycles--the Cutler Dam (Oviatt and others, 1987) and the Little Valley (Scott and others, 1983)--exposed in the eastern part of Utah Valley. Lacustrine sediment near the mountain front is mostly gravel and sand; silt and clay were deposited in quieter, deeper water on the valley (lake) bottom, in sheltered bays between headlands, and less commonly in lagoons behind bayhead barriers. Most sediment is well sorted and has clast-supported framework]

DEPOSITS YOUNGER THAN THE BONNEVILLE LAKE CYCLE (HOLOCENE TO UPPER PLEISTOCENE)

ly **Young lacustrine and marsh deposits**--Silt, clay, and minor sand deposited in Utah Lake, marshes, slow-moving streams and oxbow lakes, and in sag ponds resulting from faulting, block tilting, or lateral-spread failures. Includes mud flats, playas exposed by fluctuations of Utah Lake, and less commonly, eolian deposits associated with mud flats. Organic rich; locally may contain peat deposits as thick as 1 m. Associated with areas of high water table. Overlies and grades into fine sediment of the Bonneville lake cycle (unit lbpm). Thickness variable, typically 1-3 m

laly **Lacustrine, marsh, and alluvial deposits, undivided**--Undivided sand, silt, and clay in areas of mixed fluvial, lacustrine, and paludal environments. Mapped along margin of Utah Lake. Thickness unknown

DEPOSITS OF THE PROVO (REGRESSIVE) PHASE OF THE BONNEVILLE LAKE CYCLE (UPPER PLEISTOCENE)

lpd **Deltaic deposits**--Clast-supported pebble and cobble gravel in a matrix of sand and silt; interbedded with thin pebbly sand beds; moderately to well sorted within beds; clasts subround to round; weakly cemented by calcium carbonate. Deposited as foreset beds having original dips of 30°-35° and as bottomset beds having original dips of 1°-5°. Commonly capped with <5 m of topset alluvium (unit alp), which is a less well sorted, silty to sandy, pebble and cobble gravel. Mapped at the front of large deltas deposited by Dry Creek, American Fork, Provo River, Rock Creek, Hobble Creek, Spanish Fork, and Peteetneet Creek. Exposed thickness 10-25 m

lpg **Lacustrine gravel**--Clast-supported, openwork pebble and cobble gravel; where poorly sorted it has a matrix of sand and minor silt. Commonly interbedded with or laterally gradational to sand facies; well sorted within beds; clasts usually subround to round, but some shoreline deposits marked by a poorly sorted, calcium-carbonate cemented conglomerate consisting of angular boulders derived from nearby exposures of bedrock. Thin to thick bedded; bedding ranges from horizontal to original dips of 10°-15° on steep piedmont slopes or in constructional landforms such as beach ridges, spits, and deltas (which are mapped separately as unit lpd). Mapped from Provo shoreline to about 10 m above Utah Lake (1,368 m, 4,489 ft). Typically forms wave-built bench at the highest Provo shoreline and several less well developed shorelines lower in the map area. Gravel is commonly well cemented with calcium carbonate, especially in shorelines and beach ridges. Exposed thickness <10 m

lps **Lacustrine sand**--Predominantly sand with minor pebbly gravel and silt; generally thick bedded or massive; commonly has ripple marks and scour features. Deposited in relatively shallow water near shore during regression of Lake Bonneville; generally overlies fine-grained, deep-water (transgressive) silt and clay (unit lbm). Mapped at and below the Provo shoreline. Shorelines generally not developed in this facies, but sand forms beaches, spits, or deltas (which are mapped separately as unit lpd) where longshore current and supply of material were adequate. Exposed thickness <10 m lpm **Lacustrine silt and clay**--Predominantly calcareous silt (which is often referred to as marl) with minor clay and fine sand; apparent bedding is thick or massive but commonly rhythmic on close inspection. Blocks of silt and clay lack conchoidal fractures, which are characteristic of unit lbm. Deposited in quiet-water environments, either in moderately deep-water basins, sheltered bays between headlands, or in lagoons behind barrier bars (such as at Lindon). Commonly overlie fine-grained silt and clay (unit lbm), implying deposition in decreasing water depth of a regressive lake; however, a lack of sharp disconformity between units lpm and lbm suggests no aerial exposure between the two lake phases. Shorelines not developed on this unit. Exposed thickness <5 m

