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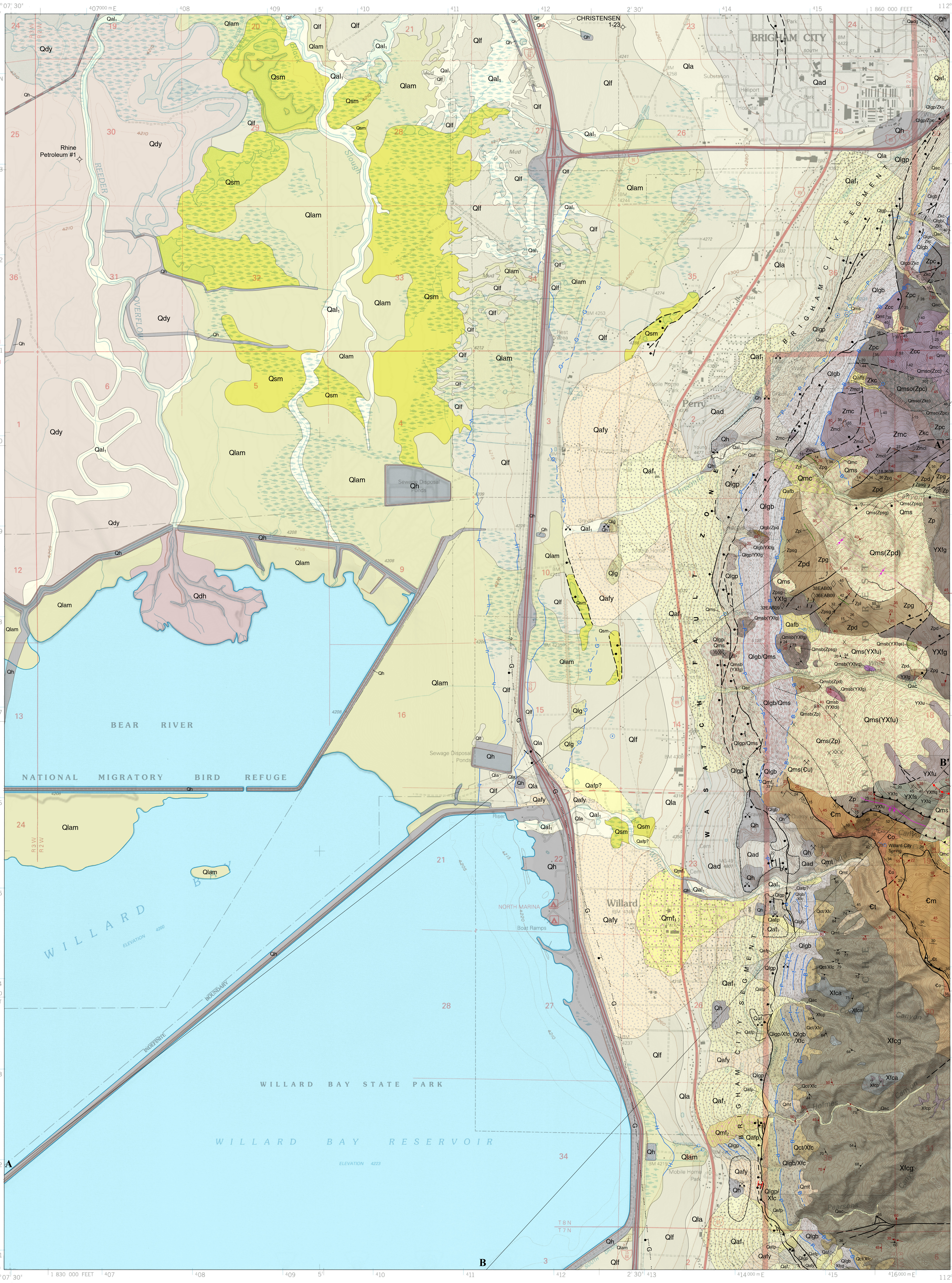

SCALE 1:24,000

1 0.5 0 1 MILE

1000 0 1000 2000 3000 4000 5000 6000 7000 FEET

1 0.5 0 1 KILOMETER

CONTOUR INTERVAL 20 FEET
SUPPLEMENTARY CONTOUR INTERVAL 5 FEET

11°35'
TRUE NORTH
MAGNETIC NORTH
APPROXIMATE MEAN DECLINATION, 2018

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GEOLOGIC MAP OF THE WILLARD QUADRANGLE, BOX ELDER COUNTY, UTAH

by
Adam P. McKean[1], Elizabeth A. Balgord[2], W. Adolph Yonkee[2], and Adam I. Hiscock[1]
2018

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U T AH
QUADRANGLE LOCATION

Base from USGS Willard 7.5' Quadrangle (1998)
Projection: UTM Zone 12
Datum: NAD 1927

Project Manager: Jon K. King
Field Mapping: Adam P. McKean, 2011-2012
GIS and Cartography: Adam P. McKean and Lori J. Steadman

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1	2	3
4		5
6	7	8

1. Bear River City
2. Brigham City
3. Mount Pisgah
4. Whistler Canal
5. Mantua
6. Plain City SW
7. Plain City
8. North Ogden

ADJOINING 7.5' QUADRANGLE NAMES

ISBN 978-1-55791-943-4
9 781557 919434

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MAP UNITS

(see booklet for complete unit descriptions)

- Qal_1 – Modern stream deposits
- Qat – Stream terrace deposits
- Qatp? – Stream terrace deposits related to regressive phase of Lake Bonneville
- Qaf_1 – Modern alluvial-fan deposits
- Qafy – Younger alluvial-fan deposits, undivided
- Qafp, Qafp? – Alluvial-fan deposits related to Provo shoreline and regressive phase of Lake Bonneville
- Qafb – Alluvial-fan deposits related to transgressive phase of Lake Bonneville
- Qdh – Historical deltaic deposits
- Qdy – Deltaic deposits
- Qh – Fill and disturbed land
- Qlf – Lacustrine fine-grained deposits
- Qlg – Lacustrine gravel and sand
- Qlgp – Lacustrine gravel and sand related to Provo shoreline and regressive phase of Lake Bonneville
- Qlgb – Lacustrine gravel and sand related to Bonneville shoreline and transgressive phase of Lake Bonneville
- Qmf_1 – Debris-flow deposits
- Qmf_2 – Older debris-flow deposits
- Qms – Landslide deposits
- Qms (Ꞓu) (Zp) (Zpg) (Zpd) (Zpsg) (YXfu) – Landslide with identifiable bedrock fragments (see unit below)
- Qmsb (Zp) – Landslide bedrock blocks (see unit below)
- Qmsb (Zpd) – Landslide bedrock blocks (see unit below)
- Qmsb (Zpsg) – Landslide bedrock blocks (see unit below)
- Qmsb (YXfvq) – Landslide bedrock blocks (see unit below)
- Qmsb (YXfdi) – Landslide bedrock blocks (see unit below)
- Qmsb (YXfqs) – Landslide bedrock blocks (see unit below)
- Qmsb (YXfg) – Landslide bedrock blocks (see unit below)
- Qmt – Talus deposits
- Qmso (Zcc) – Older landslide, with identifiable bedrock fragments and blocks (see unit below)
- Qmso (Zpc) – Older landslide, with identifiable bedrock fragments and blocks (see unit below)
- Qmso (Zkc) – Older landslide, with identifiable bedrock fragments and blocks (see unit below)
- Qsm – Spring and marsh deposits
- Qad – Fan-delta deposits
- Qadg – Deltaic and alluvial gravel deposits
- Qac – Alluvial and colluvial deposits, undivided
- Qla – Lacustrine and alluvial deposits, undivided
- Qlam – Lacustrine, alluvial, mud-flat, and marsh deposits, undivided
- Qmc – Landslide and colluvium deposits, undivided
- Qlgp/Qms – Lacustrine gravel and sand (regressive phase) over landslide deposits or bedrock
- Qlgp/Zpc – Lacustrine gravel and sand (regressive phase) over landslide deposits or bedrock
- Qlgp/Zkc – Lacustrine gravel and sand (regressive phase) over landslide deposits or bedrock
- Qlgp/YXfg – Lacustrine gravel and sand (regressive phase) over landslide deposits or bedrock
- Qlgp/Xfc – Lacustrine gravel and sand (regressive phase) over landslide deposits or bedrock
- Qlgb/Qms – Lacustrine gravel and sand (transgressive phase) over landslide deposits or bedrock
- Qlgb/Zkc – Lacustrine gravel and sand (transgressive phase) over landslide deposits or bedrock
- Qlgb/Zpd – Lacustrine gravel and sand (transgressive phase) over landslide deposits or bedrock
- Qlgb/YXfg – Lacustrine gravel and sand (transgressive phase) over landslide deposits or bedrock
- Qlgb/Xfc – Lacustrine gravel and sand (transgressive phase) over landslide deposits or bedrock
- Qct/Xfc – Colluvium and talus over Farmington Canyon Complex bedrock

WILLARD THRUST SHEET

- Zcc – Caddy Canyon Quartzite
- Zpc – Papoose Creek Formation
- Zkc – Kelley Canyon Formation
- Zmc – Maple Canyon Formation; Carbonate beds of the Maple Canyon Fm (Zmcl)
- Zp – Perry Canyon Formation, undivided
- Zpg – Graywacke member of the Perry Canyon Formation; Carbonate marker unit of the Perry Canyon Formation (Zpl)
- Zpd – Diamictite member of the Perry Canyon Formation
- Zpsg – Greenstone and slate members, undivided, of the Perry Canyon Formation
- YXfu – Facer Formation, undivided
- YXfq – Facer Formation, quartzite; Facer Formation, fuchsitic quartzite (YXffq)
- YXfs – Facer Formation, schist and phyllite
- YXfvq – Facer Formation, vein quartz, see unit Qmsb(YXfvq)
- YXfqs – Facer Formation, quartz-muscovite schist, see unit Qmsb(YXfqs)
- YXfdi – Facer Formation, diorite, see unit Qmsb(YXfdi)
- YXfg – Facer Formation, gneiss

WILLARD THRUST FOOTWALL

- Ꞓu – Cambrian, undivided, see unit Qms(Ꞓu)
- Ꞓm – Maxfield Limestone
- Ꞓo – Ophir Formation
- Ꞓt – Tintic Quartzite
- Xfc – Farmington Canyon Complex, undivided (see cross section and stacked units)
- Xfcp – Farmington Canyon Complex, pegmatite
- Xfca – Farmington Canyon Complex, amphibolite
- Xfcg – Farmington Canyon Complex, granitic gneiss


Panorama view to the south of large (approximately 1.6 mi^2 [~4 km^2]) landslide complex near Facer Creek mostly composed of Facer and Perry Canyon Formations, which can be seen in place on the left side and upper center of the photo.

GEOLOGIC SYMBOLS

- Contact – Dashed where approximately located; dotted where concealed
- 55 55 — Normal fault – Dashed where approximately located, dotted where concealed, queried where uncertain; bar and ball on downthrown side; arrow shows dip of the fault; arrows on cross section indicate direction of relative movement; red symbols and text are from Crittenden and Sorenson (1985a)
- G — Normal fault, concealed – Inferred from gravity data; bar and ball on downthrown side
- Thrust fault – Dotted where concealed; sawteeth on upper plate; open sawteeth symbols indicate very approximately located fault that is concealed by landsliding
- 55 — Attenuation fault – Dashed where approximately located, queried where uncertain; rectangle on upper plate, younger over older, low-angle-to-bedding fault in the Cambrian Ophir and Maxfield Formations; arrow shows dip of the fault; red symbols and text are from Crittenden and Sorenson (1985a)
- Unknown fault – Dashed where approximately located; dotted where concealed
- Hinge zone trace of overturned syncline – