

from horizontal to original dips of as much as 10° to 15°. Deposited

Tu Tertiary deposits—Consists of sedimentary rocks of the Salt Lake PPr Lower Permian to Pennsylvanian sedimentary rocks—Consists of in the Wellsville Mountains locally includes the West Canyon

> mentary rocks of Mississippian through Cambrian age, including the Middle and Lower Cambrian Tintic Quartzite and the Lower Cambrian Geertsen Canyon Quartzite, which are commonly included in the Brigham Group (Crittenden and Sorensen, Zb Lower part of Brigham Group (Late Proterozoic)—Includes metasedimentary rocks of the Browns Hole Formation, the Mutual Formation, the Inkom Formation, and the Caddy Canyon Quartzite ZXpf Formation of Perry Canyon (Late Proterozoic) and Facer Forma-

Cretaceous) in the Wasatch Range

BEDROCK DEPOSITS

Limestone (Lower Pennsylvanian) (Oviatt, 1986a)

Formation (Pliocene and Miocene) and Wasatch(?) Formation in

the northern Wellsville Mountains, and the Norwood Tuff (Olig-

ocene and upper Eocene), Wasatch Formation (Eocene and

Paleocene), and Evanston Formation (Paleocene and Upper

Oquirrh Formation (Lower Permian to Lower Pennsylvanian), and

tion (Early Proterozoic)—Consists of low- to high-grade metamorphic and metasedimentary rocks. Both formations are very susceptible to landsliding XAfc Farmington Canyon Complex (Early Proterozoic to Archean)-Consists of high-grade metamorphic rocks

 Contact—Dashed where approximately located Normal fault—Bar and solid ball on downdropped side along Wasatch 8(5.5) BC1 fault zone; bar and hollow ball along other faults. Dashed where

approximately located, dotted where concealed, and queried where origin is uncertain. Height of fault scarp and amount of eomorphic surface offset (in parentheses) shown in meters. Trench locations shown with cross bar and abbreviated trench name: BC1, Brigham City trench; PP1, Pole Patch trench Thrust fault—Sawteeth indicate overriding plate or block (mapped in bedrock only); dashed where approximately located, and dotted

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

---B--- Highest shoreline of the Bonneville level ---b--- Other shorelines of the Bonneville level—Mostly transgressive

---p--- Other shorelines of the Provo level—Mostly regressive ---G--- Highest shoreline of the Gilbert level

---x--- Undesignated shorelines of the Bonneville lake cycle Topographic escarpment—Escarpments along stream channels, terraces, and deltas; formed primarily by fluvial processes; may coin-

cide with geologic contacts Landslide escarpment—Major headscarps and fissures in landslides and lateral spread deposits; may coincide with geologic contacts ≠ ≠ ≠ Paleostream channels—Preserved as abandoned channels and debris

Tilted geomorphic surface—Arrow points in general direction of downward tilt

DISCUSSION

INTRODUCTION

This map, the first in a series of maps of the Wasatch fault zone, shows the surfi cial deposits and the faults that offset them along the Brigham City segment and adjacent parts of the Weber and Collinston segments of the Wasatch fault zone in northern Utah. This discussion begins with a summary of the methods used in this study which is followed with a description of the Quaternary deposits found along the Brigham City and adjacent parts of the Weber and Collinston segments, and concludes with a description of the segment boundaries, and the age, size, and distribution of fault scarps found along these segments. Together, this information can be used to begin to describe the paleoseismic history of the mapped segments and to identify key sites for further detailed studies.

Most major normal and strike-slip fault zones are thought to be composed of several seismically independent pieces or segments. Initial work on segmentation of the Wasatch fault zone, summarized in Schwartz and Coppersmith (1984), identified six discrete fault segments, but recent work by the U.S. Geological Survey has identified ten to twelve segments (Machette and others, 1986; Machette and others, 1987). The concept of fault segmentation is critically important to paleoseismic analysis of active fault zones because during a major earthquake, surface faulting usually is restricted to a single segment of the fault. In northern Utah, the Ogden and Collinston segments of Schwartz and Coppersmith (1984) have been separated into three new segments (fig. 1); northward from Salt Lake City, the Weber, Brigham City, and Collinston segments have been delineated (Machette and others, 1986; Personius, 1986; Machette and others, 1987). The size and distribution of fault scarps along the Brigham City and adjacent parts of the Weber and Collinston segments of the Wasatch fault zone are shown on the map; the age of offset surficial deposits and the size of fault scarps can be used to calculate slip rates and average recurrence intervals at various places along this part of the Wasatch Previously published geologic and soils maps exist at various scales for most of

the map area (Erickson and Wilson, 1968; Cluff and others, 1970, 1974; Chadwick and others, 1975; Miller, 1980; Crittenden and Sorenson, 1985a,b; Davis, 1985; Dover, 1985; Oviatt, 1986a). However, I remapped most of the surficial geology along the mountain front because existing maps either were not detailed enough or used outdated stratigraphic terminology. I simplified the surficial geology of the northern end of the Weber segment from unpublished mapping by A.R. Nelson (1986). Most of my mapping was done in the field on 1:12,000-scale low-sun-angle air photos flown for the Utah Geological and Mineral Survey in 1970; these photographs were particularly helpful in identifying fault scarps in surficial deposits. In addition, I used photography from the U.S. Soil Conservation Service flown in the 1950's at scales of 1:10,000 and 1:20,000. The bedrock geology of the uplifted mountain block was compiled and simplified from maps by Crittenden and Sorenson (1985a,b), Davis (1985), Dover (1985), and Oviatt (1986a). The sources of geologic data used in the compilation of this map are listed elsewhere on the plate. The scarp-measurement data shown on the map were derived from slope measurements made in the field with an Abney level and stadia rod; scarp heights and surface offsets were measured from scarp profiles plotted by computer. Terminology used to describe fault-scarp parameters follows that established by Bucknam and Anderson (1979) and Machette (1982).

QUATERNARY DEPOSITS AND DEPOSITIONAL HISTORY This discussion of late Quaternary depositional history of the Wasatch Front is summarized from Scott and others (1983) and Scott and Shroba (1985). Most of the surficial deposits along the northern Wasatch fault zone were deposited during the last cycle of Lake Bonneville (known as the Bonneville lake cycle) between 30 and 10 ka (thousands of years ago) and in the Holocene (<10 ka). Lake Bonneville began rising from a low level about 30 ka and rose slowly, with several fluctuations and pauses, to the Bonneville shoreline (1,585 m (5,200 ft) above sea level) about 16 ka. After 1,000–2,000 years at this level, the lake dropped about 110–115 m (360-380 ft) to an altitude of about 1,470-1,475 m (4,820-4,840 ft) as a consequence of catastrophic downcutting of the threshold at Red Rocks Pass in southeastern Idaho. The resulting Bonneville Flood deposited debris northward onto the Snake River Plain (Gilbert, 1890; Malde, 1968). In the map area, this rapid decline in lake level was accompanied by rapid erosion of Bonneville shoreline sands and gravels (Ibg) and deltaic deposits (Ibd); much of this debris was redeposited as deltas (Ipd, alp) at the Provo shoreline near the mouths of major canyons. Between 14 and 13 ka, the lake level began to drop in response to further downcutting of the Red Rocks threshold, isostatic rebound of shoreline areas, and changing climatic conditions. Lake Bonneville had reached the level of modern Great Salt Lake (1,283 m; 4,210 feet) about 11 ka and rose briefly to the Gilbert shoreline (1,295 m; 4,250 feet) about 10 ka. Since then, the lake level has remained within 10 m of the level of modern Great Salt Lake. As the level of Lake Bonneville receded from the Provo shoreline, alluvial fans

(af2, afp) and debris flows (cd2) were deposited at canyon mouths along the mountain front. Rates of alluvial-fan deposition appear to have declined in later Holocene time in the northern half of the map area, where deposits of late Holocene age (af1, cd1) are restricted to small deposits covering parts of the surfaces of much larger alluvial fans (af2). However, in the southern half of the map area, alluvial deposits of late Holocene age (af1) are much more abundant; most fans are covered by upper Holocene debris. Debris flows (cd1) continue to be a common phenomenon in several of the canyons in the southern part of the map area, as evidenced by the destruction that occurred at the mouths of several canyons during flows in 1912, 1923, 1936, and 1983 (Wieczorek and others,

Pre-Bonneville-lake-cycle deposits are limited to alluvial-fan remnants (af4, af5) preserved in two places in the map area, near Honeyville and Pleasant View. On the basis of soil development, the oldest deposits (af5) are probably several hundreds of thousands of years old; the younger deposits (af4), with less welldeveloped soils, may be 100,000-200,000 years old. The deposits in the Honeyville and Pleasant View areas cannot be physically correlated with each other or with other pre-Bonneville-lake-cycle glacial or lacustrine deposits.

FAULT DESCRIPTIONS

The relatively well dated sequence of Quaternary deposits in the map area greatly aids in the interpretation of Quaternary faulting along the northern Wasatch fault zone. The following discussion includes a brief description of the age, size, and distribution of fault scarps on the Brigham City and adjacent parts of the Weber and inston segments, starting with the southern segment boundary near Nort Ogden, continuing with descriptions of Quaternary faulting on the middle portion of the Brigham City segment, and finishing with a description of the northern segment boundary near Honeyville. A segment boundary exists in the southern part of the map area, 3 km north of

North Ogden (Personius, 1986). The northern part of the Weber segment trends northward along the mountain front east of North Ogden and offsets upper Holocene alluvial-fan deposits (af1) in several places before terminating near the mouth of Barrett Canyon, Preliminary evidence from an excavation at Garner Canyon, just south of the map area, shows two fault movements in the last 2,000 years on this portion of the Weber segment (Nelson and others, 1987). The southern terminus of the Brigham City segment is separated from fault scarps on the Weber segment by a 2 km gap in which no late Quaternary fault scarps are present. This segment boundary has been termed a "nonconservative barrier to Holocene rupture propagation" by Nelson and Personius (1987). The Brigham City-Weber segment boundary is located adjacent to a foundered bedrock block known as the Pleasant View spur (Gilbert, 1928) or salient; this relatively flat topped bedrock outlier is capped with remnants of a middle Pleistocene alluvial-fan complex (af5). Where these fan remnants are not covered by

Bonneville-lake-cycle deposits, the surface is broken by Quaternary normal faults of various orientations. Only two of these faults appear to have displaced Bonneville-lake-cycle deposits At least three other faults on the west flank of the Pleasant View salient postdate the Bonneville lake cycle and trend at approximately right angles to the main trace of the Brigham City segment. These three faults are marked by 3–5 m high scarps formed in Bonneville-lake-cycle lacustrine gravels. The northernmost scarp also appears to cut Holocene fluvial and lacustrine deposits (laly) near Utah Hot Springs. The springs may be localized at the intersection of this young fault and an older buried fault (Davis, 1985) that flanks the west side of the Pleasant View salient. The southernmost scarp offsets Bonneville-lake-cycle deposits and the Provo shoreline, and dies out in the Pleasant View salient. A short trench (PP1) excavated across this scarp shows about 4.5 m of net vertical displacement and evidence for three earthquake-induced surface-faulting events (fault movements

originating on the Weber and (or) Brigham City segments is unknown. The Brigham City-Weber segment boundary is also marked by an apparent change in Holocene faulting activity. Unfortunately, the main trace of the Brigham City segment between the Pleasant View salient and the range front is obscured in most places by thick oakbrush. Where scarps are visible, they are present primarily in deposits of middle to early Holocene age or older. This relationship is in contrast to the numerous scarps formed in deposits of late Holocene age on the Weber segment. Scarps on the Brigham City segment are 3-5 m high in early to middle Holocene aged alluvial- and debris-flow deposits (af2, cd2) near Maguire, Pearsons, and Holmes Canyons and 15–20 m high in Provo-shoreline-equivalent lacustrine (Ipg) and fan-delta (afp) deposits at several places between Pearsons Canyon and Brigham City. These scarp data suggest that high rates of surface faulting occurred in latest Pleistocene to middle Holocene time, but that tectonic activity may have slowed along the Brigham City segment in late Holocene time (Personius, 1986). Thus, the major change in late Quaternary faulting activity between the Weber and the Brigham City segments is the lack of high rates of surface faulting in the late Holocene on the Brigham City segment.

Several scarps have been mapped on the valley floor, west of the main fault trace from Willard to Brigham City. These features are almost always associated with sag-pondlike depressions; additional scarps may have existed, but have been destroyed by cultivation. The scarps may have originated from incipient lateral spread failures like those formed during the 1983 Borah Peak, Idaho earthquake (Youd and others, 1985). However, the Brigham City features parallel the trend of the main fault zone and have 1-2 m of relief, which is consistent with a faulting origin. The only features on the valley floor that I have positively identified as faults are those located in a gravel pit 2.5 km northwest of Willard; remnants of these faults offset Bonneville-lake-cycle gravels (Ibpg) 0.1-1 m. The areal extent of these structures is unknown because of their small displacement and because of extensive landscape modification in the area.

East of Brigham City, the single large scarp on the south side of the delta at the mouth of Box Elder canyon splits into a 0.5 km-wide zone of small, back-tilted fault blocks (fig. 2). The complexity of these back-tilted blocks suggests that they may be controlled in part by slumping. However, total vertical offset across this zone is approximately equal to offset on the single scarp on the south side of the delta. Northward, the fault offsets middle Holocene alluvial-fan deposits about 5-6 m at the mouths of Bott, Bowden, Waterfall, and Kotter Canyons; preliminary results

from a trench excavated across the scarp at Bowden Canyon (BC1) show 3 or 4 faulting events since deposition of these deposits (Personius and Gill, 1987). Total offset on late Quaternary scarps appears to gradually decrease north of Brigham City. Deposits of Provo-shoreline-equivalent alluvium (afp) are offset about 11.5 m on the north side of Baker Canyon and about 4 m east-northeast of Honeyville (6 and 15 km north of Brigham City, respectively). Excavations in a gravel pit 1 km northeast of Calls Fort (12 km north of Brigham City) exposed remnants of a fault zone in lacustrine gravels with two faulted wedges of fault scarp colluvium; these relations indicate at least three earthquake surface-faulting events of undetermined size. Because the Calls Fort gravel pit exposure is located downslope from the Provo shoreline and the fault scarp colluvium has not been subjected to lacustrine reworking, these earthquake surface-events must postdat formation of the Provo shoreline. Schwartz and Coppersmith (1984) based their Ogden-Collinston segment boundary (fig. 1) on the northernmost extent of Holocene faulting on the Wasatch fault zone. Although total offset decreases to the north, evidence indicates that the northern boundary of the Brigham City segment (this study) extends apparent Holocene faulting well beyond Schwartz and Coppersmith's Ogden-Collinston segment boundary.

East of Honeyville, the Brigham City segment changes trend from northwest to northeast and the fault zone is coincident with the steep, talus-covered mountain front. The trace of the fault zone is visible only at the mouth of Two Jump Canyon, where it offsets a pre-Bonneville-lake-cycle alluvial-fan deposit (af5) about 28 m 0.5 km to the northeast, the fault zone appears to terminate in the mountain block The fault reappears to the north in the reentrant at the mouths of Jim May and Coldwater Canyons; here the fault zone trends northwest and forms a graben in similar pre-Bonneville-lake-cycle alluvium (af5). Net offset across this graben is about 12 m. These changes in fault trend and offset of similar-aged deposits (28 m as compared with 12 m) probably mark the location of the Brigham City-Collinston segment boundary

Directly north of the Jim May-Coldwater Canyon graben, the Wasatch fault zone is coincident with the Bonneville shoreline, and is difficult to trace However, about 0.5 km north of Coldwater Canyon, a 2-km-long fault scarp in Provo-shoreline-equivalent alluvium (afp) and Bonneville-lake-cycle lacustrine deposits (lbg) is apparent on low-sun-angle photographs. This is the northernmost post-Provo-shoreline fault scarp recognized along the Wasatch fault zone. The 2-km-long scarp probably represents some extension of tectonic activity across the Brigham City-Collinston segment boundary, because the Collinston segment is characterized by lack of evidence of post-Provo-shoreline faulting for the remainder of its length. This situation may be analogous to the distribution of surface fault ing formed during the 1983 Borah Peak, Idaho, earthquake, where surface faulting appears to have jumped across the segment boundary between the reactivated Thousand Springs segment into the southern portion of the Warm Springs segment of the Lost River fault zone (Crone and Machette, 1984; Scott and others, 1985; Crone and others, 1987).

The Madsen spur (Gilbert, 1928), a bedrock outlier 2 km north of Honeyville, is adjacent to the Brigham City-Collinston segment boundary and shares severa characteristics with the Pleasant View salient and the Brigham City-Weber segment boundary. Two east-northeast-trending fault scarps form a graben on the western flank of the Madsen spur; these faults offset Bonneville-lake-cycle gravels (Ibpg), trend at nearly right angles to the main fault zone, and appear to extend through Crystal (hot) Springs. Sandstone outcrops of Lower Pennsylvanian to Lower Per mian Oquirrh Formation (Oviatt, 1986a) occur at the surface just south of these scarps, whereas thick Bonneville-lake-cycle gravels (Ibpg) are present just to the north. This relationship suggests that an escarpment probably existed prior to the Bonneville lake cycle and the faults appear to be relatively long-lived features. The faults probably continue eastward toward the mountain front, but are masked by lateral spread headscarps. Oviatt (1985, 1986a) interprets the Madsen spur to be a large landslide mass that slid out of the Jim May-Coldwater Canyon reentrant in late Fertiary time along two northeast-trending tear faults in the mountain block; the Wasatch fault zone subsequently stepped eastward, parallel to these tear faults. . The thermal waters of Crystal (hot) Springs may travel upward along the intersection of the east-northeast-trending faults and an older buried trace of the Wasatch fault zone (Davis, 1985) that forms the west flank of the Madsen spur Although it may be coincidental, the only two thermal springs present along the Brigham City segment (Mundorff, 1970) are on the segment boundaries. The thermal springs appear to be manifestations of the intersections of transverse structures (cross faults) and the Wasatch fault zone. Such intersections are commonly associated with other segment boundaries of the Wasatch fault zone (Schwartz and Coppersmith, 1984). Many other transverse structures are present in the footwall of the Brigham City segment, but the Madsen spur and Pleasant View salient faults are the only transverse structures in either the footwall or the hanging wall that show evidence of post-Provo-shoreline faulting.

Shorelines on the two lateral-spread deposits (clsp) near Honeyville, and or

another lateral-spread deposit 4 km north of Deweyville, may give a clue to the

timing of at least one earthquake surface-faulting event in the region; all these

deposits appear to have slid into the receding waters of Lake Bonneville when the

surface of the lake stood at an altitude of 1,347-1,353 m (4,420-4,440 ft) Shorelines and reworked lateral-spread deposits are preserved at and below this altitude, but not above. The lake is known to have been at the Provo shoreline (1,470-1,475 m; 4,820-4,840 ft) 13-14 ka, and had retreated to the level of modern Great Salt Lake (1,283 m; 4,210 ft) by about 11 ka (Scott and others, 1983) These dated lake levels bracket the altitude of the lateral-spread shorelines, and thus constrain the age of lake occupation at 1,347-1353 m (4,420-4,440 ft) at about 12 ka. Oviatt (1986a,b) noticed similar relations for these lateral-spread deposits near Honeyville and several others north of Deweyville. In a study of historic earthquake-induced landslides, Keefer (1984) found that lateral-spread failures required earthquakes of minimum magnitude 5.0 (M_I) and predominant minimum intensity of VII (MMI). Although it may be coincidental, this evidence suggests that at least one large-magnitude earthquake triggered several lateral-spread failures near the Brigham City-Collinston segment boundary about 12 ka. Average offset for individual earthquake surface-faulting events on the the

northern Wasatch fault zone is 2 m or less (Schwartz and Coppersmith, 1984); consequently, the 4 m of offset in alluvial-fan deposits graded to the Provo shoreline (afp) 1 km east-northeast of Honeyville is probably the result of at least two earthquake surface-faulting events. Evidence for post-lateral-spread surface faulting (the 12 ka event) is apparent on the Madsen spur faults; these fault scarps offset several shorelines, including the lateral-spread shorelines that mark the 12 ka lake level Therefore, evidence for at least two post-Provo-shoreline surface-faulting events is preserved at the extreme northern end of the Brigham City segment. The 2-kmlong scarp on the southern end of the Collinston segment is probably an extension of faulting across the segment boundary from one or more of these post-Provoshoreline earthquake surface-faulting events. My photo reconnaissance of the Wasatch fault zone northward to the Idaho border revealed no evidence of post-Provo faulting beyond this short fault scarp, despite the abundance of Bonnevillelake-cycle deposits along the mountain front.

Detailed mapping of Quaternary deposits and careful measurement of fault scarps in deposits of various ages has helped identify some of the paleoseismic characteristics of the Brigham City segment and parts of the adjacent Weber and Collinston segments of the Wasatch fault zone. The Brigham City segment has clearly been active in Holocene time; scattered 3-7 m high scarps in lower or middle Holocene alluvial deposits attest to several earthquake surface-faulting events in the last 10,000 years. Scarps along the Brigham City segment vary in size; this variation reflects the

CONCLUSION

ages of offset deposits, because older deposits preserve a longer record of fault movement. The size variation also reflects whether movements on the fault zone have been concentrated on a single scarp or on multiple strands. Net slip in deposits of a given age appears fairly constant from the southern segment boundary at the Pleasant View salient to Brigham City, but gradually declines northward to the northern segment boundary near Honeyville. Although the two segment boundaries share some characteristics, such as changes in Quaternary faulting activity and fault trend, presence of fault gaps, Holocene cross faults, and hot springs, the southern segment appears to be a more prominent, long-term (persistent) struc-The Brigham City segment apparently was very active in early to middle

Holocene time but appears to have been less active in late Holocene time. This can be interpreted in two ways; either faulting activity on the segment has declined through the Holocene and therefore the segment does not constitute a serious earthquake hazard, or the early to middle Holocene recurrence interval can be applied to the entire Holocene, in which case the Brigham City segment may be overdue for another large-magnitude earthquake. Although additional slip data from detailed trench studies as well as studies of regional seismicity are needed to assess the earthquake hazards associated with this portion of the Wasatch fault zone, maps of this type can be used to quantify some of the paleoseismic characteristics of active fault zones and identify sites for additional study.

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