DEPOSITS OF THE BONNEVILLE (TRANSGRESSIVE) PHASE OF THE BONNEVILLE LAKE CYCLE (UPPER PLEISTOCENE)

lbd **Deltaic deposits**--Clast-supported pebble and cobble gravel in a matrix of sand and silt; interbedded with thin pebbly sand; moderately to well sorted within beds; clasts subround to round; weak calcium-carbonate cementation common along bedding. Some foreset beds have rhythmic, graded bedding suggesting annual varves (Machette, 1988b). Foreset beds dip 30°-35° and bottomset beds dip 1°-5°. Mapped as eroded remnants of fan-delta complexes that were once extensive at the mouths of American Fork, Provo, Rock, and Spanish Fork Canyons. Most deltaic deposits in the map area have been reworked by streams during and after Lake Bonneville's fall to the Provo level. The section exposed in the delta north of American Fork Canyon (Machette, 1988b) may record evidence for the Keg Mountain oscillation of Currey and Oviatt (1985)--a short-lived fall from, and subsequent reoccupation of, the Bonneville shoreline that occurred between about 16ka and 14.5 ka. Exposed thickness 10 m

lbg **Lacustrine gravel**--Clast-supported pebble and cobble gravel in a matrix of sand and silt; interbedded with pebbly sand; well sorted within beds; thin to thick bedded; bedding ranges from horizontal to original dips of as much as 10°-15°; commonly well cemented with calcium carbonate, especially along shorelines. Clasts usually subround to round, but some shorelines marked by a poorly sorted conglomerate consisting of angular boulders derived from nearby exposures of bedrock. Forms constructional landforms such as beaches, bars, spits, and small deltas (which are mapped separately as unit lbd). Mapped above the Provo shoreline; commonly covered by thin (<2 m) mantle of hillslope colluvium (unit chs). Typically forms wave-built bench at the highest (Bonneville) shoreline and several less prominent shorelines between the highest Bonneville and Provo shorelines in the map area. Exposed thickness <5-10 m

lbs **Lacustrine sand**--Mostly sand with minor pebbly gravel and silt; usually thick bedded or massive; commonly has ripple marks and scour features; deposited in relatively shallow water, near shore. Commonly overlies coarse-grained beach gravel (unit lbg), implying deposition in increasingly deeper water of a transgressive lake. Mapped above the Provo shoreline. Shorelines generally not developed, but sand facies may form beaches, spits, or deltas where longshore current and supply of material were adequate. Exposed thickness <5 m

lbm **Lacustrine silt and clay**--Mostly calcareous silt (which is referred to as marl) with minor clay and fine sand; usually thick bedded or massive; deposited in quiet water, either in sheltered bays between headlands, in lagoons behind barrier bars (such as The Goosenest and similar features), or offshore in deeper water. Blocks of silt and clay are dense (compact) and have conchoidal fractures. Commonly overlies sandy to gravelly deposits, implying deposition in increasingly deeper or quieter water of a transgressive lake. Shorelines not developed on this unit. Exposed thickness <5 m

DEPOSITS OF THE BONNEVILLE LAKE CYCLE, UNDIVIDED BY PHASE (UPPERMOST PLEISTOCENE)

[Deposits mapped below the Provo shoreline and which cannot be correlated with a specific phase of the Bonneville lake cycle]

lbpg **Lacustrine gravel**--Clast-supported pebble gravel in a matrix of sand and silt; deposited during the Bonneville lake cycle. Commonly mapped from aerial photographs as subdued gravel-cored shorelines, beach ridges, or spits that have a thin (<1 m) cover of fine-grained lake sediment (units lbpm, lbm, or lpm). Exposed thickness <5 m

lbps **Lacustrine sand**--Sand and minor silt of the Bonneville lake cycle. Consists of thin, discontinuous areas of sand related to subdued shorelines. Thickness commonly 1-5 m

lbpm **Lacustrine silt and clay**--Clay, silt, and minor fine sand of the Bonneville lake cycle; deposited in moderately deep to deep water, or quiet shallow water (lagoons). Commonly buried by Holocene alluvial-fan sediment (units af1 and af2) or by silt and clay (unit ly) of Utah Lake; may contain small deposits of these units. Thickness unknown

ALLUVIAL DEPOSITS

[These deposits consist of variable amounts of gravel, sand, and silt, and minor amounts of clay deposited by perennial and intermittent streams. Map units are separated into five ages of stream (flood-plain and terrace) alluvium and alluvial-fan deposits. The relative ages and correlation of stream and fan deposits are based on the following criteria: (1) relation to lacustrine deposits and shoreline features of known age, (2) position relative to modern stream level, (3) degree of soil development, and (4) morphologic expression, such as degree of preservation of initial surface morphology or degree of dissection]

DEPOSITS OF STREAM ALLUVIUM

[Stream deposits are mapped on flood plains and as thin strath terrace deposits along perennial streams; gravel in these deposits generally is more rounded and better sorted than in equivalent-age alluvial-fan deposits. The sediment is commonly well sorted and has a clast-supported framework (that is, the framework consists of pebbles and cobbles in direct contact and the matrix material fills voids between clasts). Stream deposits are differentiated by their positions relative to lake levels during the Bonneville lake cycle and to modern stream levels]

al1 **Stream alluvium, unit 1 (upper Holocene)**--Pebble and cobble gravel in a matrix of sand, silt, and minor clay; contains thin discontinuous sand lenses; moderately sorted; clasts subangular to rounded; thin to medium bedded. Surfaces characterized by bar-and-swale topography, as well as modern drainage channels. Deposited by perennial streams such as Dry Creek, American Fork River, Provo River, Hobble Creek, and Spanish Fork River. Forms modern flood plains and terraces less than 2 m above stream level that grade downslope into upper Holocene alluvial-fan deposits (units af1 and afy). May include minor amounts of locally derived colluvium along steep stream embankments. Exposed thickness <5 m

al2 **Stream alluvium, unit 2 (middle Holocene to uppermost Pleistocene)**--Pebble and cobble gravel in a matrix of sand, silt, and minor clay; contains thin sand lenses; moderately sorted; clasts subangular to rounded; thin to medium bedded. Surface characterized by subdued bar-and-swale topography. Deposited mainly by perennial streams (see unit al1). Forms terraces 2-5 m above modern stream level that grade downstream into alluvial-fan deposits (units af2 and afy). Terraces generally cut across lacustrine sediment of Bonneville lake cycle. Exposed thickness <5 m aly **Younger stream alluvium, undivided (Holocene to uppermost Pleistocene)**--Undivided stream alluvium (units al1 and al2); consists of sandy pebble to cobble gravel that postdates regression of Lake Bonneville from the Provo level. Forms terraces and flood plains along most ephemeral streams. Thickness variable, generally <5 m

alp **Stream alluvium related to the Provo phase of the Bonneville lake cycle (uppermost Pleistocene)**--Pebble and cobble gravel in a matrix of sand, silt, and minor clay; contains thin sand lenses; poorly to moderately sorted; clasts subangular to rounded; thin to medium bedded. Large remnants are fluvial topset beds that grade into Provo-level deltas (unit lpd) preserved along Dry Creek, American Fork and Provo Rivers, Hobble Creek, Spanish Fork River, and Peteetneet Creek. Includes several levels of terraces that grade to recessional Provo shorelines on deltas. Thickness typically 2-5 m; thicker in cut-and-fill channels

alb **Stream alluvium related to the Bonneville phase of the Bonneville lake cycle (upper Pleistocene)**--Pebble and cobble gravel in a matrix of sand, silt, and minor clay; contains thin sand lenses; poorly to moderately sorted; clasts subangular to rounded; thin to medium bedded. Large remnants are fluvial topset beds of Bonneville-level deltas (unit lbd) preserved at mouths of American Fork River, Rock Canyon, and Spanish Fork River. Thickness typically 2-5 m

al3 **Stream alluvium unit 3, related to undifferentiated phases of the Bonneville lake cycle (upper Pleistocene)**--Sand and gravel deposited by streams graded to undifferentiated levels and phases of the Bonneville lake cycle. Commonly mapped as isolated remnants of high terraces along perennial streams. Thickness unknown

alo **Older stream alluvium, undivided (middle Pleistocene; probably pre-Little Valley lake cycle)**--Undivided stream alluvium (mostly equivalent to unit af5 in age) that consists of well oxidized, slightly indurated sand and well-rounded gravel; probably predates the Little Valley lake cycle of Scott and others (1983). Mapped along the saddle between Peteetneet Creek (Payson Canyon) and piedmont of Loafer Mountain, where it is unconformable on Neogene sedimentary rocks (unit Tn). Intertongues with or is overlain by unit af5. Alignment of three isolated and rounded gravel knolls suggest that an ancient stream of Payson Canyon drained to the east of Tithing Mountain sometime in the middle Pleistocene. Headward cutting of Peteetneet Creek (through Tithing Mountain) later in middle(?) Pleistocene time apparently captured the drainage from Payson Canyon, and uplift of the Payson salient caused the stream's entrenchment in bedrock (units TpK, Tpv, and Pzl). Thickness unknown, probably less than 10 m

ALLUVIAL-FAN DEPOSITS

[Alluvial-fan deposits are restricted mainly to the piedmont (alluvial apron at the mountain front) at the mouths of ephemeral streams. The sediment commonly is poorly sorted and matrix-supported (that is, consists of pebbles and cobbles which float in a fine-grained matrix of sand, silt, and clay). Fan deposits are thick along the base of the mountain front, and typically thickest on the downthrown side of Wasatch fault zone]

af1 **Fan alluvium, unit 1 (upper Holocene)**--Pebble and cobble gravel, bouldery near bedrock source areas, in a matrix of sand, silt, and minor clay. Clasts angular to subrounded, with sparse well-rounded clasts derived from gravel (unit lbg) of the Bonneville lake cycle; medium to thick bedded or massive. Deposited by intermittent streams, debris flows, and debris floods graded to modern stream level. Forms small, discrete terraces and fans on older alluvial fans (unit af2) and large fans that bury lacustrine deposits. Locally includes deposits of units cd1 and af2 too small to map separately. No shorelines of Lake Bonneville are present on surfaces formed by this unit. Exposed thickness <5 m af2 **Fan alluvium, unit 2 (middle Holocene to uppermost Pleistocene)**--Pebble and cobble gravel, locally bouldery, in a matrix of sand, silt, and minor clay; poorly sorted clasts angular to subrounded; sparse well-rounded clasts derived from gravel of Bonneville lake cycle; medium to thick bedded or massive. Deposited by perennial and intermittent streams, debris flows, and debris floods graded to or slightly above modern stream level. Forms large fans that are incised in the fine-grained lacustrine sediment (units lpm, lps, lbm, and lbs) or that bury lacustrine shoreline sediment (units lpg and lbg). Also preserved downslope from distal portions of younger alluvial fans (unit af1). Locally includes deposits of units cd1, cd2, and af1, which are too small to map separately. No shorelines of Lake Bonneville are present on surfaces formed by this unit. Exposed thickness <10 m

afy **Younger fan alluvium, undivided (Holocene to uppermost Pleistocene)**--Undivided fan alluvium that postdates the regression of Lake Bonneville from the Provo level of Utah Valley. Mapped in areas where units af1 and af2 are complexly overlapping or too small to show separately or in areas where the specific age of Holocene deposits has not been determined. Thickness unknown

afp **Fan alluvium related to the Provo phase of the Bonneville lake cycle (uppermost Pleistocene)**--Pebble and cobble gravel, locally bouldery, in a matrix of sand, silt, and minor clay; poorly to moderately sorted; clasts angular to well rounded (where derived from lacustrine gravel); medium to thick bedded or massive. Deposited by streams associated with the Provo (regressive) phase of the Bonneville lake cycle. Reworked in part from deltaic or fan-delta deposits. Forms fans graded to the main Provo shoreline or to other regressive shorelines above Utah Lake. Regressive shorelines locally preserved on the surfaces of fans graded to levels below the main Provo shoreline. Preserved mostly as eroded remnants; Holocene stream and fan alluvium overlaps or fills channels cut in deposits of unit afp. Exposed thickness <10 m

afb **Fan alluvium related to Bonneville phase of the Bonneville lake cycle (upper Pleistocene)**--Pebble and cobble gravel, locally bouldery, in a matrix of sand, silt, and minor clay; poorly sorted; clasts angular to subangular; medium to thick bedded or massive. Deposited as alluvial fans by streams graded to a transgressing Lake Bonneville and its highest shoreline. Locally has minor shorelines cut across fan surfaces, but commonly is covered by younger alluvium (units alp and aly) and Holocene colluvium. Exposed thickness <5 m

af3 **Fan alluvium unit 3, related to undivided phases of the Bonneville lake cycle (upper Pleistocene)**--Undifferentiated alluvial-fan deposits (units afp and afb) deposited during the transgressive or regressive phases of the Bonneville lake cycle. Commonly mapped at mouths of tributary and ephemeral streams where physical correlation with deposits of the Bonneville lake cycle cannot be established. Thickness unknown

af4 **Fan alluvium, unit 4 (upper to middle Pleistocene; pre-Bonneville lake cycle)**--Matrix-supported (in the upper part) and clast-supported pebble and cobble gravel, locally bouldery, in a matrix of sand, silt, and clay; poorly sorted; clasts angular to subrounded; lacks rounded lacustrine gravel. Forms small fans and fan remnants that are commonly preserved above and cut by the Bonneville shoreline; the largest remnants are on the piedmont southeast of Payson and on the foothills between the American Fork and Provo Rivers. Correlative deposits are buried by Bonneville lake cycle sediment downslope from the Bonneville shoreline over most of the map area. Best exposed in basement excavations and road cuts for subdivisions on the piedmont both east and west of Loafer Canyon (south of Salem at south end of Utah Valley). Fan alluvium probably grades laterally to lacustrine sediment of the Little Valley lake cycle (below 4,900 ft; Scott and others, 1983), although this relation has not been observed in the map area. Exposed thickness <5 m af5 **Fan alluvium, unit 5 (upper to middle Pleistocene; pre-Little Valley lake cycle)**--Matrix-supported (in the upper part) and clast-supported pebble, cobble, and boulder gravel in a matrix of sand, silt, and clay; poorly sorted; clasts angular to subrounded; lacks rounded lacustrine gravel; medium to thick bedded or massive. Preserved mainly as remnants of high surfaces that lack fan morphology and are deeply dissected; best exposed on the piedmont both east and west of Loafer Canyon (south of Salem) and along the Wasatch fault zone between the Provo and American Fork Rivers. Correlative deposits are buried by lacustrine sediment downslope from the Bonneville shoreline over most of the map area. The fan alluvium probably grades laterally to lacustrine sediment of the Pokes Point (pre-Little Valley) and older lake cycles of the Bonneville basin (see Scott and others, 1983; Machette and Scott, 1988), although this relation was not observed in the map area. Exposed thickness <20 m

afo **Older fan alluvium, undivided (upper to middle Pleistocene; pre-Bonneville lake cycle)**--Undifferentiated fan alluvium (units af4 and af5) that predates the Bonneville lake cycle. Mapped where high-level alluvial-fan deposits are poorly exposed or lack distinct geomorphic expression. Thickness unknown

GLACIAL DEPOSITS

[Although most of these deposits are preserved in high, east- and north-facing valleys on the eastern side of the Wasatch Range, the following descriptions are from exposures along Dry Creek, northeast of Alpine (in the northeast part of the map area). Till forms lateral and terminal moraines; glacial outwash forms terraces graded to the moraines. Glacial deposits are coarse-grained, primarily cobble- to boulder-size clasts of quartz monzonite (unit Tpi) derived from the Little Cottonwood stock (exposed north of Dry Creek) and limestone and sandstone derived from Paleozoic rocks (mainly south of Dry Creek). Evidence for the last two Pleistocene glaciations is preserved in the map area: the Bells Canyon advance, which is considered equivalent to the Pinedale glaciation of the Rocky Mountains, and the Dry Creek advance, which is considered equivalent to the Bull Lake glaciation of the Rocky Mountains (Scott, 1988, p. 81). In high mountain valleys, the mapped distribution includes the area of glaciation as shown by Mulvey (1985). The distribution of glacial units are from Mulvey (1985) and from my interpretation of aerial photographs]

DEPOSITS OF THE BELLS CANYON ADVANCE (UPPER PLEISTOCENE, PINEDALE EQUIVALENT)

gbco **Outwash**--Sandy cobble to boulder gravel (at mouth of Dry Creek) to sandy pebble gravel (at town of Alpine); well sorted; clasts are subangular to subround. Clasts show little evidence of weathering. Soils consists of A/Bw or Bt(weak)/Cox profiles. Mapped only along Dry Creek where it can be traced to moraines of unit gbct. Along other glaciated streams in the map area, outwash is included with units alp or alb. Thickness 1-20 m, 5 m common

gbct **Till**--Sandy cobble to boulder gravel in a matrix of silt and minor clay. Gravel is matrix supported; clasts are angular to subround; crudely bedded or massive. Till forms tent-shaped lateral moraines along Dry Creek, whereas the terminal moraine, which was deposited at the Wasatch fault zone, is mostly eroded. Clasts show little evidence of weathering. Soils consist of A/Bw or Bt(weak)/Cox profiles. Locally includes some till of Dry Creek advance, which was overridden by glaciers of the Bells Canyon advance. Thickness variable, locally as much as 25 m

DEPOSITS OF THE DRY CREEK ADVANCE (UPPERMOST MIDDLE PLEISTOCENE, BULL LAKE EQUIVALENT)

gdco **Outwash**--Sandy cobble to boulder gravel; poorly bedded; moderately well sorted; subangular to subround, becomes markedly finer downstream (sandy pebble gravel). Clasts in outwash show evidence of intense weathering; quartz monzonite clasts are decomposed to gruss, limestone clasts are deeply pitted, and sandstone clasts are weathered and oxidized (see Hunt and others, 1953, p. 27; Eardley and others, 1957; Scott and others, 1983). Soil profile is A/Bt(moderate)/Cox. Mapped only along Dry Creek where it can be traced to moraines of unit gdct. This age outwash is not recognized along other glaciated streams in map area. Thickness unknown

gdct **Till**--Sandy cobble to boulder gravel in a matrix of silt and minor clay. Gravel is matrix supported; clasts are angular to subround; crudely bedded or massive. Most of the lateral moraines have been overriden by glaciers of the younger Bells Canyon advance and buried by its till (unit gbct). However, the terminal moraine, which advanced about 0.6 km west of the Wasatch fault zone, is preserved as a hummocky boulder-strewn ridge between Dry Creek and Chipman Creek. Clasts in the till show evidence of strong weathering; quartz monzonite clasts are decomposed to gruss, limestone clasts are deeply pitted, and sandstone clasts are weathered and oxidized (see Hunt and others, 1953, p. 27; Eardley and others, 1957; Scott and others, 1983). Soils have A/Bt(moderate)/Cox profiles. Topographic profiles across the faulted moraine indicate about 30 m of displacement. Thickness variable, locally as much as 25 m

EOLIAN DEPOSITS

es **Eolian sand and silt (Holocene to uppermost Pleistocene)**--Sand, fine to medium grained, and minor silt and clay; calcareous; loose to moderately firm where cemented by secondary calcium carbonate. Sand is primarily upper Holocene and generally forms dunes that are from 1- to 3-m thick and locally derived from beaches and from river flood plains. Silt is calcareous and has minor amounts of fine sand and clay and is friable to moderately firm where cemented by calcium carbonate. Silt is primarily latest Pleistocene to early Holocene in age and is derived from fine-grained lacustrine sediment of Utah Valley and adjacent basins. Forms a mantle from 1- to 2-m thick on stable geomorphic surfaces. Most of the argillic B horizons of late Pleistocene age soils are derived from this silt

COLLUVIAL DEPOSITS

[These deposits consist of poorly sorted to unsorted, gravity-induced deposits; composition of clasts generally reflects the materials from which they were derived. Two ages of debris-flow deposits (units cd1 and cd2; mainly on figs. 3-5) are differentiated by their surface morphology and relations to present stream level and to alluvial deposits of similar age. Age of other colluvial deposits is uncertain]

cd1 **Debris flows, unit 1 (upper Holocene)**--Primarily matrix-supported cobble and boulder gravel in a mixture of silt, sand, and clay; unsorted and unstratified except for interbedded fluvial sand and gravel layers containing as much as 3 percent organic matter where material is not oxidized. Commonly covered with coarse, angular rubble and has fresh-appearing levees and channels. Flows commonly deposited on surface of Holocene alluvial fans (units af1 and af2) and at the mouths of canyons. For example, although not shown on the map, levees and channel of a young flow (unit cd1) are preserved on the debris-flow fan formed by unit cdy on the northeast side of Springville. Many of the youngest flows were deposited during the wet year of 1983. Thickness <10 m cd2 **Debris flows, unit 2 (middle Holocene to uppermost Pleistocene)**--Primarily matrix-supported cobble and boulder gravel in a mixture of silt, sand, and clay; usually unsorted and unstratified except for interbedded layers of fluvial sand and gravel, which are common. Oxidation generally has destroyed original organic matter (such as roots and tree limbs) that is common in flows, thus inhibiting dating by radiocarbon methods. Mapped along major drainages that head in steep mountain valleys, although other deposits too small to map are included in unit af2. Thickness <10 m

cdy **Debris flows, undivided (Holocene to uppermost Pleistocene)**--Primarily matrix-supported cobble and boulder gravel in a mixture of silt, sand, and clay; usually unsorted and unstratified. Most undifferentiated debris flows are unit cd2. Deposits of unit cdy too small to map separately are included in units af2 and afy. Thickness <10 m

cfs **Fault-scarp colluvium (Holocene to uppermost Pleistocene)**--Pebble, cobble, and boulder gravel in a mixture of sand, silt, and minor clay; unsorted to poorly sorted. Proximal facies commonly poorly stratified, clast-supported gravel; distal facies commonly better stratified, matrix-supported pebbly sand and silt. Clasts usually angular to subangular owing to short transport distance, but may contain rounded gravel from lacustrine units of the Bonneville lake cycle. Commonly forms a mantle from 1- to 2-m thick on the scarp above fault and a wedge >2 m thick on the down-dropped side of the fault. Although present along most fault scarps, it is only mapped along large (>10-m-high) scarps on 1:10,000-scale geologic maps (figs. 3-5)

chs **Hillslope colluvium (Holocene to upper Pleistocene)**--Pebble, cobble, and boulder gravel, commonly clast supported, in a matrix of sand, silt, and clay; usually unsorted, poorly stratified; clasts generally angular to subangular owing to short transport distances but may contain rounded gravel from lacustrine units of the Bonneville lake cycle. Includes debris-flow and landslide deposits too small to map separately. Deposited by slope-wash and mass-wasting processes on steep (15°-35°) slopes along the mountain front and in steep-sided stream canyons. Exposed thickness <5 m

crf **Rockfall deposits (Holocene to upper Pleistocene)**--Clast-supported cobble and boulder gravel; unsorted and unstratified; angular to subangular. Rockfall usually accumulates below steep bedrock cliffs that have been undercut by erosion at the Bonneville shoreline. Most extensive deposits are derived from the Oquirrh Formation (unit Pzm) west of Spanish Fork Canyon along the Bonneville shoreline. Forms talus cones at or near the angle of repose (33°-35°). Thickness 1-5 m on steep slopes, 5-20 m on benches

clsp **Lateral-spread deposits (Holocene to upper Pleistocene)**--Pebbly sand, sand, and silt of the Bonneville lake cycle redeposited by lateral spreading as a result of liquefaction, probably during major earthquakes. Horizontal bedding of original sediment is usually contorted or destroyed by movement. Two probable lateral-spread failures were mapped by Miller (1982) in Utah Valley along the front of the Provo-level deltas (unit lpd). The upper parts of the failures have headscarps, elongate grabens and ridges parallel to the headscarps, and undrained depressions between the ridges. The lower (distal) parts of the failures are characterized by hummocky topography (<1 m of relief). These features are similar to those described from large lateral spreads near Farmington, Utah, by Van Horn (1975), and in North Ogden, Utah, by Miller (1980). Other smaller deposits in Utah Valley have similar features and appear to be associated with liquefaction of Holocene flood-plain deposits (unit aly) or, possibly as at Salem, with failure of lacustrine bars that impounded lagoons. Thickness unknown but probably <15 m

clsy **Younger landslide deposits (Holocene to upper Pleistocene)**--Unsorted, unstratified deposits that typically are small slump-earthflows of gravelly sand to silt (derived from sediment of Bonneville lake cycle) but includes one massive slide block derived mainly from Manning Canyon Shale (upper unit of Pzl) but including large blocks of Oquirrh Formation (unit Pzm). The massive block slide is on the north bank of the Provo River and appears to be a reactivated part of an older slide block (unit clso). However, many older slide blocks also may have been active recently. The earthflows are restricted to steep slopes adjacent to the Bonneville shoreline and to steep canyons in the Wasatch Range. Thickness variable; earthflows typically are 1-5 m, slide blocks are <25 m clso **Older landslide deposits (upper Pleistocene to upper Tertiary?)**--Unsorted, unstratified massive slide blocks derived mainly from the Paleozoic Manning Canyon Shale (upper unit of Pzl) but including large blocks of Paleozoic Oquirrh Formation (unit Pzm). Where exposed, these masses are typically dark colored owing to a matrix of black to gray Manning Canyon Shale. Blocks of mostly coherent bedrock (sandstone and limestone) may give the landslide masses the appearance of being intact bedrock, but bedding attitudes within the mass are chaotic. Large landslides are common along the lower half of the western face of the Wasatch Mountains on relatively steep slopes; they are particularly abundant along and above the Wasatch fault zone from Hessetts Hollow (about 2 km south of American Fork Canyon; fig. 3) on the north to Slide Canyon (due east of Provo) on the south. Baker and Crittenden (1961) and Baker (1964b) mapped these areas as thrust sheets of Oquirrh Formation over Manning Canyon Shale (younger over older); however, Bryant (in press) and I interpret these structures as relatively low angle gravity-induced block landslides. In many places, the slide blocks have been displaced by Quaternary movement of the Wasatch fault zone, although fault scarps are difficult to trace through the landslides. Most of the landslide deposits that extend below 1,575-m (5,160-ft) altitude have Bonneville-level shorelines etched across them, thus indicating a >15 ka age. However, relations with older alluvial-fan deposits (units af4, af5, and afo) and the presence of strongly developed soils on stable surfaces of the slide blocks indicate many of the slides occurred much earlier in the Pleistocene (more than several hundred thousand years ago) or perhaps in the late Tertiary. Maximum thickness undetermined; exposures of slide blocks >25 m thick are common

ca **Colluvium and alluvium, undivided (Holocene to middle Pleistocene)**--Comprised of undifferentiated stream and fan alluvium, hillslope colluvium, and small landslide deposits. Mapped within the Wasatch Range, mainly using aerial photographs. Thickness variable

ARTIFICIAL DEPOSITS

f **Artificial fill and associated disturbed ground** (historic)--Consists primarily of locally derived surficial debris disturbed during construction of small reservoirs, flood-control structures, factories, and highways. Although present throughout the map area, only the largest of these areas are shown. Thickness unknown

BEDROCK

[Bedrock units are not shown in detail on this map. The entire section, which ranges from Tertiary to Precambrian in age, is divided into six units. The outcrop pattern of these units provides generalized information about source rocks for alluvial and colluvial units and a simplified sketch of major structural relations within the Wasatch Range. Descriptions and thickness of units are summarized from Davis (1983). For more information, consult detailed bedrock geologic maps in the area (see index of geologic mapping) or Davis' 1983 geologic compilation of the southern Wasatch Front]

Tn **Neogene sedimentary rocks**--Consists of sedimentary rocks of the Salt Lake Formation (Pliocene and Miocene) or its time equivalent. Includes calcareous tuffaceous siltstone and sandstone in the Loafer Mountain area, calcareous fanglomerate with locally interbedded soils and debris flows in the foothills south of Provo Canyon, and a mixture of fine- to coarse-grained sandstone and conglomerate in the eastern half of the Traverse Mountains. Thickness unknown, locally more than 100 m

Tpv **Paleogene volcanic rocks**--Within the map area, these rocks include early Tertiary volcanics at Little Mountain south of Payson and Oligocene andesite (Crittenden and others, 1973) in the central and western part of the Traverse Mountains. Thickness tens to hundreds of meters

Tpi **Paleogene intrusive rocks**--Quartz monzonite exposed in the southern part of the Little Cottonwood stock (31 Ma; Crittenden and others, 1973) north and east of Wasatch fault zone, at the north end of the map area

TpK **Paleogene and Upper Cretaceous sedimentary rocks, undivided**--Within the map area, this group of rocks includes Eocene Colton Formation (100-170 m thick; sandstone, siltstone, and shale), Paleocene Flagstaff Limestone (100-180 m thick), and Paleocene and Upper Cretaceous North Horn Formation (120-150 m thick; red conglomerate, shale, and siltstone). Exposed near the crest and backside of the Wasatch Range in the southern part of the map area and along the Wasatch fault zone at the mouth of Spanish Fork Canyon and Payson Canyon

