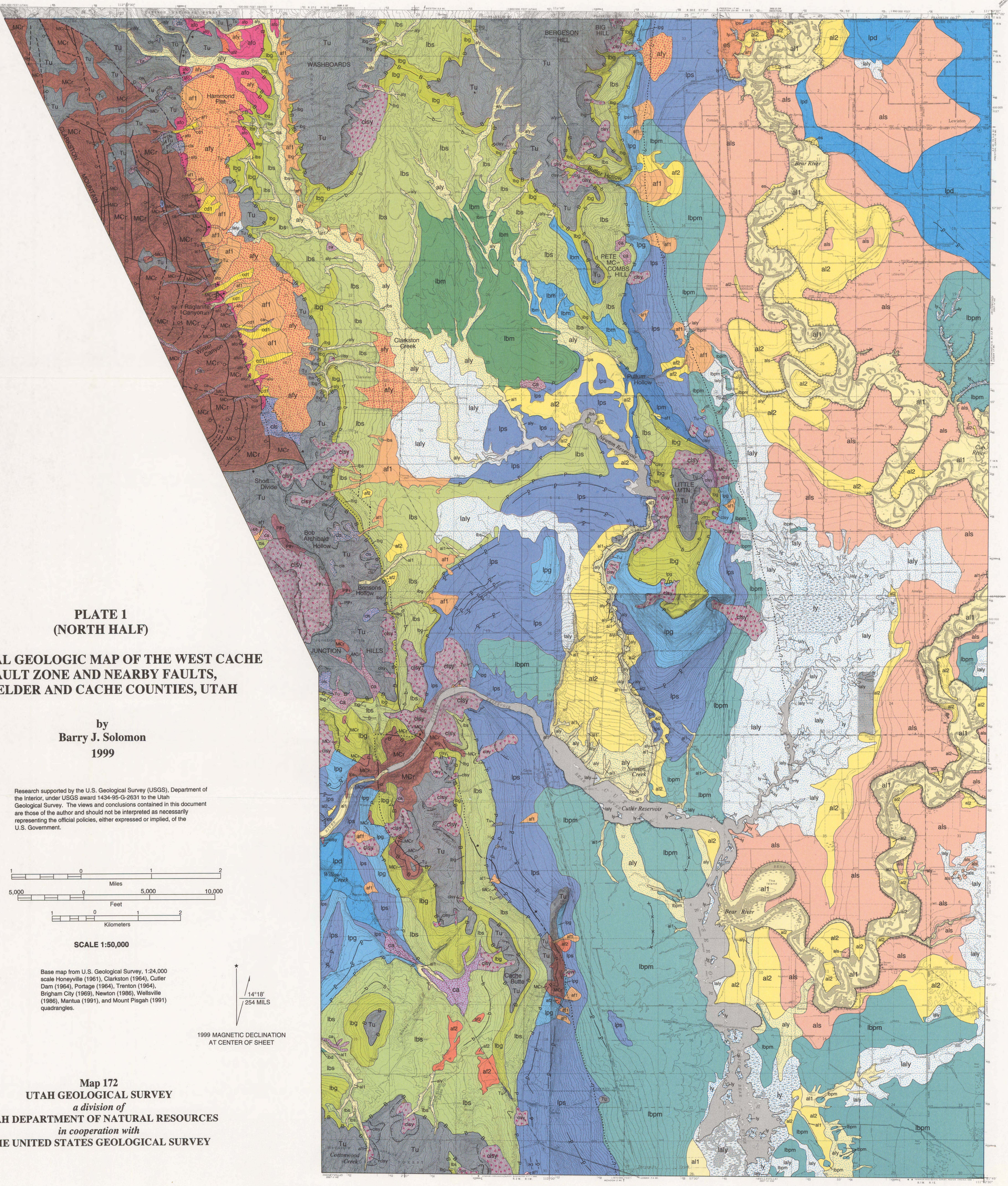

PLATE 1
(NORTH HALF)

SURFICIAL GEOLOGIC MAP OF THE WEST CACHE FAULT ZONE AND NEARBY FAULTS, BOX ELDER AND CACHE COUNTIES, UTAH

by
Barry J. Solomon
1999

Research supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award 1434-95-G-2631 to the Utah Geological Survey. The views and conclusions contained in this document are those of the author and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

1 0 1 2
Miles

5,000 0 5,000 10,000
Feet

1 0 1 2
Kilometers

SCALE 1:50,000

Base map from U.S. Geological Survey, 1:24,000 scale Honeyville (1961), Clarkston (1964), Cutler Dam (1964), Portage (1964), Trenton (1964), Brigham City (1969), Newton (1986), Wellsville (1986), Mantua (1991), and Mount Pisgah (1991) quadrangles.

14°18'
254 MILS

1999 MAGNETIC DECLINATION AT CENTER OF SHEET

Map 172
UTAH GEOLOGICAL SURVEY
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PLATE 1
(SOUTH HALF)

SURFICIAL GEOLOGIC MAP OF THE WEST CACHE FAULT ZONE AND NEARBY FAULTS, BOX ELDER AND CACHE COUNTIES, UTAH

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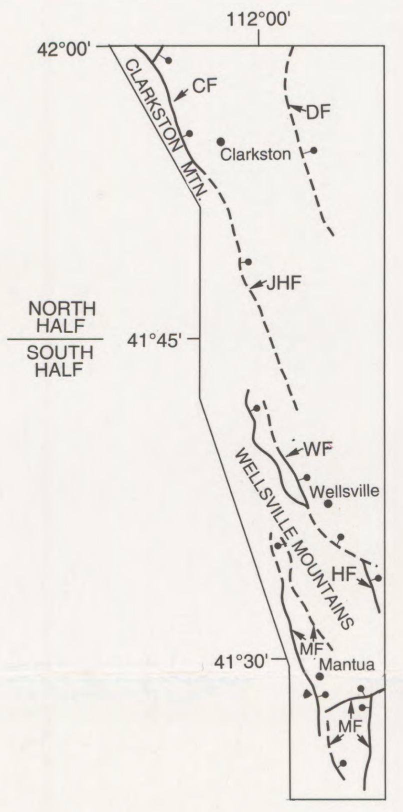
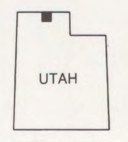


INDEX MAP

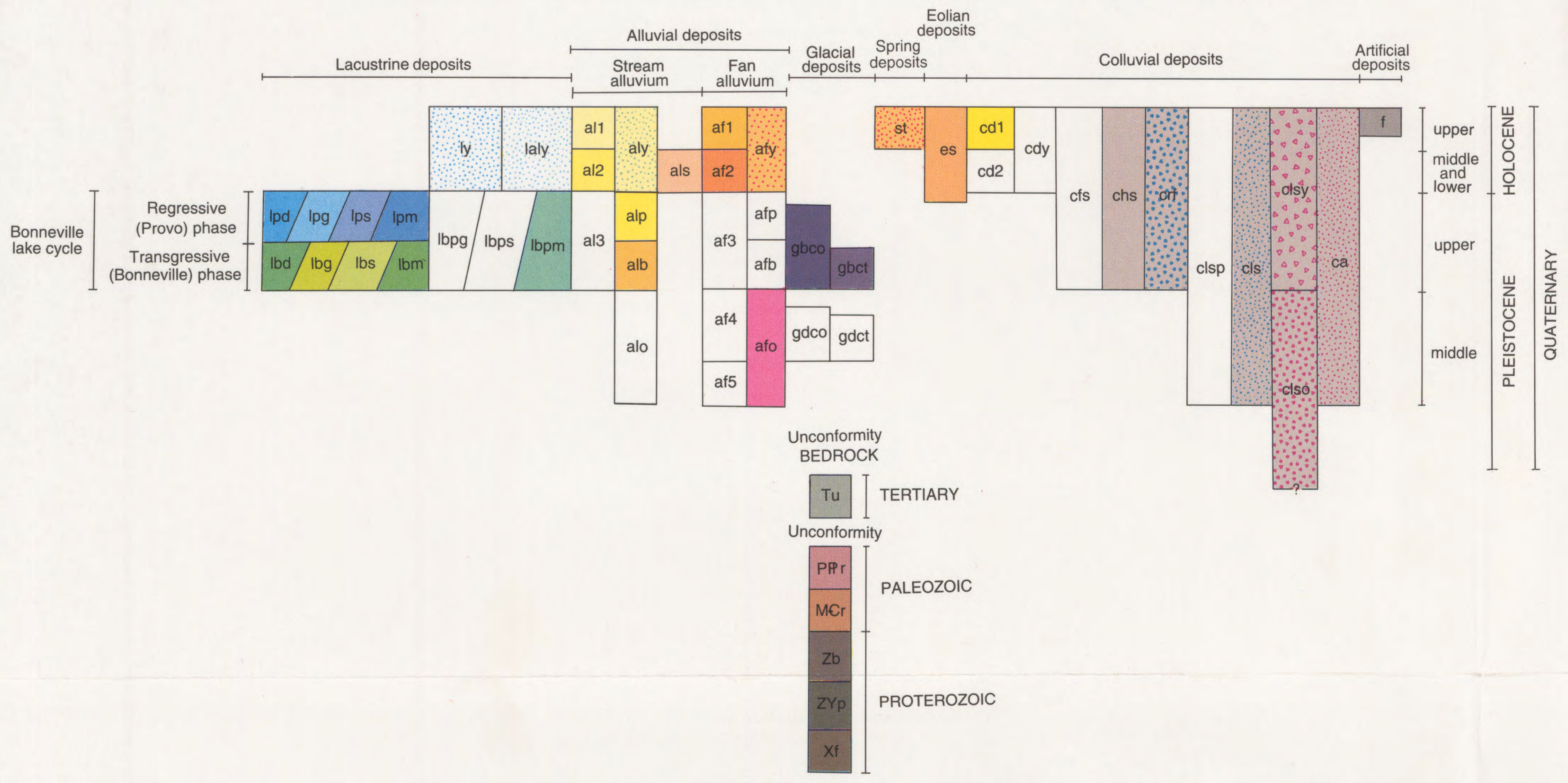
[The West Cache fault zone includes the Clarkston (CF), Junction Hills (JHF), and Wellsville (WF) faults. Nearby faults are the Dayton (DF), Hyrum (HF), and Mantua (MF) faults.]



MAP LOCATION

CORRELATION OF MAP UNITS

[This correlation shows surficial deposits mapped along the West Cache fault zone and nearby faults, as well as the Wasatch and East Cache fault zones, Utah. Map units without pattern/color in the correlation do not appear on this map, but are included to aid correlation with other maps in this series]



DESCRIPTION OF MAP UNITS

(appendix in text pamphlet has detailed descriptions)

LACUSTRINE DEPOSITS

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

- ly — Younger lacustrine and marsh deposits
- laly — Lacustrine, marsh, and alluvial deposits, undivided

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

- lpd — Deltaic deposits
- lpg — Lacustrine gravel and sand
- lps — Lacustrine sand and silt
- lpm — Lacustrine silt and clay

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

- lbd — Deltaic deposits
- lbg — Lacustrine gravel and sand
- lbs — Lacustrine sand and silt
- lbm — Lacustrine silt and clay

UNDIVIDED DEPOSITS OF THE BONNEVILLE LAKE CYCLE
(UPPER PLEISTOCENE)

- lbpm — Lacustrine silt and clay

ALLUVIAL DEPOSITS

DEPOSITS OF STREAM ALLUVIUM

- al1 — Stream alluvium, unit 1 (upper Holocene)
- al2 — Stream alluvium, unit 2 (middle Holocene to uppermost Pleistocene)
- aly — Younger stream alluvium, undivided (Holocene to uppermost Pleistocene)
- als — Alluvial sand and silt of natural levees (middle Holocene to uppermost Pleistocene)
- alp — Stream alluvium related to the Provo phase of the Bonneville lake cycle (uppermost Pleistocene)
- alb — Stream alluvium related to the Bonneville phase of the Bonneville lake cycle (upper Pleistocene)

ALLUVIAL-FAN DEPOSITS

- af1 — Fan alluvium, unit 1 (upper Holocene)
- af2 — Fan alluvium, unit 2 (middle Holocene to uppermost Pleistocene)
- afy — Younger fan alluvium, undivided (Holocene to uppermost Pleistocene)
- afo — Older fan alluvium, undivided (upper to middle Pleistocene; pre-Bonneville lake cycle)

GLACIAL DEPOSITS

DEPOSITS OF BELLS CANYON AGE
(UPPER PLEISTOCENE, PINEDALE EQUIVALENT)

- gbco — Outwash
- gbct — Till

SPRING DEPOSITS

- st — Spring travertine (upper Holocene)

EOLIAN DEPOSITS

- es — Eolian sand and silt (Holocene to uppermost Pleistocene)

COLLUVIAL DEPOSITS

- cd1 — Debris flows, unit 1 (upper Holocene)
- chs — Hillslope colluvium (Holocene to upper Pleistocene)
- crf — Rock-fall (talus) deposits (Holocene to upper Pleistocene)
- clsy — Younger landslide deposits (Holocene to upper Pleistocene)
- clso — Older landslide deposits (upper Pleistocene to upper Tertiary?)
- cls — Landslide deposits, undivided (Holocene to middle Pleistocene)
- ca — Colluvium and alluvium, undivided (Holocene to middle Pleistocene)

FILL DEPOSITS

- f — Artificial fill (historical)

BEDROCK

- Tu — Tertiary sedimentary rocks (Paleogene and Neogene)
- PIPr — Younger Paleozoic sedimentary rocks (Lower Permian to Pennsylvanian)
- MCr — Older Paleozoic sedimentary rocks (Mississippian to Cambrian)
- Zb — Lower part of Brigham Group (Upper Proterozoic)
- ZYp — Formation of Perry Canyon (Upper or Middle Proterozoic)
- Xf — Facer Formation (Lower Proterozoic)

MAP SYMBOLS

Contact

Normal fault - Bar and solid ball on downdropped side of faults with evidence of Quaternary movement; bar and hollow ball, or no bar and ball, along other faults. Dashed where approximately located, dotted where concealed, and queried where location is uncertain.

Strike-slip fault - Arrows show relative movement; dashed where approximately located.

Thrust fault - Sawteeth indicate overriding plate or block; dashed where approximately located.

Major shorelines related to levels of the Bonneville lake cycle - May coincide with geologic contacts.

—B——B— **Highest shoreline of the Bonneville level**

—b——b— **Other shorelines of the Bonneville level** - Mostly transgressive.

—P——P— **Highest shoreline of the Provo level**

—p——p— **Other shorelines of the Provo level** - Mostly regressive.

—x——x— **Undesignated shorelines of the Bonneville lake cycle**

Topographic escarpment - Escarpments along stream channels, terraces, and deltas; formed primarily by fluvial processes. Where escarpments coincide with geologic contacts, hachures extend upslope.

Landslide escarpment - Main and minor scarps formed by landsliding; may coincide with geologic contacts; hachures extend downslope; dashed where approximately located.

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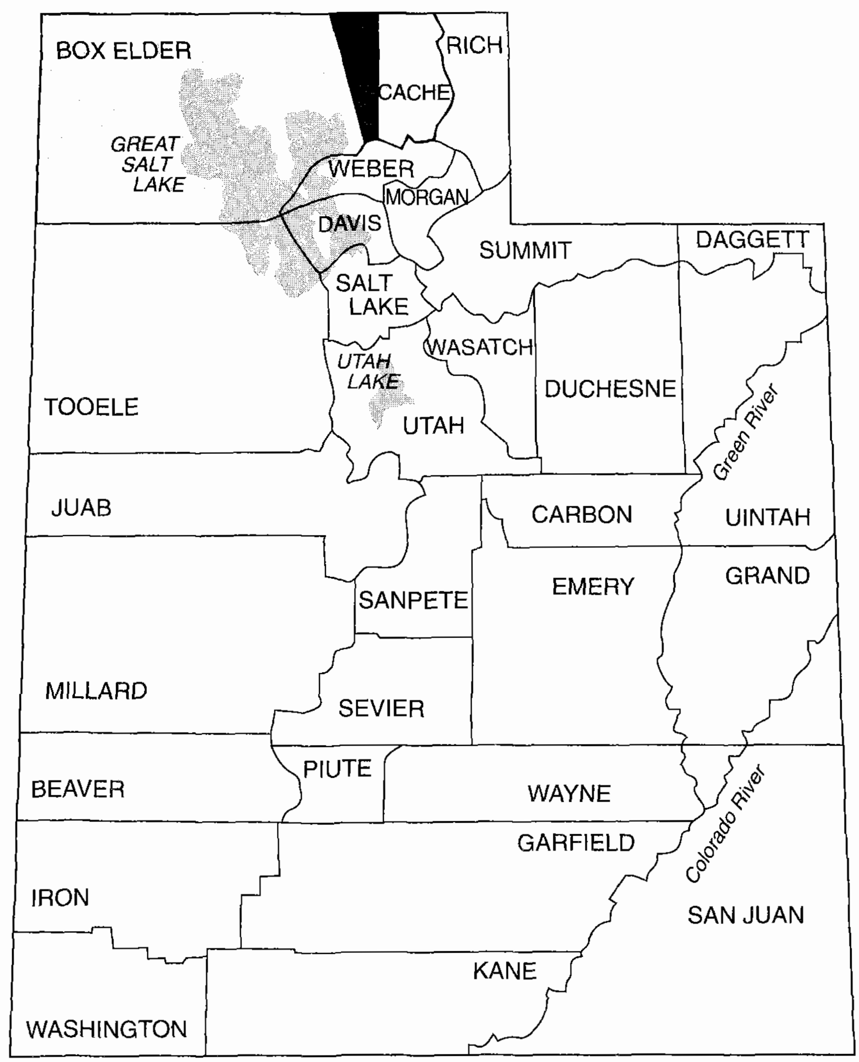

MAP 172 **1999**
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Solomon SURFICIAL GEOLOGIC MAP OF THE WEST CACHE FAULT ZONE AND NEARBY FAULTS, BOX ELDER AND CACHE COUNTIES, UTAH UGS Map 172

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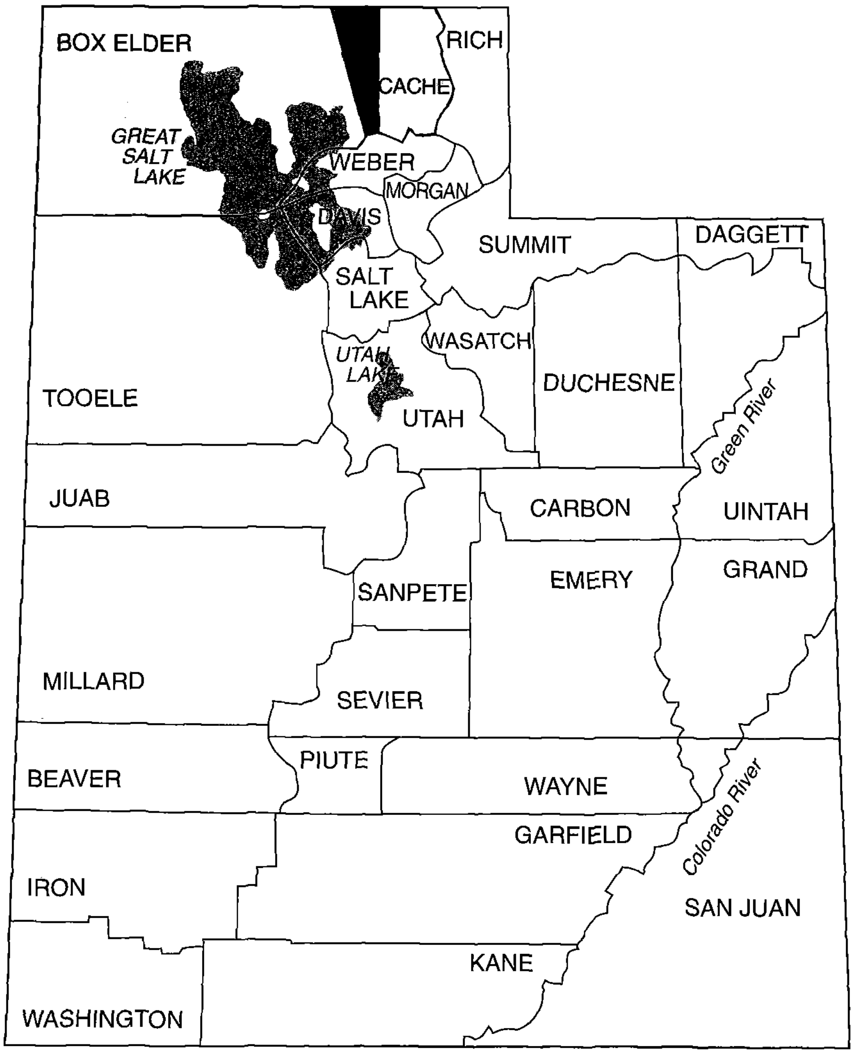

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UTAH GEOLOGICAL SURVEY

UTAH GEOLOGICAL SURVEY

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SURFICIAL GEOLOGIC MAP OF THE WEST CACHE FAULT ZONE AND NEARBY FAULTS, BOX ELDER AND CACHE COUNTIES, UTAH

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Utah Geological Survey

ABSTRACT

The West Cache fault zone (WCFZ) extends about 56 kilometers (35 mi) along the west side of Cache Valley in northern Utah, and another 37 kilometers (23 mi) into southern Idaho. I mapped about 910 square kilometers (350 mi^2) in northern Utah, including the WCFZ and three other nearby Quaternary faults. Mapping was compiled at a scale of 1:24,000 and is published at a scale of 1:50,000.

The Quaternary geology of the region is dominated by late Pleistocene deposits of Lake Bonneville. The lake lasted from about 30,000 to 12,000 ^{14}C yr B.P., but the lake occupied Cache Valley in northern Utah from only about 25,000 to 13,000 ^{14}C yr B.P. Static levels of Lake Bonneville are recorded by shoreline complexes which are useful datums for evaluating late Pleistocene structure and stratigraphy. I mapped 9 Lake Bonneville surficial units and 2 major Lake Bonneville shorelines, as well as 24 other Quaternary geologic units, 6 pre-Quaternary bedrock units, and several minor Lake Bonneville shorelines.

Three normal faults are recognized in the WCFZ of Utah, and they are, from north to south, the Clarkston, Junction Hills, and Wellsville faults. These three faults are geographic divisions of the WCFZ, although evidence suggests that the Clarkston fault is a seismically independent structural segment. Quaternary normal faults in three other adjacent areas may also be associated with the WCFZ, but they are not included because of their lack of demonstrable continuity with the WCFZ and lack of paleoseismic data. These nearby faults are, from north to south, the Dayton, Hyrum, and Mantua faults. Together, the WCFZ and nearby faults form a distinctive right-stepping, en echelon pattern in the western half of Cache Valley in northern Utah and southern Idaho.

Detailed surficial geologic mapping of the WCFZ and nearby faults in this study identified stratigraphic and structural relationships not described in previous mapping. Although data suggest a late Pleistocene age for most recent displacement along the faults, surficial evidence for the age of surface faulting in some locations is ambiguous. No conclusive evidence of Holocene faulting was found. I have therefore proposed several trench locations to help determine the size and timing of earthquakes along the WCFZ and nearby faults. Correlations of events on various sections of the WCFZ and nearby faults will be used to help assess fault continuity, segmentation, and rupture patterns.

INTRODUCTION

The Wasatch, East Cache, and West Cache fault zones (WFZ, ECFZ, and WCFZ) are in and adjacent to Cache Valley in northern Utah (figure 1). All displace the surface and show evidence of late Quaternary movement. Under the National Earthquake Hazards Reduction Program (NEHRP), the U.S. Geological Survey (USGS) and its contractors produced 1:50,000-scale surficial geologic maps of the WFZ (Personius, 1990; Machette, 1992; Personius and Scott, 1992; Nelson and Personius, 1993; Harty and others, 1997) and ECFZ (McCalpin, 1989). I mapped the gap between the adjoining WFZ and ECFZ (plate 1), showing surficial deposits and faults that displace them along the WCFZ and nearby faults in northern Utah. The goal of my study, as for other mapping studies along the WFZ and ECFZ, is to provide basic geologic data needed for accurate assessments of paleoseismic history and earthquake hazards associated with Quaternary faults. Funding for this study was provided jointly by the Utah Geological Survey (UGS) and the USGS under the NEHRP.

The WCFZ extends about 56 kilometers (35 mi) along the west side of Cache Valley in northern Utah, and another 37 kilometers (23 mi) into southern Idaho (Rember and Bennett, 1979; Sullivan and others, 1988). The fault zone lies 110 kilometers (70 mi) north of downtown Salt Lake City, and the cities of Logan (population 32,800 - 1990 census) and Brigham City (population 15,600 - 1990 census) are 16 and 10 kilometers (10 and 6 mi), respectively, from the WCFZ. Three faults are recognized in the WCFZ of Utah (figure 2). These faults are, from north to south: (1) the Clarkston fault, at the eastern edge of Clarkston Mountain near the Utah-Idaho border; (2) the Junction Hills fault, at the eastern edge of the Junction Hills between Clarkston Mountain and the Wellsville Mountains; and (3) the Wellsville fault, at the eastern edge of the Wellsville Mountains west and south of Wellsville. These three faults are geographic divisions of the WCFZ. Although long normal and strike-slip fault zones are usually comprised of several seismically independent structural segments, information is insufficient to imply that all three faults of the WCFZ are segments subject to independent surface rupture. However, evidence discussed in this report suggests that the Clarkston fault is an independent structural segment, separated from the Junction Hills fault by a segment boundary at the Short Divide fault.

Quaternary faults in three other adjacent areas (figure 2) may also be associated with the WCFZ, but they have not been

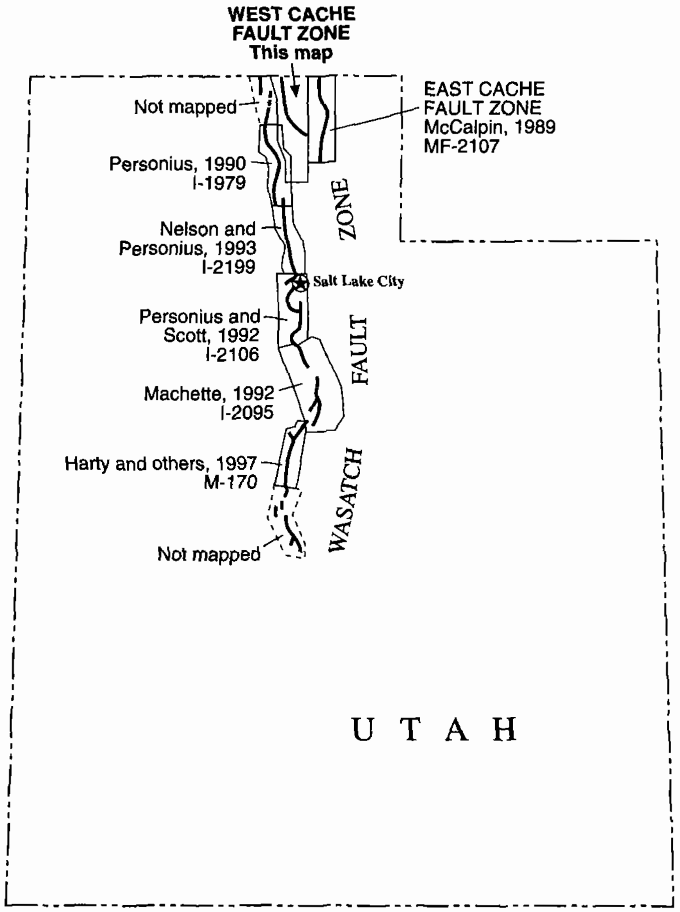

Figure 1. Index map showing the series of fault maps along the Wasatch, West Cache, and East Cache fault zones (modified from Machette, 1992).

previously included because of their lack of demonstrable continuity with the WCFZ and lack of paleoseismic data. These nearby faults are, from north to south: (1) the Dayton fault, 11 kilometers (7 mi) east of the Clarkston fault in north-central Cache Valley; (2) the Hyrum fault, on the southwest side of Cache Valley in the southern Wellsville Mountains, extending 13 kilometers (8 mi) beyond the southern end of the Wellsville fault; and (3) several faults near the town of Mantua, in the interior of the Wellsville Mountains and Wasatch Range southwest of the Hyrum fault. Together, faults in the WCFZ and nearby faults form a distinctive pattern of right-stepping, en echelon normal faults in the western half of Cache Valley in northern Utah and southern Idaho.

Cluff and others (1974) defined the WCFZ in their photogeologic investigation of active faults in southern Idaho and northern Utah. They mapped fault scarps and lineaments in the fault zone, but did not map surficial geologic units. The present study is the first systematic attempt to map and describe the Quaternary geology along the fault zone, including data on the age and distribution of fault scarps. Exploratory trenching was beyond the scope of this study, and no trenching has been conducted in the WCFZ by other investigators. Trenching is necessary for a better understanding of the paleoseismic history of the WCFZ, and this map helps identify key sites for detailed studies of the fault zone's history.

METHODS

Numerous maps of surficial geology, soils, bedrock geology, and faults exist at various scales for most of the mapped area and were consulted for this project (figure 3). Maps showing surficial geology (Williams, 1948, 1958, 1962; Bjorklund and McGreevy, 1971; Davis, 1985; Crittenden and Sorensen, 1985; Dames and Moore, 1985; Oviatt, 1986a, 1986b; Barker and Barker, 1993; Dover, 1995; Robert Biek and Jon King, unpublished geologic map of the Clarkston quadrangle, 1996) provided information on Quaternary stratigraphic and geomorphic relations. However, I remapped the surficial geology along the mountain front, interior basins, and valley floor because existing maps are of insufficient detail or include outdated stratigraphic terminology and concepts. Gradational contacts between some lacustrine and alluvial units were interpreted from U.S. Conservation Service soil maps (Erickson and Mortensen, 1974; Chadwick and others, 1975).

Maps showing bedrock geology were compiled and simplified to show generalized stratigraphic and structural relations within mountain blocks, including Clarkston Mountain (Hanson, 1949; Robert Biek and Jon King, unpublished geologic maps of the Clarkston and Portage quadrangles, 1996); the Washboards (Robert Biek and Jon King, unpublished geologic map of the Clarkston quadrangle, 1996); Bergeson Hill, Big Hill, Pete McCombs Hill, and Little Mountain (Dover, 1995; Robert Biek and Jon King, unpublished geologic map of the Clarkston quadrangle, 1996); the Junction Hills (Oviatt, 1986a); the Wellsville Mountains (Oviatt, 1986b; Dover, 1995; Jensen and King, 1995); and the Wasatch Range (Crittenden and Sorensen, 1985; Dover, 1995). Geology of the eastern slope of the Wellsville Mountains, and of the Wasatch Range in the vicinity of Mantua, was revised from Personius (1990) to show additional bedrock- and surficial-geologic detail. Fault maps by Cluff and others (1974) and Sullivan and others (1988) show details of suspected surface-fault ruptures and other lineaments in Quaternary unconsolidated deposits along the fault zone, but no paleoseismic assessments of fault movement have been conducted.

Mapping of mountain fronts and interior basins in the WCFZ and along nearby faults was done on 1:15,000-scale color aerial photographs (1991, U.S. Department of Agriculture [USDA]); mapping of the Cache Valley floor was done on 1:20,000-scale black-and-white aerial photographs (1966, USDA). Air-photo mapping was field checked and compiled onto 1:24,000-scale topographic base maps. The compiled geologic maps were reduced and published at a scale of 1:50,000 (plate 1).

Differentiation of Quaternary geologic units follows standard convention and is based on age-dependent criteria such as geomorphic expression, landform preservation, soil development, and topographic and stratigraphic position. To maintain continuity, geologic mapping symbols are identical to those used in the USGS surficial geologic maps of the adjacent WFZ and ECFZ (McCalpin, 1989; Personius, 1990), with the addition of two geologic units. Sand and silt deposited in natural levees by the Bear River (unit als), and a spring deposit of travertine near Trenton (unit st), are designated to reflect unique deposits either absent or undifferentiated in adjacent map areas. Detailed descriptions of geologic units (plate 1) are in the appendix; many of the descriptions were either taken directly or modified from other USGS surficial geologic maps of the WFZ and ECFZ.

In addition to using mapped geology, slip rates are estimat-

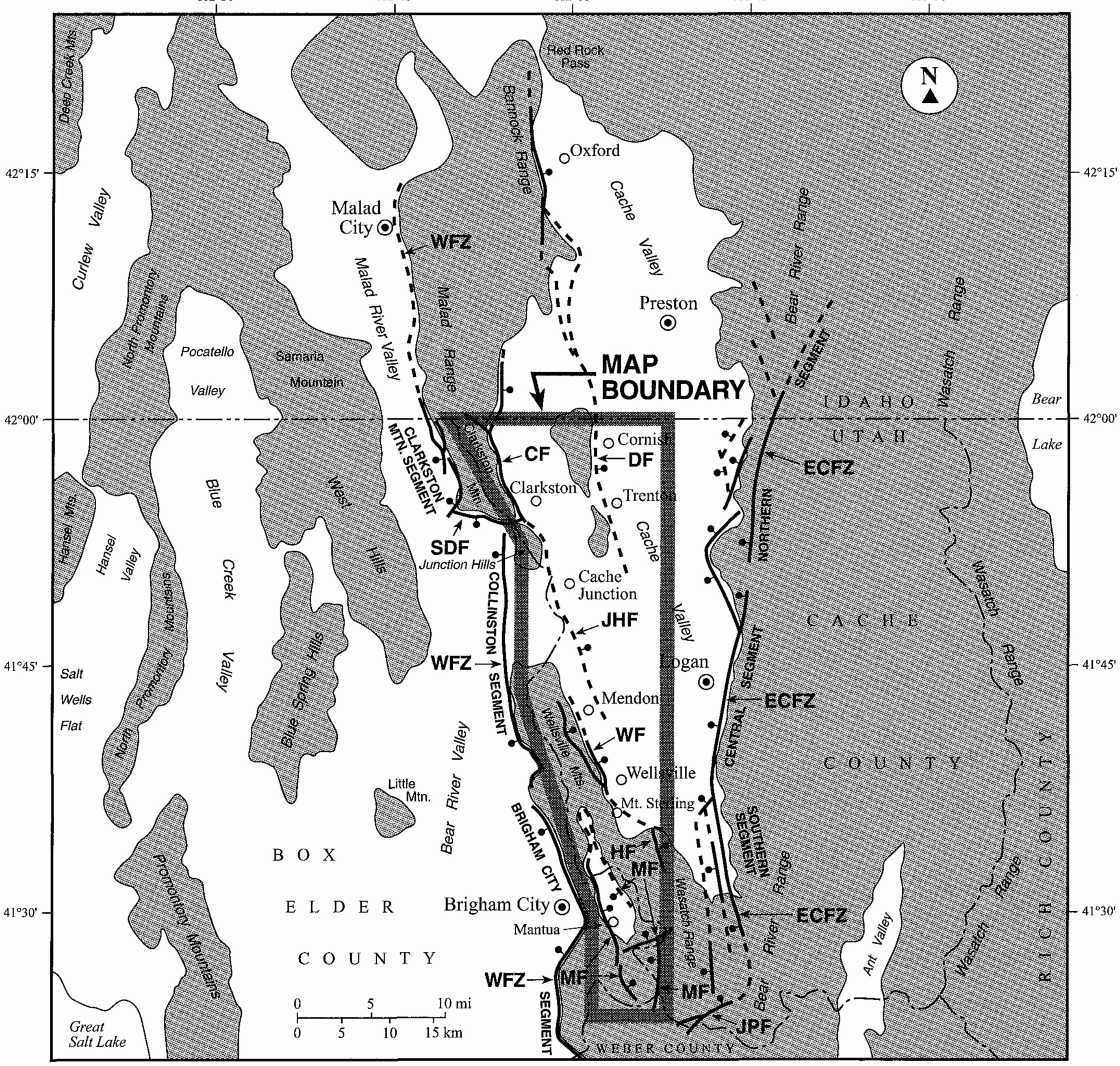

Figure 2. *Simplified traces of the West Cache fault zone (WCFZ) and nearby faults (modified from Rember and Bennett, 1979; McCalpin, 1989; Nelson and Sullivan, 1992; and Hecker, 1993), shown by heavy lines with a bar and ball on the downdropped side. The WCFZ in Utah includes, from north to south, the Clarkston fault (CF), Junction Hills fault (JHF), and Wellsville fault (WF). Nearby faults mapped in this report are, from north to south, the Dayton fault (DF), Short Divide fault (SDF), Hyrum fault (HF), and Mantua faults (MF). Other nearby faults include the Wasatch fault zone (WFZ), East Cache fault zone (ECFZ), and James Peak fault (JPF).*

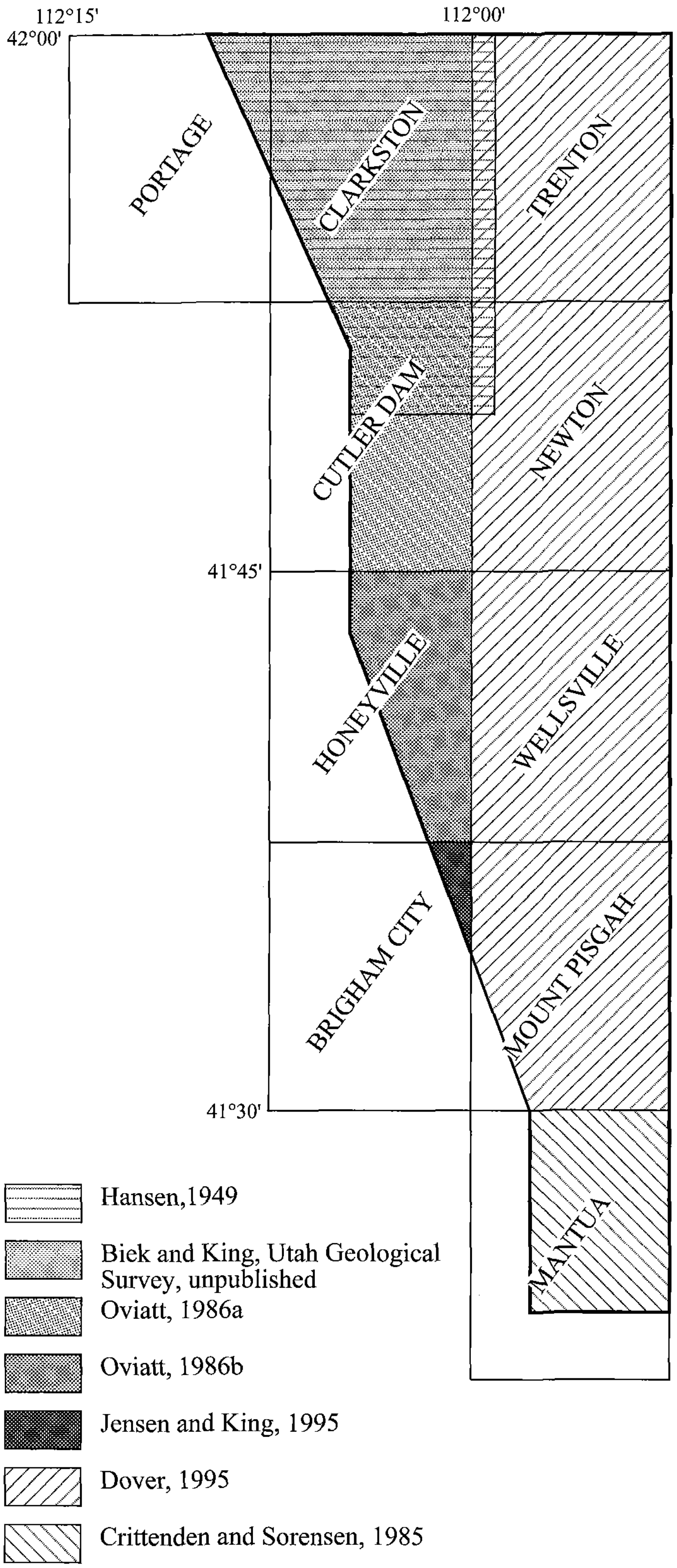

Figure 3. *Sources of geologic data used in compilation of this map. Other sources that cover parts of the map area but were not used in the compilation are listed in the text.*

ed from stratigraphic displacement and ages of faulted Quaternary deposits and Lake Bonneville shorelines. However, these slip rates represent average rates based on amounts of displacement of dated horizons or features. They do not represent true slip rates based on slip during a bracketed interval between two events of known age. Slip rates determined for this study are calculated only for comparison with slip rates calculated in a similar manner for other faults and are probably greater than true slip rates. Fault-scarp profiles were not measured because scarps were destroyed by post-rupture erosion, were obscured by active colluvial processes and dense vegetation, or were at the bedrock-alluvial contact and not found in unconsolidated deposits. Without scarp profiles or trenches, a chronology for multiple events is lacking and recurrence intervals cannot be determined.

Major shorelines associated with the transgressive (Bonneville shoreline) and regressive (Provo shoreline) phases of the most recent cycle of Lake Bonneville provide a means of relative age dating in the Lake Bonneville basin. Ages of the Bonneville Lake cycle are reported in radiocarbon years before present according to lake chronologies of Currey (1990) and Oviatt and others (1992).

The following informal time- and rock-stratigraphic designations are used to divide the Quaternary Period: (1) Holocene (0-10,000 years ago), (2) latest (uppermost) Pleistocene (10,000-16,800 years ago; Pleistocene age later [deposits younger] than the Bonneville flood), (3) late (upper) Pleistocene (10,000-130,000 years ago; including latest [uppermost] Pleistocene when undifferentiated), (4) middle Pleistocene (130,000-750,000 years ago), and (5) early (lower) Pleistocene (750,000-1.6 million years ago).

QUATERNARY DEPOSITS AND DEPOSITIONAL HISTORY

Cache Valley occupies a structural basin in the Middle Rocky Mountains physiographic province (Stokes, 1977), and is also a geomorphic subbasin of the Bonneville basin, an area of internal drainage for much of the past 15 million years. Several successive lakes existed in the Bonneville basin during this time, but the Quaternary geology of the valley is dominated by late Pleistocene deposits of Lake Bonneville. The Bonneville lacustral cycle was coincident with the last global ice age of marine isotope stage 2, and lasted from about 30,000 to 12,000 ^{14}C yr B.P., but the lake occupied Cache Valley in northern Utah from only about 25,000 to 13,000 ^{14}C yr B.P. (Currey and Oviatt, 1985; Oviatt and others, 1992). Static levels of Lake Bonneville are recorded by shoreline complexes, some of which are mapped within the WCFZ. These shorelines are useful datums for evaluating late Pleistocene structure and stratigraphy.

Lacustrine History and Deposits

Lake Bonneville began to rise from levels close to those of modern-day Great Salt Lake about 30,000 ^{14}C yr B.P. and, by about 25,000 ^{14}C yr B.P., transgressed into Cache Valley. The lake rose gradually, but experienced a major, climatically induced oscillation between 21,000 and 20,000 ^{14}C yr B.P. that produced the Stansbury shoreline (Oviatt and others, 1990). The lake eventually resumed its rise, but the rise slowed as the lake level approached an external basin overflow threshold at Red Rock Pass (1,552 meters [5,093 ft]) near Zenda, southern Idaho. Lake Bonneville reached this threshold and occupied its highest shoreline, which Gilbert (1875) named the Bonneville beach, after 15,500 ^{14}C yr B.P. The lake remained at this level perhaps as late as 14,500 ^{14}C yr B.P., with one possible oscillation (the Keg Mountain oscillation of Currey [1990]). Sediments deposited at the Bonneville level and during the prior Lake Bonneville transgression include map units lbd, lbg, lbs, lbm, and, in part, lbpm.

About 14,500 ^{14}C yr B.P., headward erosion of the Snake River-Bonneville basin drainage divide caused the catastrophic incision of the Red Rock Pass threshold, which lowered the lake level 108 meters (354 ft) in less than two months (Jarrett and Malde, 1987; O'Connor, 1993). Oviatt (1986a) found evidence that during this period, all of the water in the main body of Lake Bonneville between the Bonneville beach and the newly established Provo shoreline (1,444 meters [4,737 ft]) was discharged through three small passes in the Junction Hills into Cache Valley, and then out through Red Rock Pass to the Snake River. This rapid drawdown of the lake level removed an enormous weight from the earth's crust, which resulted in crustal rebound from isostatic compensation (Crittenden, 1963). In western Cache Valley, isostatic rebound and regional tectonics have uplifted the highest of the Bonneville shorelines as much as 27 meters (89 ft) to elevations of from 1,567 to 1,579 meters (5,140-5,180 ft [table 1]). Similarly, the highest Provo shoreline has been uplifted as much as 22 meters (72 ft) to elevations of from 1,452 to 1,466 meters (4,765-4,810 ft [table 1]).

After 14,000 ^{14}C yr B.P., Lake Bonneville became a hydrologically closed system as overflow ceased and the climate warmed, shrinking the lake and dropping its level rapidly from the Provo shoreline. Sediments deposited at the Provo level and during the subsequent Lake Bonneville regression include map units lpd, lpg, lps, lpm, and, in part, lbpm. By about 13,000 ^{14}C yr B.P., the lake had regressed from Cache Valley, and by about 12,000 ^{14}C yr B.P. had dropped to levels possibly at or lower than those of modern-day Great Salt Lake (Currey and Oviatt, 1985; Oviatt and others, 1992). Great Salt Lake then transgressed to form the Gilbert shoreline (about 1,296 meters [4,252 ft] in the adjacent Bear River Valley [Personius, 1990]) between 11,000 and 10,000 ^{14}C yr B.P., but this expansion did not reach

Table 1. Altitudes of prominent shorelines in the West Cache fault zone

Shoreline altitudes in the Bonneville basin vary because of differential crustal rebound from isostatic compensation as Lake Bonneville receded (Crittenden, 1963; Currey, 1982), and from regional tectonics. Prior to rebound, the altitude of the Bonneville shoreline threshold was 1,552 meters (5,192 ft) and the Provo shoreline threshold was 1,444 meters (4,737 ft) (Currey and Oviatt, 1985). Shorelines along deep margins of ancient Lake Bonneville show proportionately more rebound than shorelines along shallow lake margins. n.a., not applicable.

Area	Highest Provo Shoreline (meters/feet)	Highest Bonneville Shoreline (meters/feet)	Remarks
Clarkston fault			
Clarkston	n.a.	1,570/5,151[1]	Bonneville shoreline below Clarkston fault.
Washboards	n.a.	1,570/5,150[2]	Bonneville shoreline below Clarkston fault.
Dayton fault			
Big Hill	1,452/4,765[2]	1,567/5,1402	Both shorelines above Dayton fault.
Pullum Hollow	1,460/4,790[1]	n.a.	Provo shoreline above Dayton fault.
Junction Hills fault			
Bob Archibald Hollow	n.a.	1,579/5,180[2]	Bonneville shoreline cut into Clarkston faultscarp.
Cutler Dam	1,462/4,795[2]	1,575/5,168[1]	Both shorelines above Junction Hills fault.
Southwest of Cache Junction	1,460/4,790[2]	1,579/5,180[2]	Both shorelines above Junction Hills fault.
Wellsville fault			
Southwest of Mendon	1,460/4,790[2]	1,573/5,160[2]	Both shorelines below Wellsville fault.
East of Mt. Sterling	1,466/4,810[1]	n.a.	Provo shoreline below Wellsville fault.
Mantua faults			
Mantua	n.a.	1,576/5,170[2]	Bonneville shoreline below Mantua faults.
Hyrum fault			
Baxter Pothole	n.a.	1,577/5,174[1]	Near intersection of Wellsville and Hyrum faults.

[1]*Data from Currey (1982). Accuracy is from ± 2 to ± 3 meters (± 7 to ± 10 ft).*

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

Cache Valley (Currey, 1982). Young lacustrine sediments, including undivided marsh and alluvial deposits (units ly and laly), were deposited after regression of Lake Bonneville in wetlands along the Cache Valley floor and in intermontane ephemeral lakes formed in sinkholes in the Wasatch Range near Mantua.

Alluvial History and Deposits

Cache Valley and the small, interior basins of the Wasatch Range near Mantua have been characterized by alluvial-fan deposition that accompanied mountain uplift throughout the Quaternary. Alluvial-fan deposits older than the Bonneville lake cycle (unit afo) are preserved in the foothills of Clarkston Mountain and the Wellsville Mountains on remnants of extensive, dissected pediment surfaces (the McKenzie Flat surface of Williams, 1948) cut into Tertiary deposits (unit Tu). Similar alluvial-fan deposits near Mantua in the Wasatch Range are derived from erosion of the surface nearby. McCalpin (1989) estimates the age of similar deposits in eastern Cache Valley as probably 100,000 to 200,000 years old, based on the considerable amount of surface erosion and strong soil development. Deposition of these fans ceased as either fault movement or climatic conditions lowered the local base level and streams incised the fans.

With the transgression of Lake Bonneville, the fan deposits were truncated by the highest Bonneville shoreline and covered by lake beds at lower elevations. Stream alluvium graded to the Bonneville shoreline (unit alb) was locally deposited, and is preserved at Box Elder Creek near Mantua. As the level of Lake Bonneville receded to the Provo shoreline, additional stream alluvium (unit alp) was deposited, and is preserved at Box Elder Creek and at Narrow Canyon in the Wellsville Mountains. After lake regression from the Provo shoreline, throughout the latest Pleistocene and into the Holocene, deposition of alluvial fans (units af1, af2, and afy) has been rapid and extensive, burying and eroding Lake Bonneville shorelines and deposits at canyon mouths along the range front. Studies of alluvial fans in northern Utah suggest that many of these alluvial sediments were deposited during a major fan-building episode from about 4,000 to 5,000 years ago (Williams, 1956; Machette and others, 1992).

Stream alluvium (units al1, al2, and aly) was deposited concurrently with fan alluvium in mountain drainages and on the Cache Valley floor. Middle Holocene to uppermost Pleistocene stream alluvium (unit al2) is preserved on elevated terraces above modern floodplains (unit al1) of the Bear, Cub, Little Bear, and Logan Rivers and smaller drainages, and in abandoned floodplains and channels such as the ancestral Clarkston Creek at its junction with Newton Creek. In northern Cache Valley, the Bear River periodically overflowed its floodplain and deposited sand (unit als), derived from the Provo-level delta (unit lpd), in adjacent levees. These sandy, well-drained deposits underlie some of the best agricultural land in Cache Valley.

Colluvial Deposits

Colluvial deposits cover a small percentage of the mapped area but include units that record evidence of important geologic hazards in Cache Valley and nearby areas. Upper Holocene debris-flow deposits (unit cd1) are preserved at the surface of some alluvial fans (units af1 and afy), and also probably constitute a large part of the alluvial-fan sediment. Debris flows are a historically significant hazard along range fronts in northern Utah, and were particularly abundant during the wet years of 1983 and 1984 (Kaliser and Slosson, 1988). Several large landslides, perhaps as old as late Tertiary (units cls, clso, and clsy), are associated with failure of underlying Tertiary and Paleozoic sedimentary rocks and nearshore Lake Bonneville deposits. Most landslides are of uppermost Pleistocene age (unit clsy) and were caused either by wave erosion of the Bonneville shoreline, rapid dewatering of oversteepened slopes during the Bonneville flood, or earthquakes. However, some landslides, such as those which disrupt alluvial-terrace deposits (unit al2) near the Little Bear River east of Wellsville, are obviously younger and are evidence of an ongoing threat. Local Holocene to upper Pleistocene deposits of rock-fall debris (unit crf) are present on steep mountain slopes and above stream channels in canyons in the southern part of the mapped area. Holocene to upper Pleistocene hillslope colluvium (unit chs) locally covers slopes in the southern part of the mapped area, particularly in small basins south of Mantua filled by soft Tertiary deposits. Undifferentiated colluvium and alluvium (unit ca) is found where colluvium-covered hillsides grade imperceptibly into alluvium-filled valleys.

Other Deposits

A variety of other Quaternary deposits are mapped in the WCFZ. These deposits are volumetrically small but important to the interpretation of the Quaternary history of the area. Glacial till and outwash (units gbct and gbco) equivalent to the Bells Canyon advance of Madsen and Currey (1979) are found near the crest of the Wellsville Mountains (Oviatt, 1986b) and in valleys of the Wasatch Range (Crittenden and Sorensen, 1985). This advance is associated with the Pinedale glaciation of the Rocky Mountains from about 45,000 to 15,000 years ago (Porter and others, 1983; Scott, 1988). The till forms lateral and terminal moraines in shallow cirques, and the outwash forms terraces graded to the moraines. Several small upper Holocene spring deposits are aligned along the range front from Pete McCombs Hill to Little Mountain, in the vicinity of the Dayton fault. Most spring deposits are too small to map, but one (unit st) forms a large cone of travertine with a spring-fed pool at its center. Small patches of uppermost Pleistocene to Holocene eolian sand (unit es) are mapped near Cornish as dunes derived from Lake Bonneville deltaic and post-Bonneville alluvial-levee deposits (units lpd and als). Calcareous, eolian silt (loess) eroded from fine-grained lakebeds (units lbm, lpm, and lbpm) is locally present as an unmappable, thin mantle on Lake Bonneville shoreline benches. Modern artificial fill (unit f) associated with reservoir and highway construction covers small areas.

FAULT DESCRIPTIONS

Williams (1948) mapped several subparallel faults that form major topographic boundaries along range fronts in and south of western Cache Valley, Utah. Cluff and others (1974) defined the WCFZ as a discontinuous zone of scarps including some of the faults mapped by Williams (1948). The WCFZ extends along the western edge of Cache Valley from approximately Oxford, Idaho, on the north, to Mt. Pisgah, Utah, on the south. This discussion includes a brief description of the age, height, and distribution of fault scarps in the WCFZ of Utah and on nearby faults mapped by Williams (1948). The relatively well-dated sequence of Quaternary deposits in the map area aids in the interpretation of Quaternary faulting. The discussion starts with the northernmost of the three geographic subdivisions of the WCFZ, continues with descriptions of faulting southward along the other two subdivisions, and finishes with descriptions, from north to south, of the three nearby faults possibly associated with the WCFZ.

West Cache Fault Zone

The WCFZ in Utah extends for 56 kilometers (35 mi) along the western edge of Cache Valley from the Utah-Idaho border to about 6 kilometers (4 mi) southeast of Wellsville (figure 2). The fault zone consists of three down-to-the-east normal faults that include, from north to south, the Clarkston, Junction Hills, and Wellsville faults. Evidence suggests that the Clarkston fault is a seismically independent structural segment, but information is insufficient to imply that the remaining sections, which are differentiated by distinct topographic and geologic features, are segments. Seismic-reflection data (Smith and Bruhn, 1984; Evans, 1991; Evans and Oaks, 1996) indicate that the WCFZ has significantly less displacement than the ECFZ, suggesting that the WCFZ is antithetic to the ECFZ (Sullivan and others, 1988).

Clarkston Fault

The Clarkston fault was first mapped by Williams (1948) and Hanson (1949), although Williams (1948) included faulting to the south near the Junction Hills as part of the Clarkston fault. For my study, the Clarkston fault includes only the significant east-facing break in slope along the eastern edge of Clarkston Mountain in the Malad Range of Utah. Additional faults are found in the WCFZ north of the Utah-Idaho border, but these, as well as the Junction Hills fault, are morphologically distinct and are not considered part of the Clarkston fault. In this restricted sense, the Clarkston fault extends from the Utah-Idaho border southward to Short Divide, which separates Clarkston Mountain to the north from the Junction Hills to the south.

The Clarkston fault is 11 kilometers (7 mi) long and, for most of its length, consists of a single, sinuous fault strand with discontinuous down-to-the-east normal fault scarps. The only variation from this pattern is at its northern end adjacent to Hammond Flat, where two faults diverge northward from the single range-front fault to the south. One branch trends northwestward into the interior of Clarkston Mountain where it displaces bedrock outcrops, and the other branch continues northward along the range front where it displaces upper to middle Pleistocene fan alluvium and Tertiary sedimentary rocks (units afo and Tu) and becomes more subdued near the Utah-Idaho border. South of the divergence, the Clarkston fault displaces mostly upper to middle Pleistocene fan alluvium and Tertiary sedimentary rock (units afo and Tu) on the hanging wall from Paleozoic sedimentary rock on the footwall. Holocene to uppermost Pleistocene fan alluvium and debris flows apparently cover the fault at canyon mouths, which are separated from each other by steep range-front faceted spurs. The fault is also covered by Holocene to middle Pleistocene landslide debris (unit cls) along the range front southwest of Clarkston.

Although I did not find any conclusive evidence of Holocene displacement, I did note two areas of potential Holocene displacement. The first area is at the mouth of Raglanite Canyon, 3 kilometers (2 mi) northwest of Clarkston. At Raglanite Canyon, fan alluvium (unit afo) on both sides of the fault is displaced about 10 meters (30 ft); although mapped as upper to middle Pleistocene age, locally thin deposits of younger, Holocene alluvium may be present. The second area is at the mouth of Winter Canyon, 0.8 kilometers (0.5 mi) south of Raglanite Canyon. At Winter Canyon, a scarp about 3 meters (10 ft) high is visible in Holocene to middle Pleistocene colluvium and alluvium (unit ca) in the stream channel, but I mapped the scarp as an unfaulted drape of sediment on older, pre-Holocene faulted deposits. Topographic profiling across these scarps was not attempted because of the thick vegetation and soft, loose, organic-rich soil on the surface of the scarps. Without scarp profiles or radiometric-age data, no definitive evidence exists to suggest Holocene activity along the Clarkston fault. However, these sites are recommended for exploratory trenches during further paleoseismic study.

The Clarkston fault lies at elevations above the highest shoreline of Lake Bonneville. However, the elevation of the Bonneville shoreline near the Clarkston fault, north of Short Divide at the south end of Clarkston Mountain, is distinctly lower than the shoreline elevation to the south (table 1). North of Short Divide, the Bonneville shoreline is at an elevation of about 1,570 meters (5,151 ft), but south of the divide the shoreline is at an elevation of about 1,579 meters (5,180 ft). Hanson (1949) maps an east-west fault near Short Divide that separates two distinctly different geologic terranes; Paleozoic sedimentary rocks (unit M€r) north of the fault are separated by an estimated 3,000 meters (10,000 ft) of stratigraphic throw from Tertiary sedimentary rocks (unit Tu) south of the fault. Machette and others (1992) identify this fault as the boundary between the Clarkston Mountain and Collinston segments of the WFZ, and Zoback (1983) shows the fault as a major transverse structural feature on her gravity map. The projected eastward extension of the Short Divide fault, and its intersection with the Clarkston fault, are covered by post-Bonneville-Lake-cycle landslide deposits (unit clsy), so their precise relationship cannot be determined. The difference in Bonneville shoreline elevations across this projection, though, suggests independent surface rupture of the Clarkston fault from the Junction Hills fault to the south, with the shoreline elevation lowered on the hanging wall of the Clarkston fault. Therefore, the Short Divide fault is probably a segment boundary in the WCFZ as well as the WFZ, and I believe the Clarkston fault north of Short Divide is a seismically independent structural segment of the WCFZ.

The difference in Bonneville shoreline elevations across Short Divide could be due to movement on either the Clarkston fault, Junction Hills fault, or WFZ alone, or to a combination of events on these faults which differentially lowered the shoreline on the hanging wall of the Clarkston fault and raised the shoreline along the Junction Hills fault. Field evidence was insufficient to resolve these uncertainties. If the difference in shoreline elevations represents 9 meters (30 ft) of displacement from multiple seismic events along the Clarkston fault after regression of Lake Bonneville from its highest shoreline about 16,800 years ago, the maximum slip rate since the latest Pleistocene is 0.54 mm/yr (0.021 in/yr) (table 2). For comparison, average slip rates for the northern segment of the ECFZ are 0.16 to 0.36 mm/yr (0.0063-0.014 in/yr) since Miocene extension of Cache Valley began (Evans, 1991) and 0.25 to 0.50 mm/yr (0.010-0.020 in/yr) since the early Pleistocene (McCalpin, 1994). Average Holocene slip rates for the central segments of the WFZ are 1 to 2 mm/yr (0.04-0.08 in/yr) (Machette and others, 1992), whereas slip rates for other Quaternary faults in Utah usually range between 0.01 and 0.5 mm/yr (0.0004-0.02 in/yr) (Hecker, 1993).

Paleoearthquake magnitude on the Clarkston fault can be estimated from the length of surface rupture using the relation-

Table 2. *Estimated slip rates of faults in and near Cache Valley*

Slip rates in mm/yr. n.a., not applicable.

West Cache Fault Zone			Nearby Faults			East Cache Fault Zone		
Since Miocene	**Since Early Pleistocene**	**Since Latest Pleistocene**	**Since Miocene**	**Since Early Pleistocene**	**Since Latest Pleistocene**	**Since Miocene**	**Since Early Pleistocene**	**Since Latest Pleistocene**
Clarkston Fault			**Dayton Fault**			**Northern Segment**		
n.a.	n.a.	0.54	0.02-0.04[1]	n.a.	n.a.	0.16-0.36[2]	0.25-0.50[3]	n.a.
Junction Hills Fault			**Hyrum Fault**			**Central Segment**		
0.04-0.06[1]	n.a.	0.11-0.16[4]	n.a.	n.a.	n.a.	0.29-0.54[2]	0.02-0.13[3]	0.28[3]
Wellsville Fault			**Mantua Faults**			**Southern Segment**		
n.a.	n.a.	0.15[5]	n.a.	n.a.	n.a.	0.47-0.8[2]	0.01-0.067[3]	n.a.

[1]*Calculated for this study using data from Evans (1991)*
[2]*Evans (1991)*
[3]*McCalpin (1994)*
[4]*Calculated for this study using data from Oviatt (1986a)*
[5]*Calculated for this study using data from Oviatt (1986b)*

ship of Wells and Coppersmith (1994). Moment magnitude (M) is related to surface-rupture length (SRL = 11 kilometers [7 mi]) by the formula M = a + b * log (SRL) where "a" and "b" are regression coefficients (4.86 and 1.32, respectively) determined by Wells and Coppersmith (1994) using only data from normal faults. From this relationship, the inferred paleoearthquake magnitude on the Clarkston fault is 6.2. Paleoearthquake magnitude can also be estimated from the maximum displacement per event (Wells and Coppersmith, 1994), but uncertainties associated with the number and nature of events along the Clarkston fault preclude using this method.

Junction Hills Fault

The Junction Hills fault was first mapped by Williams (1948) as the southern part of the Clarkston fault, consisting of the linear eastern edge of the Junction Hills and Cache Butte south of Clarkston Mountain as well as a fault in Lake Bonneville beds along the northeast side of Cache Butte. This terminology was continued by Williams (1962) and Cluff and others (1974), but Oviatt (1986a) made no reference to the Clarkston fault when he mapped the Cache Butte area, and Hecker (1993) differentiated the fault in the Cache Butte area as a separate section of the WCFZ based on the map of Oviatt (1986a). As defined here the Junction Hills fault starts at the range front east of Short Divide, continues southeastward along the eastern margin of the Junction Hills and Cache Butte, and ends concealed beneath younger deposits east of the northern Wellsville Mountains.

The Junction Hills fault is 25 kilometers (16 mi) long with a discontinuous down-to-the-east normal fault trace. East of Short Divide the fault displaces Tertiary sedimentary rock (unit Tu), but for most of its length the fault is concealed beneath Lake Bonneville deposits (units lbg, lbs, lps, and lbpm) and, locally, by Holocene to upper Pleistocene landslide debris (unit clsy) and upper Holocene fan alluvium (unit af1). After the fault exits Tertiary rocks near Short Divide, the concealed fault is assumed to parallel the Bonneville shoreline, which occupies a narrow bench adjacent to a steep shoreline scarp. South of Cutler Reservoir the fault diverges from the shoreline and is mapped as a single scarp in bedrock. The steep shoreline scarp continues south of the reservoir to Cache Butte, but the fault trends southeastward toward three short lineaments on the northeast margin of Cache Butte. The concealed Junction Hills fault continues past the lineaments and ends beneath Holocene alluvium (unit al1) of the Little Bear River east of Mendon.

The only conclusive evidence of Quaternary displacement along the Junction Hills fault is associated with the three short lineaments northeast of Cache Butte. Lineament lengths range from 460 to 610 meters (1,500-2,000 ft). Two are below the Provo shoreline and the other is between the Bonneville and Provo shorelines; the Provo shoreline is continuous across the lineament projections. All three lineaments are clearly visible as tonal variations on air photos, but fault scarps at the ground surface are subtle and subdued after degradation by several decades of repeated plowing. A fault is exposed near the central lineament in a stream cut in the NW1/4 NE1/4 sec. 1, T. 12 N., R. 2 W. At this exposure, Oviatt (1986a) reports that the fault strikes N 5° W and dips between 35° and 45°E, but I measured a dip of 75° E. He found about 2.4 meters (8 ft) of displacement in the basal transgressive gravel of Lake Bonneville and evidence for multiple pre-Bonneville displacement events. Displacement of the overlying regressive deposits of Lake Bonneville is uncertain because of their poor exposure. No fault exposures were found near the other two lineaments, but I assume they are also of tectonic origin. The latest fault displacement associated with the lineaments occurred sometime after transgressive lakebeds were deposited, but a minimum age of faulting cannot be determined from the existing outcrop. Contamination of uppermost beds by agricultural activity would reduce the utility of exploratory trenches, but a more accurate chronology of the sequence of fault-related events on the Junction Hills fault may be obtained by careful examination and logging of the stream exposure.

The altitude of the lakebeds at the stream cut, about 1,430 meters (4,700 ft), is related to lake levels by the time-altitude diagram of Oviatt and others (1992). At that altitude, displacement of transgressive lakebeds occurred no earlier than their deposition about 21,000 ^{14}C yr B.P. and, if overlying regressive lakebeds are displaced, the latest fault rupture may be no older than about 15,000 ^{14}C yr B.P. Using this time frame and the observed displacement of Bonneville beds, maximum slip rates for the Junction Hills fault range from 0.11 to 0.16 mm/yr (0.0043-0.0063 in/yr) since latest Pleistocene. For comparison, average slip rates for the central segment of the ECFZ are 0.29 to 0.54 mm/yr (0.011-0.021 in/yr) since Miocene extension of Cache Valley began (Evans, 1991), 0.02 to 0.13 mm/yr (0.0008-0.005 in/yr) since the early Pleistocene (McCalpin, 1994), and 0.28 mm/yr (0.01 in/yr) during post-Bonneville time (McCalpin, 1994). Evans (1991) estimates net slip of 600 to 1,200 meters (2,000-4,000 ft) on the WCFZ in the vicinity of the Junction Hills fault since Miocene extension of Cache Valley began, resulting in an average slip rate of 0.04 to 0.06 mm/yr (0.0016-0.0024 in/yr).

Wellsville Fault

The Wellsville fault was mapped in reconnaissance by Williams (1948, 1962), Cluff and others (1974), and Dover (1995), and in more detail by Oviatt (1986b) and Barker and Barker (1993). Williams (1962) and Barker and Barker (1993) mapped the fault as a single concealed strand that bounds the eastern edge of the Wellsville Mountains, but Williams (1948) earlier recognized limited fault exposure where Tertiary sedimentary rock (unit Tu) is in fault contact with Paleozoic sedimentary rock (unit PIPr) along the range front west of Wellsville. Cluff and others (1974), Oviatt (1986b), and Dover (1995) mapped the fault as two strands, an eastern fault similar to the concealed range-front fault mapped in earlier studies but with additional exposures in bedrock northwest of Wellsville, and a western fault primarily in bedrock but also displacing Pleistocene fan alluvium. For this study, the Wellsville fault includes both fault traces and extends along the eastern side of the Wellsville Mountains from near Mendon southeastward to the mouth of McMurdie Hollow in southern Cache Valley.

The Wellsville fault is 20 kilometers (12 mi) long and consists of two large subparallel, left-stepping, down-to-the-east normal faults, and several smaller normal faults. The western fault extends 13 kilometers (8 mi) from Pole Canyon on the north to Wide Canyon on the south. This fault has a sinuous, north-trending trace on the east side of the Wellsville Mountains. For most of its length, the western fault marks the sharp boundary between the Oquirrh Formation dip slopes (unit PIPr) and Tertiary and Quaternary deposits (units Tu and alo), but the fault scarp crosses Pleistocene alluvial fans (unit alo) near Deep Canyon. The western fault is roughly parallel to the strike of bedding in the Oquirrh Formation except for a reentrant between Bird Canyon and Coldwater Lake. The area east of Coldwater Lake is a graben underlain by Tertiary sedimentary rock between upthrown blocks of Oquirrh Formation, with the southern closure of the graben formed by the intersection of the main and antithetic faults near Shumway Canyon. The western fault continues southeast in Paleozoic sedimentary rocks until it intersects the range front and is concealed by Lake Bonneville deposits (unit lbg) near the projected intersection of the western and eastern faults at Wide Canyon. Where exposed, the western fault lies entirely above the highest shoreline of Lake Bonneville.

The eastern fault extends 16 kilometers (10 mi) from Gibson Canyon on the north to the mouth of McMurdie Hollow on the south. Much of the northernmost 6 kilometers (4 mi) of the eastern fault displaces a narrow wedge of Tertiary sedimentary rocks (unit Tu) in the hanging wall along the range front from Paleozoic sedimentary rocks (unit PIPr) in the footwall. However, the eastern fault is covered by Quaternary surficial deposits (units af1, al1, clso, and clsy) between bedrock outcrops, and is also concealed at its northern end by the Pleistocene alluvial fans (unit afo) which are displaced by the western fault. The southernmost 10 kilometers (6 mi) are entirely concealed by Lake Bonneville and younger deposits (units lbg, lbm, lpg, lpd, lps, af1, aly, clsy, and cd1), and are defined by the range front. However, the Wellsville Mountains front is much less linear than, and lacks the triangular-faceted spurs of, the Clarkston Mountain front.

Evidence of Quaternary displacement is found in two areas along the Wellsville fault. Near the mouth of Deep Canyon, Oviatt (1986b) noted 15 meters (50 ft) of displacement in middle to upper Pleistocene alluvial-fan deposits (unit afo), but upper Holocene alluvium (unit al1) in the canyon is apparently not displaced. I did not measure a scarp profile near Deep Canyon because of the dense vegetation and thick cover of loose soil. A trench across this scarp is impractical because of its height, but a trench downslope at the base may uncover the main trace and smaller related faults with local deposits of Holocene alluvium or colluvium that could prove useful to interpret the timing of earthquakes along the Wellsville fault.

At the mouth of Pine Canyon, I found several small faults and tilted beds exposed in the wall of a gravel pit excavated on the edge of prograding spits (unit lbg) near the Bonneville shoreline. The wall is about 5 meters (16 ft) high and is cut into topset and foreset beds of gravel and sand tilted and displaced by multiple small faults. The faults have various orientations, but the dominant trend is N 30° W, dipping down-to-the-southwest 40 degrees. Cumulative displacement across these faults is at least 2 meters (7 ft). The location of the eastern Wellsville fault is 1.1 kilometers (3,500 ft) west of the gravel pit, but a landslide lies below the toes of the spits, with the main landslide scarp subparallel to the dominant trend of faults in the pit. Because of the landslide proximity and subparallel trends of the small faults and main landslide scarp, I believe the deformation in the gravel pit results from failure of spit foreset beds along the main landslide scarp rather than from faulting along the Wellsville fault. I do not recommend trenching at this site.

Assuming that the 15 meters (50 ft) of displacement observed near Deep Canyon occurred during the past 100,000 years (the estimated minimum age of the faulted alluvial-fan deposits), the maximum slip rate for the Wellsville fault since the late Pleistocene is 0.15 mm/yr (0.0059 in/yr). For comparison, average slip rates for the southern segment of the ECFZ are 0.47 to 0.8 mm/yr (0.019-0.03 in/yr) since Miocene extension of Cache Valley began (Evans, 1991) and 0.010 to 0.067 mm/yr (0.0004-0.003 in/yr) since the early Pleistocene (McCalpin, 1994).

Nearby Faults

Quaternary faults in three nearby areas may also be associated with the WCFZ, but they have not been previously included because of their lack of demonstrable continuity with the WCFZ and lack of paleoseismic data. Although I found no conclusive evidence to clarify this relationship, the nearby faults are mapped and discussed here to provide a complete picture of surficial geology in the gap between the maps of the adjacent WFZ (Personius, 1990) and ECFZ (McCalpin, 1989). The nearby faults include, from north to south, the Dayton and Hyrum faults and several faults in the Mantua area (figure 2). The Dayton and Hyrum faults are down-to-the-east normal faults in, respectively, north-central and southern Cache Valley; the Mantua faults are down-to-the-basin normal faults that bound small intermontane basins in the southern Wellsville Mountains and northern Wasatch Range.

Bjorklund and McGreevey (1971) identify another structure, named the Newton fault by Dames and Moore (1985), parallel to and west of the Dayton fault in central Cache Valley. However, the Newton fault is not mapped in other studies (Williams, 1948, 1958, 1962; Dover, 1995), and the steep gravity gradient (Peterson and Oriel, 1970), significant displacement of bedrock reflectors in seismic profiles (Evans and Oaks, 1996), and possible surficial evidence that define the Dayton fault are absent along the inferred trace of the Newton fault. The Newton fault undoubtedly is real because of its position adjacent to linear bedrock hills, but the data indicate that the Newton fault does not perceptibly displace Quaternary deposits, even at depth, and I do not show it on my geologic map.

Dayton Fault

The Dayton fault was mapped in reconnaissance by Williams (1948, 1958, 1962) as a buried fault on the eastern, linear edge of hills in central Cache Valley, Utah, 11 kilometers (7 miles) east of the Clarkston fault. Williams (1962) described, but did not map, the northern extension of the Dayton fault beyond the Utah-Idaho border to Red Rock Pass at the northern end of Cache Valley in southern Idaho. This extension, mapped by Bjorklund and McGreevey (1971), includes faulting later mapped by Cluff and others (1974) as the northern part of the WCFZ near Oxford, Idaho. I restrict the Dayton fault to the buried fault in Utah and its northward extension to the intersection with the WCFZ as mapped by Cluff and others (1974). In Utah, the Dayton fault bounds the eastern edge of Bergeson, Big, and Pete McCombs Hills just south of the Utah-Idaho border, and extends southeast to the eastern edge of Little Mountain. This linear bedrock ridge, bounded by the Newton fault on the west and the Dayton fault on the east, is a basement high designated the Little Mountain block by Peterson and Oriel (1970). The block separates two deep troughs in northern Cache Valley, the Clarkston trough to the west and the Cache Valley trough to the east, filled by 2,100 to 2,400 meters (7,000-8,000 ft) of Cenozoic strata.

The Dayton fault is 37 kilometers (23 mi) long, of which 16 kilometers (10 mi) are in Utah. The fault includes several branches in Idaho, but in Utah the fault is a single down-to-the-east, concealed normal fault. Exposed rock on the Little Mountain block is predominantly of the Tertiary Salt Lake Formation (unit Tu), although underlying Cambrian rock (unit M€r) is exposed on the northeastern flank of Little Mountain. Pleistocene unconsolidated deposits, particularly those of Lake Bonneville (units lbg, lbs, lbm, lpg, lps, lpm, and lbpm), overlap the bedrock and conceal the fault. The range front is linear, with linearity emphasized by the Provo shoreline of Lake Bonneville, but triangular faceted spurs are absent.

I found no evidence of displaced Quaternary surficial deposits related to the Dayton fault, consistent with the continuity of Lake Bonneville deposits overlying the Dayton fault found by Keaton (1984) in his study of a potential reservoir site in the region. Williams (1962) reports brecciation of rocks in the Salt Lake Formation on the eastern side of Bergeson Hill and Little Mountain (referred to by Williams [1962] as Newton Hill), and several small faults in rock along Bergeson Hill, but maps the Dayton fault as concealed beneath Quaternary deposits. Dover (1995) maps faulted Tertiary bedrock on the eastern side of Little Mountain, and I observed several small faults and tilted beds in Lake Bonneville deposits (unit lpg) exposed in the wall of a gravel pit on the southeastern edge of Little Mountain in the SW1/4 section 10, T. 13 N., R. 1 W. However, I relate all of this deformation to failure near the main scarp of mapped landslides (unit clsy), similar to deformation in the gravel pit near Pine Canyon along the Wellsville fault. I inspected a 1-meter (3-ft) deep trench across the buried Dayton fault trace on the side of Pete McCombs Hill in the SE1/4 section 17, T. 14 N., R. 1 W., presumably excavated for irrigation or drainage, and observed an unbroken sequence of Lake Bonneville beds (units lpg and lps) along the entire 300-meter (1,000-ft) trench length. Several warm springs and associated spring deposits (the largest of which I map as unit st) are aligned at the base of the hills in sections 8, 28, and 33, T. 14 N., R. 1 W., and section 3, T. 13 N., R. 1 W. In the absence of surficial evidence for faulting in Quaternary deposits, I attribute the spring alignment either to discharge from an unconfined aquifer at its intersection with the ground surface along the range front, discharge through a leaky confining layer near the edge of a zone of artesian pressure, or discharge through a faulted confining layer beneath unfaulted, permeable Bonneville lakebeds. Because of the absence of surficial evidence for the Dayton fault and the ambiguity of its subsurface location, I do not recommend trenching along the Dayton fault.

Evans (1991, plate 4C) shows 400 meters (1,300 ft) of net slip at the base of the Tertiary section on the Dayton fault east of Big Hill, determined from seismic-reflection profiles. From this data, I calculate an average slip rate of 0.02 to 0.04 mm/yr (0.0008-0.002 in/yr) since Miocene extension of Cache Valley began. For comparison, average slip rates for the northern segment of the ECFZ are 0.16 to 0.36 mm/yr (0.0063-0.014 in/yr) during the same time interval (Evans, 1991).

Hyrum Fault

The Hyrum faults were first mapped by Williams (1948) as a pair of northwest-trending, down-to-the-east normal faults. These faults displace Paleozoic and Tertiary rocks truncated by a Pleistocene pediment referred to by Williams (1948) as the McKenzie Flat surface, ranging in elevation from about 1,700 to 1,800 meters (5,500-6,000 ft). The western fault was also mapped by Williams (1958) and Dover (1995), and it is this fault that I refer to here as the Hyrum fault. The eastern fault, renamed the Willow Grove fault by Williams (1962) and remapped by McCalpin (1989), lies beyond the eastern boundary of my map.

The linear Hyrum fault is in the southeastern Wellsville Mountains and is 7 kilometers (4 mi) long, of which the northern 5 kilometers (3 mi) are in the map area. At its northern end, the concealed projection of the fault is terminated by the concealed Wellsville fault along the range front. A 2 kilometer (1 mi) length of the fault near its northern end displaces bedrock beveled by the overlying McKenzie Flat erosional surface, with Paleozoic sedimentary rocks (unit PPr) in the footwall and Tertiary sedimentary rocks (unit Tu) in the hanging wall. Beyond this bedrock displacement, the fault is alternately concealed beneath Tertiary rocks and exposed displacing Paleozoic rocks. In exposed rock, the fault scarp is roughly linear but subdued. The fault does not displace Lake Bonneville sand and gravel (unit lbg) at its northern end, nor does it appear to displace post-Bonneville stream alluvium (unit aly) in channels to the south. Dover (1995) maps additional displacement in Tertiary rocks near the southern end of the Hyrum fault, north of its termination by a northwest-trending normal fault in bedrock, but these rocks are not in my map area.

The youngest rocks demonstrably displaced by the Hyrum fault are of Tertiary age. However, the intermittent fault exposures and their association with outcrops of Paleozoic rock suggest preferential erosion of the softer Tertiary rock along the fault. The fault is preserved only in the more resistant outcrops of Paleozoic rock or along the faulted contact between Paleozoic and Tertiary rocks. Additionally, most fault exposures are along canyon walls or ridge slopes below the McKenzie Flat surface. Along ridge crests, the overlying erosional surface is commonly continuous and unfaulted; where scarps are locally found along ridge crests, they probably represent differential erosion in resistant bedrock, rather than a scarp that offsets the erosional surface.

The McKenzie Flat surface is estimated by Williams (1958) to be of Pleistocene age and, thus, the latest displacement along the Hyrum fault must have occurred between deposition of Tertiary rocks and their erosion during the Pleistocene. Later fault inactivity is demonstrated by the lack of displacement in Lake Bonneville deposits and younger alluvium, and by termination of the Hyrum fault by transverse faults at both ends. As previously discussed, the Wellsville fault to the north was active in the Pleistocene, but probably not in the Holocene. The unnamed fault to the south, an extension of faults in the Mantua area discussed below, is exposed only in bedrock and was also apparently inactive during the Holocene. For these reasons, I do not recommend trenching across the Hyrum fault. Because of differential erosion between faulted outcrops of resistant Paleozoic rock and softer Tertiary rock across the scarp, and because of insufficient stratigraphic control, a slip rate for the Hyrum fault was not determined.

Mantua Faults

The faults near Mantua were first studied by Gilbert (1928) in his classic examination of geologic structure in the Basin and Range province. Gilbert (1928) believed that Mantua Valley and small basins in a linear topographic depression to the northwest, which he called the Dry Lake trough, were in a graben with longitudinal boundary faults aligned with the trough axis. Williams (1948) first mapped the geology of northern Mantua Valley and the Dry Lake trough, but attributed the physiography of the basins to stream erosion along transverse faults followed by subsequent carbonate dissolution and collapse to form sinkholes; he found no evidence of longitudinal faults. Crittenden and Sorensen (1985) mapped the remainder of the Mantua faults from Mantua southward in detail, indicating some Quaternary displacement along predominantly longitudinal faults. Personius (1990) included the area both north and south of Mantua in his geologic map of the Brigham City segment of the WFZ, with the Mantua faults mapped in reconnaissance as longitudinal, but only along the west side of the basins. Dover (1995) mapped northern Mantua Valley and the Dry Lake trough in greater detail, returning to the graben interpretation of Gilbert (1928). My interpretation of the Mantua faults follows that of Crittenden and Sorensen (1985) and Dover (1995), with exceptions noted below.

The Mantua faults are a network of anastomosing faults within small intermontane basins of the southern Wellsville Mountains and northern Wasatch Range. The fault zone extends a distance of 23 kilometers (14 mi) from the head of Wellsville Canyon in the north to the North Fork of the Ogden River in the south. Distinctive geologic and physiographic features characterize various parts of the fault zone. These features include, from north to south: (1) an asymmetric valley (west of Wellsville Canyon), (2) an equidimensional basin (the sinkhole south of Babbitt Shanty Hill), (3) Paleozoic bedrock hills (from Sardine Summit to Round Hill), (4) an embayment of the Bonneville basin (Mantua Valley), (5) more Paleozoic bedrock hills (between Mantua and Devils Gate Valleys), and (6) three basins underlain by Tertiary bedrock (Clay and Devils Gate Valleys and the intervening sinkhole). With the exception of the Bonneville embayment, all parts of the Mantua fault zone are above the highest shoreline of Lake Bonneville. Each part of the fault zone is bounded by longitudinal, down-to-the-basin normal faults concealed along linear range fronts, and the parts are primarily separated from each other by transverse normal faults. The fault zone generally trends northwest-southeast, but the trend of the southernmost part of the fault zone is north-south, changing at a large northeast-trending transverse fault that bounds the southern edge of Clay Valley. Transverse faults are commonly terminated by longitudinal faults, but the Clay Valley fault terminates some longitudinal faults near its eastern extremity.

In the north, from Wellsville Canyon to a reentrant formed by Babbitt Shanty Hill, an asymmetric valley is bounded by Paleozoic bedrock (units MЄr and PIPr). Units in the valley include post-Bonneville unconsolidated material (units afy, ca, la, and laly) and isolated knobs of Tertiary sedimentary rock (unit Tu). A piedmont slope on the western side of the valley with surficial post-Bonneville alluvial-fan deposits (unit afy) is presumably underlain by older alluvial fans (unit afo) that give the slope its shape and skew the valley axis to the east along the range front. Between Babbitt Shanty Hill and a bedrock sill near Sardine Summit to the south, a roughly equidimensional, flat-floored basin is also bounded by Paleozoic bedrock, but surficial material within the basin includes only post-Bonneville units, and Tertiary rock is absent. From the sill southward to Mantua Valley, Paleozoic bedrock hills separated by colluvium-covered slopes lie within the basin. Ash exposed in a road cut here was identified by Oviatt (written communication referenced in Sullivan and others [1988]) as the Lava Creek B Ash, deposited about 620,000 years ago (Christiansen, 1979), indicating that at least some of the sediments filling these basins date from the middle Pleistocene.

The Mantua Valley floor, around the margin of Mantua Reservoir, is underlain by Lake Bonneville sediment (unit lbg) deposited when the valley was a shallow embayment connected to the main body of Lake Bonneville in the Bear River Valley by a strait through Box Elder Canyon. Lake deposits are surrounded by alluvial-terrace deposits of Box Elder Creek (units alb and alp) and pre- and post-lake fan alluvium (units afo and afy). Paleozoic bedrock hills are predominant southeast of Mantua Valley, but Tertiary sedimentary rock either crops out or is found beneath shallow colluvium in small basins near the south end of the Mantua fault zone, including Clay Valley, Devils Gate Valley, and the intervening unnamed sinkhole.

I found no displacement of surficial Quaternary deposits by the Mantua faults in this study. Personius (1990) mapped Quaternary displacement in Holocene to middle Pleistocene undifferentiated alluvium and colluvium along the western boundary fault near the head of Wellsville Canyon. Range-front linearity, faceted spurs, disrupted drainage, valley asymmetry, and the thick wedge of alluvial-fan deposits indicate significant uplift along the fault during the Quaternary, probably continuing into the late Pleistocene, but I found no evidence of displacement in post-Bonneville alluvial fans at the mouths of several canyons along the range front. Sullivan and others (1988) inferred late Quaternary displacement on western boundary faults along most of the fault zone from similar geomorphic evidence, but I did not find displaced post-Bonneville deposits elsewhere and doubt Holocene activity. Crittenden and Sorensen (1985) mapped Quaternary displacement of colluvium and slopewash along several faults east and northeast of Devils Gate Valley, but I reinterpret the faulting as concealed beneath Quaternary colluvium (unit ca) adjacent to either linear bedrock scarps or buried linear bedrock ridges. The topography again suggests Quaternary movement, but I agree with Sullivan and others (1988) who concluded that there was no late Quaternary displacement in this area.

With the exception of the Clay Valley fault, transverse faults are probably older than, or contemporaneous with, longitudinal faults. Transverse fault scarps are only in bedrock and, where projected through surficial deposits, are typically mapped on the basis of subdued bedrock scarps and crude alignments of bedrock hills. The scarp along the range front at the south edge of Clay Valley, however, is much sharper and continues both northeast and southwest of the valley in linear stream channels. This morphology and the continuity of the Clay Valley fault across longitudinal faults of suspected Quaternary age indicate that the Clay Valley fault is also of Quaternary, probably Pleistocene, age. This differs with the interpretation of Sullivan and others (1988, plate 1A) who do not include the Clay Valley fault on their map of faults exhibiting evidence of Quaternary displacement.

Although I do not suspect Holocene activity along the Mantua faults, I recommend three areas for further investigation and possible trenching to provide conclusive evidence for timing of fault movement. These areas are: (1) the linear range front near the head of Wellsville Canyon at the north end of the Mantua fault zone, with Pleistocene alluvial fans buried by Holocene fan deposits; (2) the linear range front along the southern edge of Clay Valley, filled by colluvium-covered Tertiary bedrock; and (3) the eastern margin of Devils Gate Valley, with Quaternary colluvium and alluvium overlying linear fault scarps along bedrock ridges. Additional paleoseismic data are needed to determine slip rates for the Mantua faults.

SUMMARY

The WCFZ in Utah extends 56 kilometers (35 mi) along the western edge of Cache Valley from the Utah-Idaho border to 6 kilometers (4 mi) southeast of Wellsville. The fault zone includes three faults that are, from north to south, the Clarkston, Junction Hills, and Wellsville faults. All three faults were probably active in the late Pleistocene, with the most recent activity no older than latest Pleistocene along the Junction Hills fault during occupation of the valley by Lake Bonneville, and possibly that young along the Clarkston fault. Maximum displacement along the Clarkston fault since the latest Pleistocene may be as much as 9 meters (30 ft), estimated from differences in elevation of the Bonneville shoreline near the Clarkston and Junction Hills faults. Maximum displacement along the Junction Hills fault since the latest Pleistocene is 2.4 meters (8 ft), measured at a fault exposure in Lake Bonneville deposits. The lack of fault scarps in Holocene deposits across the Clarkston fault shows that this fault has likely not been active in the Holocene. Repeated plowing of fault scarps in latest Pleistocene deposits across the Junction Hills fault destroyed evidence for the age of the most recent event along this fault, but faulting is at least as young as latest Pleistocene. Subdued range-front morphology along the Wellsville fault indicates the absence of Holocene activity for this fault. However, surficial evidence for the age of surface rupture in some locations along the WCFZ is ambiguous. I propose trench locations at Raglanite and Winter Canyons along the Clarkston fault, near the faulted stream cut along the Junction Hills fault, and at Deep Canyon along the Wellsville fault to provide conclusive evidence for the size and timing of earthquakes along the WCFZ.

An east-west-trending transverse, normal fault near Short Divide at the southern end of Clarkston Mountain separates Paleozoic from Tertiary rocks by an estimated 3,000 meters (10,000 ft) of stratigraphic throw. The concealed projection of this fault obliquely intersects the juncture of the Clarkston and Junction Hills faults. The difference in Bonneville shoreline elevations across the fault projection implies independent surface rupture of the Clarkston and Junction Hills faults. The Short Divide fault is an apparent segment boundary and indicates that the Clarkston fault is a seismically independent structural segment of the WCFZ. Evidence for segmentation between the Junction Hills and Wellsville faults is inconclusive.

The maximum slip rate for the Clarkston fault since the latest Pleistocene (0.54 mm/yr [0.021 in/yr]), calculated from the differential elevation of the Bonneville shoreline across the segment boundary, is considerably greater than slip rates calculated for the other sections of the WCFZ (0.11 to 0.16 mm/yr [0.0043-0.0063 in/yr]). However, shoreline elevations may have been affected by movement on the Junction Hills fault or WFZ, resulting in an overestimate of the Clarkston fault slip rate. The sharp range-front morphology along the Clarkston fault compared to fault morphology elsewhere in the WCFZ, though, suggests that paleoseismicity along the Clarkston fault was more active than other faults in the WCFZ during the Quaternary. The inferred paleoearthquake magnitude along the Clarkston fault, calculated from surface rupture length, is 6.2.

Faults in three other areas also either exhibit Quaternary displacement or may have been active during the Quaternary. These faults are, from north to south, the Dayton fault, the Hyrum fault, and faults near Mantua. Paleoseismic and physical evidence for their inclusion within the WCFZ is lacking, but their mapping and description is important to understand the paleoseismicity of the region. The Dayton fault bounds the eastern side of an uplifted bedrock block in central Cache Valley. The fault does not displace Holocene surficial deposits, but the linear range front suggests fault activity during the Pleistocene. The Hyrum fault is at the southern end of the Wellsville fault. The youngest deposits displaced by the Hyrum fault are Tertiary, an overlying Pleistocene erosional surface is not faulted, and the northern end of the Hyrum fault is truncated by the Wellsville fault. Most recent activity along the Hyrum fault may be Pleistocene but older than the Wellsville fault.

The Mantua faults bound a linear topographic depression in the southern Wellsville Mountains and northern Wasatch Range. The fault zone consists of longitudinal faults along the depression boundaries and transverse faults across the depression. No faults displace surficial deposits, but scarp morphology of longitudinal faults suggest late Pleistocene movement. Scarp morphology of transverse faults and their common truncation by

longitudinal faults show that transverse faults are either contemporaneous with or older than longitudinal faults, with the exception of the Clay Valley fault. The continuity and scarp morphology of this fault suggest late Pleistocene movement.

Although a Pleistocene age is indicated for the most recent activity along the Dayton, Hyrum, and Mantua faults, evidence for the age of most recent faulting along the Mantua faults is less conclusive and may be younger. I propose trench locations at the head of Wellsville Canyon, the southern edge of Clay Valley, and the eastern margin of Devils Gate Valley to provide additional evidence for the size and timing of earthquakes in the Mantua area.

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APPENDIX

DESCRIPTION OF MAP UNITS

LACUSTRINE DEPOSITS

Lacustrine 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 Bonnevelle lake cycle) in the Bonneville basin and deposited in younger lakes, marshes, and slow-moving streams. Lacustrine deposits in the map area are divided by age into four groups: (1) deposits that post-date the Bonneville lake cycle (younger than 12,000 ^{14}C yr B.P.), (2) deposits associated with the Provo shoreline and the regressional phase of the lake cycle (14,500 to 12,000 ^{14}C yr B.P.), (3) deposits associated with the Bonneville shoreline and the transgressional phase of the lake cycle (30,000 to 14,500 ^{14}C yr B.P.), and (4) undivided Bonneville-lake-cycle sediments deposited topographically below the Provo shoreline that cannot be assigned to either phase of the Bonneville lake cycle (30,000 to 12,000 ^{14}C yr B.P.). Lacustrine sediments deposited near mountain fronts are mostly gravel and sand; silt and clay were deposited in quieter, deeper water on the Cache Valley (lake) bottom, in a sheltered bay behind headlands, in intermontane ephemeral lakes, and less commonly in lagoons behind barrier beaches.

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

ly **Younger lacustrine and marsh deposits** - Silt, clay, and minor sand deposited in intermontane ephemeral lakes in sinkholes near Mantua Reservoir and in marshes, slow-moving streams and oxbow lakes along the lower reaches of the Bear, Little Bear, and Logan Rivers. Associated with areas of high water table. Commonly organic rich; locally may contain peat deposits as thick as 1 meter (3 ft). Commonly overlies, grades into, and is reworked from fine sediment of the Bonneville lake cycle (unit lbpm), and may contain Lake Bonneville sediment. Thickness variable, typically 1 to 3 meters (3-10 ft).

laly **Lacustrine, marsh, and alluvial deposits, undivided** - Undivided sand, silt, and clay in areas of mixed lacustrine, paludal, and alluvial environments. Mapped in intermontane basins near Mantua Reservoir; along the lower reaches of the Bear, Little Bear, and Logan Rivers; and near the juncture of Clarkston Creek and Newton Reservoir. Thickness variable, typically 1 to 3 meters (3-10 ft).

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

lpd **Deltaic deposits** - Clast-supported pebble and cobble gravel in a matrix of sand and minor silt, interbedded with thin sand beds, grading downslope to silt and fine sand in the distal portion of deltas. Moderately to well sorted within beds; clasts subround to round; weakly cemented by calcium carbonate. Deposited as foreset beds with original dips of 30 to 35 degrees and as bottomset beds with original dips of 1 to 5 degrees. Locally capped with undifferentiated topset beds less than 5 meters (16 ft) thick of less well sorted, silty to sandy, pebble and cobble alluvial gravel. Mapped in the northeast corner of the map area in the distal Bear River delta, east of Wellsville in the distal Blacksmith Fork delta (McCalpin, 1989), and at the mouths of Wellsville Canyon and Willow Creek. Exposed thickness less than 25 meters (82 ft).

lpg **Lacustrine gravel and sand** - Clast-supported pebble and cobble gravel, in a matrix of sand and minor silt. Commonly interbedded (sometimes rhythmically) with thin sand beds and laterally gradational to lacustrine sand. Well sorted within beds, clasts commonly subround to round, but some shorelines marked by a poorly sorted beach conglomerate consisting of angular boulders as much as several meters in diameter in a sandy, calcium-carbonate-cemented matrix. Thin to thick bedded; bedding ranges from horizontal to original dips of 10 to 15 degrees on steep piedmont slopes or in constructional landforms such as beach ridges, bars, and spits. The most prominent constructional landforms underlain by unit lpg are the Sterling bar (Williams, 1962) that crosses the south end of Cache Valley south of Wellsville and a spit nearly 1 mile (2 km) long west of Wellsville. Mapped at and below the Provo shoreline, grading downslope into deposits of map unit lps. Typically forms wave-built bench at the highest Provo shoreline and several less well-developed shorelines at lower elevations. Exposed thickness less than 5 meters (16 ft).

lps **Lacustrine sand and silt** - Coarse to fine sand, silt, and minor clay. Rhythmic bedding common; well sorted within beds; thin bedded; ripple laminations common; bedding ranges from horizontal to original dips of as much as 10 degrees. Deposited in relatively shallow water near shore during regression of Lake Bonneville; generally overlies fine-grained, deep-water, transgressive silt and clay (unit lbm) and grades downslope into undivided transgressive and regressive silt and clay (unit lbpm). Mapped at and below the Provo shoreline, most extensively downslope of the Sterling bar near Wellsville. Forms beaches, bars, and spits where longshore current and supply of material were adequate. Exposed thickness less than 10 meters (33 ft).

lpm **Lacustrine silt and clay** - Predominantly calcareous silt (commonly 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 either near shore in areas underlain by fine-grained bedrock west of Trenton, where unit includes minor sand and gravel, or in a quiet-water environment such as a sheltered bay or lagoon behind a spit east of Wellsville. Shorelines not developed on this unit. Exposed thickness less than 5 meters (16 ft).

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 minor silt; interbedded with thin sand beds; moderately to well sorted within beds; clasts subround to round; weak carbonate cementation common. Deposited as foreset beds with original dips of 30 to 35 degrees; mapped only at the apex of the fan-delta complex which extends westward beyond the map boundary along Cottonwood Creek (Oviatt, 1986a). Exposed thickness less than 5 meters (16 ft).

lbg **Lacustrine gravel and sand** - 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 15 degrees. Clasts commonly subround to round, but shorelines along steep mountain fronts locally marked by a poorly sorted beach conglomerate consisting of angular boulders as much as several meters in diameter in a sandy, calcium-carbonate-cemented matrix. Deposited in beaches, bars, and spits. Mapped between the Bonneville and Provo shorelines, grading downslope into units lbs and lbm; typically forms wave-built benches at the highest (Bonneville) shoreline, and several less well developed intermediate shorelines. Exposed thickness less than 20 meters (66 ft).

lbs **Lacustrine sand and silt** - Coarse to fine sand, silt, and minor clay; typically rhythmically bedded; good sorting within beds; ripple laminations common; bedding ranges from horizontal to original dips as much as 10 degrees. Deposited as nearshore sediments in beaches and spits. Commonly mapped between deposits of unit lbg upslope and the Provo shoreline downslope, but grades downslope into finer grained deposits of unit lbm northeast of Clarkston. Exposed thickness less than 10 meters (33 ft).

lbm **Lacustrine silt and clay** - Predominantly calcareous silt (commonly referred to as marl), with minor clay and fine sand; thick bedded to massive. Blocks of silt and clay are dense and have conchoidal fractures. Deposited either near shore in small lagoons south of Wellsville and in areas underlain by fine-grained bedrock on Pete McCombs Hill, where unit includes minor sand and gravel, or in a quiet-water environment such as the sheltered bay between headlands northeast of Clarkston. Commonly overlies sandy deposits (unit lbs), implying deposition in increasingly deeper or quieter water of a transgressive lake. Shorelines not developed on this unit. Exposed thickness less than 5 meters (16 ft).

UNDIVIDED DEPOSITS OF THE BONNEVILLE LAKE CYCLE (UPPER PLEISTOCENE)

lbpm **Lacustrine silt and clay** - Silt, clay, and minor fine sand of the Bonneville lake cycle; commonly thick bedded; deposited in deep and (or) quiet water on the basin floor. Indistinct shorelines preserved where not destroyed by cultivation. Usually in gradational contact with unit lps upslope and units laly, als, and al1 downslope, and may contain small deposits of these units. Estimated maximum thickness 15 meters (49 ft).

ALLUVIAL DEPOSITS

These deposits consist of variable amounts of gravel, sand, and silt, and minor amounts of clay, deposited by perennial and intermittent streams and debris flows. Map units are separated into six deposits of stream (floodplain and terrace) alluvium and four alluvial-fan deposits.

DEPOSITS OF STREAM ALLUVIUM

Stream deposits are mapped on floodplains 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 with a clast-supported framework. Stream deposits are differentiated by: (1) their positions relative to levels of the Bonneville lake cycle and modern streams and (2) grain size.

al1 **Stream alluvium, unit 1 (upper Holocene)** - Pebble and cobble gravel, gravelly sand, silty sand, and minor clay; moderately sorted; clasts subangular to rounded; thin to medium bedded. Deposited by perennial streams such as Bear River, Cub River, Little Bear River, and Logan River, where finer grained deposits predominate on the Cache Valley floor, and Box Elder Creek and Newton Creek, where coarser grained deposits predominate on steeper slopes. May include minor sheetwash and slump deposits overlying alluvium along steep stream embankments. Forms floodplains and low terraces less than 5 meters (16 ft) above modern stream level. Floodplains characterized by bar and swale topography and active stream channels. Deposits along Bensons Hollow, Coldwater Canyon, Raglanite Canyon, and Shumway Canyon grade downslope into upper Holocene alluvial-fan deposits (unit af1). Exposed thickness less than 5 meters (16 ft).

al2 **Stream alluvium, unit 2 (middle Holocene to uppermost Pleistocene)** - Pebble and cobble gravel, gravelly sand, silty sand, and minor clay; moderately sorted; clasts subangular to rounded; thin to medium bedded. Deposited by perennial streams such as Bear River, Cub River, Little Bear River, Logan River, and the ancestral Clarkston Creek at its junction with Newton Creek near present-day Newton Reservoir, where finer grained deposits predominate on the Cache Valley floor, and Box Elder Creek and Newton Creek, where coarser grained deposits predominate on steeper slopes. Forms terraces more than 5 meters (16 ft) above modern stream level; terrace surfaces characterized by subdued bar-and-swale topography. Terraces are inset into Bonneville-lake-cycle lacustrine sand, silt, and clay (units lps and lbpm), except along Box Elder Creek where the terrace of unit al2 is inset into an older alluvial terrace (unit alp). Exposed thickness less than 5 meters (16 ft).

aly **Younger stream alluvium, undivided (Holocene to uppermost Pleistocene)** - Pebble and cobble gravel, gravelly sand, silty sand, and minor clay; undivided stream alluvium (units al1 and al2) that postdates regression of Lake Bonneville from the Provo level. Grades downslope into unit af1 at the mouth of Wellsville Canyon and into unit afy at the mouth of Sardine Canyon. Includes small areas of hillslope colluvium. Mapped along ancestral channels of the Bear and Little Bear Rivers near Cutler Reservoir, where the intermediate position of unit aly between younger and older alluvium (units al1 and al2) prevents precise age assignment; on elevated alluvial terraces along Newton Creek, where a similar intermediate position also prevents precise age assignment; and along Clarkston Creek and numerous smaller perennial and intermittent streams in mountain canyons, where insufficient relief prevents distinguishing late Holocene from older deposition. Exposed thickness less than 10 meters (33 ft).

als **Alluvial sand and silt of natural levees (middle Holocene to uppermost Pleistocene)** - Silty sand and sandy silt, with minor clay; sand fine to medium grained, moderately well sorted, subangular to subround; thin to medium bedded. Deposited by the Bear River as its channel was incised through the Bear River delta (unit lpd); the river overflowed its normal banks downstream and deposited its load of deltaic sand and silt in embankments (levees) adjacent to the floodplain. Overlies Bonneville-lake-cycle lacustrine sand, silt, and clay (units lpd, lps, and lbpm). Exposed thickness less than 5 meters (16 ft).

alp **Stream alluvium related to the Provo phase of the Bonneville lake cycle (uppermost Pleistocene)** - Pebble and cobble gravel, gravelly sand, silty sand, and minor clay; moderately sorted;

clasts subangular to rounded; thin to medium bedded. Deposited by streams graded to the Provo shoreline (unit lpg) at Narrow Canyon and by equivalent-age streams at Box Elder Creek on terraces above a younger alluvial terrace (unit al2) and inset into an older alluvial terrace (unit alb). Exposed thickness less than 5 meters (16 ft).

alb **Stream alluvium related to the Bonneville phase of the Bonneville lake cycle (upper Pleistocene)** - Pebble and cobble gravel, gravelly sand, silty sand, and minor clay; moderately sorted; clasts subangular to rounded; thin to medium bedded. Deposited by streams graded to the Bonneville shoreline (unit lbg) at Box Elder Creek, south of Mantua Reservoir, where deposits of this unit are on the highest of four adjacent terrace levels (units al1, al2, alp, and alb). Exposed thickness less than 5 meters (16 ft).

ALLUVIAL-FAN DEPOSITS

Alluvial-fan deposits are present on the piedmont (alluvial apron at the mountain front), typically at the mouths of ephemeral streams; fan deposits are thickest along the base of the mountain front, on the downthrown side of the West Cache fault zone and nearby faults. The sediment is commonly poorly sorted with a matrix-supported framework. Fan deposits are differentiated by: (1) their positions relative to levels of the Bonneville lake cycle and modern streams, (2) degree of soil development, and (3) morphologic expression, such as degree of preservation of initial surface morphology or degree of dissection.

af1 **Fan alluvium, unit 1 (upper Holocene)** - Pebble and cobble gravel, bouldery near bedrock outcrops, in a matrix of sand, silt, and minor clay; poorly sorted; clasts angular to subrounded, with sparse rounded clasts from gravel (unit lbg) of the Bonneville lake cycle; medium to thick bedded to massive. Deposited by intermittent streams, debris floods, and debris flows graded to modern stream level. Forms small, coalescing fan complexes at the base of the Washboards along Clarkston Creek; small, steep alluvial cones on older alluvial fans (unit afy) at canyon mouths at the base of Clarkston Mountain; and discrete fans that bury lacustrine deposits (units lbg, lbs, lpg, and lps) along the Wellsville Mountains front. 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. Typically thins downslope; exposed thickness less than 5 meters (16 ft).

af2 **Fan alluvium, unit 2 (middle Holocene to uppermost Pleistocene)** - Pebble and cobble gravel, bouldery near bedrock outcrops, in a matrix of sand, silt, and minor clay; poorly sorted; clasts angular to subrounded, with sparse rounded clasts from gravel (unit lbg) of the Bonneville lake cycle; medium to thick bedded to massive. Deposited by intermittent streams, debris floods, and debris flows graded to and just above modern stream level. Forms fans that bury lacustrine shoreline sediments (units lpg, lps, lbg, and lbs) at several canyon mouths near Clarkston and Cache Butte, and at Deep Canyon and Pullum Hollow; preserved downslope from distal portions of a younger alluvial fan (unit af1) at Butler Hollow, burying offshore lacustrine sediments (unit lbpm). Locally includes deposits of units cd1 and af1 too small to map separately. No shorelines of Lake Bonneville are present on surfaces formed by this unit. Typically thins downslope; exposed thickness less than 5 meters (16 ft).

afy **Younger fan alluvium, undivided (Holocene to uppermost Pleistocene)** - Pebble and cobble gravel, bouldery near bedrock outcrops, in a matrix of sand, silt, and minor clay; undivided fan alluvium (units al1 and al2) that postdates regression of Lake Bonneville from the Provo level. Forms coalescing fans that bury lacustrine shoreline sediments (units lpg, lps, lbg, and lbs), older alluvial-fan deposits (unit afo), and bedrock (units Tu, M€r, and Zb) along the Clarkston Mountain front, near Big Hill, and from Wellsville south. Mapped in areas where outcrops of units af1 and af2 are complexly overlapping, they are too small to show separately, or the specific age of Holocene alluvial-fan deposits has not been determined. Exposed thickness less than 5 meters (16 ft).

afo **Older fan alluvium, undivided (upper to middle Pleistocene; pre-Bonneville lake cycle)** - Pebble and cobble gravel, locally bouldery, in a matrix of sand, silt, and minor clay; poorly sorted; clasts angular to subrounded, with no recycled gravel of the Bonneville lake cycle; medium to thick bedded to massive. Forms poorly exposed, elevated alluvial-fan deposits above modern streams; dissected fan surfaces lack distinct geomorphic expression. Mapped west of Mendon as a mantle on a gently inclined bench correlative with the McKenzie Flat surface of Williams (1948); along the Clarkston Mountain front possibly underlain by the McKenzie Flat surface in the hanging wall of the Clarkston fault; and on the margins of Mantua and Clay Valleys, derived from the erosive cycle that created the McKenzie Flat surface in adjacent areas. Older fan alluvium is at higher altitude and truncated by the highest shoreline of Lake Bonneville. Exposed thickness less than 10 meters (33 ft).

GLACIAL DEPOSITS

Glacial deposits are preserved in east- and west-facing valleys near the crest of the Wellsville Mountains above 2,100 meters (6,900 ft) and in east- and north-facing valleys in the Wasatch Range above 1,800 meters (5,800 ft). Till forms lateral and terminal moraines; outwash forms terraces graded to the moraines. Glacial deposits are coarse grained, with clasts composed mainly of Paleozoic quartzite (units PIPr and M€r). The deposits are considered to be equivalent to the Bells Canyon advance in Little Cottonwood Canyon (Madsen and Currey, 1979; Scott, 1988), and the Pinedale glaciation of the Rocky Mountains (Porter and others, 1983) on the basis of geomorphic expression (steep slopes and sharp-crested moraines). The distribution of glacial units in the Wellsville Mountains is from Oviatt (1986b), and excludes colluvium and avalanche-debris deposits interpreted as till by Church (1943); the distribution of glacial units in the Wasatch Range is from Crittenden and Sorensen (1985). The mapped distribution is included in the area of glaciation shown by Mulvey (1985).

DEPOSITS OF BELLS CANYON AGE (UPPER PLEISTOCENE, PINEDALE EQUIVALENT)

gbco **Outwash** - Silty cobble to boulder gravel, with minor sand; poorly sorted; clasts are subangular to subround. Mapped only in the Wasatch Range near the head of Box Elder Creek, downslope from moraines of unit gbct. Exposed thickness less than 10 meters (33 ft).

gbct **Till** - Silty to sandy cobble to boulder gravel. Clasts are matrix supported, angular to subround; crudely bedded or massive. Mapped in shallow cirques and a short distance down valley in the Wellsville Mountains at the heads of Brushy, Jim May, Pine, and Shumway Canyons, and in the Wasatch Range at the heads of Box Elder Creek and North Fork Ogden River. Exposed thickness less than 30 meters (100 ft).

SPRING DEPOSITS

st **Spring travertine (upper Holocene)** - Limestone, dense, finely crystalline, massive, cream colored. Mapped southwest of Trenton in a low, rounded cone with a circular, spring-fed pool at its center. Several smaller spring deposits of thin, spongy, calcium carbonate tufa encrustations are present along the range front from Pete McCombs Hill to Little Mountain but are too small to map separately, and are included with units lbpm, lps, and laly. Exposed thickness less than 2 meters (7 ft).

EOLIAN DEPOSITS

es **Eolian sand and silt (Holocene to uppermost Pleistocene)** - Sand, fine to medium grained, and minor silt; siliceous; loose to moderately firm where cemented by secondary calcium carbonate. Mapped near Cornish as dunes locally derived from Lake Bonneville deltaic and post-Bonneville alluvial-levee deposits (units lpd and als). Calcareous, wind-blown silt (loess), primarily latest Pleistocene to early Holocene in age, is locally present as a thin (less than 1 meter [3 ft] thick) mantle on stable geomorphic surfaces elsewhere, but outcrops cannot be differentiated at the map scale; loess is most common as argillic soils on wave-built benches at the Provo level (units lpg and lpm) from Bergeson Hill to Little Mountain. Exposed thickness less than 3 meters (10 ft).

COLLUVIAL DEPOSITS

These deposits consist of poorly sorted to unsorted, gravity-induced deposits; composition of clasts reflects the materials from which they were derived. Debris-flow deposits (unit cd1) are more areally restricted than similar deposits included with fan alluvium (units afo, afy, af2, and af1) and are differentiated from them by surface morphology and position relative to modern stream level and to alluvial-fan deposits of similar age (unit af1).

cd1 **Debris flows, unit 1 (upper Holocene)** - Clast- and matrix-supported cobble and boulder gravel, in a matrix of silt, sand, clay, and minor pebbles; unsorted and unstratified except for sparse interbedded fluvial sand and gravel layers. Surfaces commonly covered with coarse, angular rubble and fresh-appearing levees and channels graded to modern stream level. Commonly deposited on surfaces of upper Holocene alluvial fans (unit af1). Mapped at the mouths of several canyons in Clarkston Mountain and Wide Canyon in the Wellsville Mountains, and on mountain slopes near the sinkhole north of Devils Gate Valley in the Wasatch Range. Exposed thickness less than 10 meters (33 ft).

chs **Hillslope colluvium (Holocene to upper Pleistocene)** - Pebble, cobble, and boulder gravel, gravelly sand, silty sand, sandy silt, and silty clay; commonly unsorted and unstratified except for a basal concentration of clasts; clasts commonly angular to subangular, rarely containing rounded gravel from lacustrine units of the Bonneville lake cycle. Mapped at Sardine Canyon and west of Sardine Summit, where deposits are coarser grained and derived from Paleozoic rocks (units M€r and PIPr) by slope wash and mass-wasting processes on moderate to steep mountain slopes, and at Clay and Devils Gate Valleys and vicinity, where deposits are finer grained and derived from Tertiary basin fill (unit Tu) by slope wash, creep, and weathering of fine-grained deposits on gentler slopes. Includes debris-flow, talus, and landslide deposits too small to show separately. Exposed thickness less than 5 meters (16 ft).

crf **Rock-fall (talus) deposits (Holocene to upper Pleistocene)** - Boulder, cobble, and pebble gravel, commonly clast supported, with a sparse sand and silt matrix; unsorted and unstratified; clasts angular to subangular. Mapped on talus-covered slopes at the head of canyons on Wellsville Cone and Box Elder Peak, and as talus cones in Wellsville Canyon and southeast of Devils Gate Valley. Derived from Paleozoic rocks (units M€r and PIPr) by gravity processes on steep mountain slopes and below canyon walls. Exposed thickness less than 10 meters (33 ft).

clsy **Younger landslide deposits (Holocene to upper Pleistocene)** - Unsorted, unstratified deposits of gravel, sand, and silt; typically slumps and earthflows with main scarps in Tertiary sedimentary rocks (unit Tu), failure of adjacent outcrops of nearshore Lake Bonneville deposits (units lbg, lbs, lpg, and lps), and disruption of the Bonneville shoreline. Younger landslide deposits are common along mountain fronts from Wells-ville northward. Although most deposits were probably formed contemporaneous with latest Pleistocene wave erosion of the Bonneville shoreline, dewatering of oversteepened slopes by rapid lake regression, or earthquakes, some occurred considerably later; these include slumps and flows (possibly liquefaction induced) of lacustrine sand (unit lps) beneath Little Bear River alluvial-terrace deposits (unit al2) east of Mendon formed after Holocene incision by the river to its present level, a large landslide complex on the west side of the Junction Hills with fresh scarps and closed depressions suggestive of recent activity, and a slide block northeast of Devils Gate Valley that appears to be a reactivated part of an older landslide (unit clso). Exposed thickness less than 25 meters (82 ft).

clso **Older landslide deposits (upper Pleistocene to upper Tertiary?)** - Unsorted, unstratified deposits of gravel, sand, and silt; typically slumps and earth flows with main scarps hidden on colluvium-covered slopes; failure is attributed to granular deposits of Tertiary sedimentary rocks (unit Tu), visible in nearby exposures. Mapped only northeast of Devils Gate Valley, where part of an older landslide deposit was reactivated (unit clsy) and nearby landslide debris is morphologically similar. Exposed thickness less than 25 meters (82 ft).

cls **Landslide deposits, undivided (Holocene to middle Pleistocene)** - Unsorted, unstratified deposits of gravel, sand, silt, and bedrock blocks; typically slides, slumps, and earth flows below moderately steep slopes. Slumps and earth flows in Tertiary sedimentary rocks (unit Tu) are mapped along the Clarkston Mountain front south of Clarkston, in the Junction Hills, along the Wellsville Mountains front north of Wellsville, and in the Wasatch Range near Devils Gate Valley; a slump in Paleozoic sedimentary rocks (unit M€r) is mapped in the Wellsville Mountains in Rattlesnake Canyon (in the Manning Canyon Shale; Jensen and King, 1995); and massive block slides in Paleozoic sedimentary rocks (unit M€r) are mapped in the Wellsville Mountains at Stoddard Hill (in the Mississippian Little Flat Formation; Jensen and King, 1995) and near Snow Canyon (in the Devonian Water Canyon Formation; Davis, 1985). Undivided landslide deposits are above the Bonneville shoreline and their relation to Bonneville-lake-cycle deposition is unclear. Exposed thickness less than 25 meters (82 ft).

ca **Colluvium and alluvium, undivided (Holocene to middle Pleistocene)** - Undifferentiated stream and fan alluvium, hillslope colluvium, and small landslide deposits. Mapped in upper reaches of smaller canyons and along larger drainages without distinct slope breaks where colluvium-covered hillsides grade imperceptibly into alluvium-filled valleys. Thickness unknown.

ARTIFICIAL DEPOSITS

f **Artificial fill (historical)** - Consists primarily of locally derived surficial debris excavated during reservoir and highway construction. Mapped at Newton Dam and in the embankment beneath Utah Highway 91 where it crosses the sinkhole south of Wellsville Canyon. Although present throughout the map area, only the largest fill deposits 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 Malad and Wasatch Ranges and Wellsville Mountains. Descriptions of units are summarized from Davis (1985), Dover (1995), and detailed bedrock geologic maps in the area (figure 3), which should be consulted for more information.

Tu **Tertiary sedimentary rocks (Paleogene and Neogene)** - Conglomerate, tuffaceous sandstone and siltstone, freshwater limestone, and tuff. Previously mapped as the Salt Lake Formation (Pliocene and Miocene) and its time equivalents along range fronts north of Mantua, where it may, in part, be of Pleistocene age (Jon King, verbal communication, 1996). Mapped as the Norwood Tuff (Oligocene and Eocene), Wasatch Formation (Eocene and Paleocene), and Evanston(?) Formation (Paleocene and Upper Cretaceous) in the Wasatch Range south of Mantua (Crittenden and Sorensen, 1985).

PIPr **Younger Paleozoic sedimentary rocks (Lower Permian to Pennsylvanian)** - Sandstone, quartzite, and limestone. Mapped primarily as the Oquirrh Formation (Lower Permian to Lower Pennsylvanian) in the Junction Hills and Wellsville Mountains, underlain by the West Canyon Limestone (Lower Pennsylvanian) in the Wellsville Mountains (Oviatt, 1986b).

M€r **Older Paleozoic sedimentary rocks (Mississippian to Cambrian)** - Limestone, dolomite, quartzite, sandstone, siltstone, and shale. Mapped throughout Clarkston Mountain and the Wasatch Range, locally in the Junction Hills, and on the western and southeastern flanks of the Wellsville Mountains. Includes (from top to bottom) Great Blue Formation (Upper Mississippian), Humbug Formation (Upper Mississippian), Deseret Limestone (Upper and Lower Mississippian), Lodgepole Limestone (Lower Mississippian), Beirdneau Formation (Upper Devonian), Hyrum Formation (Upper and Middle Devonian), Water Canyon Formation (Lower Devonian), Laketown Dolomite (Silurian), Fish Haven Dolomite (Lower Silurian and Upper Ordovician), Swan Peak Formation (Middle Ordovician), Garden City Formation (Ordovician), St. Charles Formation (Lower Ordovician and Upper Cambrian), Nounan Formation (Middle Cambrian), Bloomington Formation (Middle Cambrian), Blacksmith Limestone (Middle Cambrian), Ute Limestone (Middle Cambrian), Langston Dolomite (Middle Cambrian), and Geertsen Canyon Quartzite (Lower Cambrian).

Zb **Lower part of Brigham Group (Late Proterozoic)** - Quartzite, sandstone, siltstone, and minor conglomerate and tuff. Mapped in the Wasatch Range at Box Elder and Perry Canyons, and along North Fork Ogden River (Crittenden and Sorensen, 1985). Includes (from top to bottom) Browns Hole Formation, Mutual Formation, Inkom Formation, Caddy Canyon Quartzite, Papoose Creek Formation, and Maple Canyon Formation.

ZYp **Formation of Perry Canyon (Late or Middle Proterozoic)** - Mudstone, sandy mudstone, and slate. Mapped in the Wasatch Range in two small outcrops at the head of North Fork Ogden River (Crittenden and Sorensen, 1985). Includes the basal mudstone member.

Xf **Facer Formation (Early Proterozoic)** - Quartzite, schist, and phyllite. Mapped in the Wasatch Range at the head of North Fork Ogden River (Crittenden and Sorensen, 1985). Includes the quartzite member, the schist and phyllite member, and undifferentiated members of the Facer Formation.

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Related publications from the Utah Geological Survey

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