Pzu **Paleozoic sedimentary rocks, upper part (Lower Permian)**--Consists of Phosphoria Formation (cherty limestone, dolomite, phosphatic and siliceous shale), Diamond Creek Sandstone, and Kirkman Limestone. About 600 m thick in exposures adjacent to Spanish Fork Canyon in southeast part of map area

Pzm **Paleozoic sedimentary rocks, middle part (Lower Permian and Pennsylvanian)**--Oquirrh Formation (Lower Permian to Lower Pennsylvanian). In map area, unit consists solely of basin facies (south of the Deer Creek fault) and consists of very thick sequence of monotonous interbedded sandstone, limestone, and cherty limestone, with sparse quartzite beds in upper part; forms an allochthonous (thrust-transported) block about 5 km thick at Provo Canyon

Pzl **Paleozoic sedimentary rocks, lower part (Lower Pennsylvanian, Mississippian, Devonian, and Cambrian)**--Sedimentary rocks that include (from top to bottom) Lower Pennsylvanian to Upper Mississippian Manning Canyon Shale (500 m thick; stippled unit), Upper Mississippian Great Blue Limestone 850 m thick) and Humbug Formation (sandstone, limestone, and dolomite; 160 m thick), Upper and Lower Mississippian Deseret Limestone (175 m thick), Lower Mississippian Gardison Limestone (275 m thick), Lower Mississippian and Upper Devonian Fitchville Formation (dolomite and limestone; 30-80 m thick); undivided Upper and Middle Cambrian rocks (250-700 m thick; and Lower Cambrian Tintic Quartzite (290-350 m thick). Thickness of combined unit depends on amount of section exposed along Wasatch fault zone

p€ **Proterozoic and Archean rocks (Precambrian)**--Includes Late Proterozoic Mutual Formation (sandstone, shale, and conglomerate) and Protoerozoic Mineral Fork Tillite (bouldery siltstone) mainly north of American Fork Canyon; Middle Proterozoic Big Cottonwood Formation (quartzite, phyllite, and slate) and Early Proterozoic and Archean Farmington Canyon Complex (high-grade metamorphic rocks) in Slate Canyon east of Provo and on Dry Mountain south of Payson. Thickness dependent on amount of section exposed along Wasatch fault zone

SYMBOLS

Contact--Solid where well located or defined; dashed where approximately located; dotted where concealed

Gradational contact--Contact between two units that intertongue or between two differentiated units (such as al1 and al2) and its undifferentiated counterpart (aly)

12(9)
AF

Normal fault--Bar and solid ball on down-dropped side along Wasatch fault zone; bar and hollow ball along other faults. Dashed where approximately located; dotted where concealed. Height of fault scarp and amount of offset of geomorphic surface (in parentheses) shown in meters. Location of exploratory trenches shown by following symbols: AF, American Fork Canyon; RC, Rock Creek; DH, Deadmans Hollow; HC, Hobble Creek; MN, Mapleton North; MS, Mapleton South; WC, Water Canyon; and WH, Woodland Hills

Thrust fault--Sawteeth on overriding plate or block (mapped in bedrock only); dashed where approximately located; dotted where concealed

Anticline--Solid arrows show folded lake beds as indicated by geophysical surveys of Utah Lake. Hollow arrows show anticline in surficial units

Syncline--Solid arrows show folded lake beds as indicated by geophysical surveys of Utah Lake. Hollow arrows show syncline in surficial units

22 **Dip and strike of deformed Neogene fanglomerate (unit Ns)**

Major, continuous or prominent shorelines related to levels of the Bonneville lake cycle and its successor, Utah Lake--May coincide with contact, topographic escarpment, or topographic crest of lacustrine bar or spit

— —B— — **Highest shoreline of the Bonneville (transgressive) phase**

— —b— — **Other shorelines of the Bonneville phase**--Mostly transgressive

— —P— — **Highest shoreline of the Provo (regressive) phase**--Dotted where buried by younger units or removed by erosion

— —p— — **Other shorelines below the highest Provo shoreline**--Mostly of the Provo phase, but may include some shorelines of the Bonneville (transgressive) phase

— —U— — **Shorelines of Utah Lake**

Topographic crest of lacustrine bar or spit

Topographic crest of lateral- or terminal-glacial moraine (units gbct and gdct)

? **Topographic escarpment**--Escarpment along stream channels, terraces, and deltas; formed primarily by fluvial processes. Where escarpment coincides with the contact between map units, hachures face upslope; queried where position of escarpment is poorly located. Height of escarpment (in meters) shown in selected areas

Landslide escarpment--Major headscarp and (or) fissure in landslide (unit clsy or clso) or lateral spread (unit clsp) deposit; may coincide with geologic contacts

Paleostream channel--Preserved margin of abandoned stream channel or debris-flow levee. Half-head of arrow on outer edge of feature

Broadly tilted geomorphic surface--Arrow points in general direction of downwarp

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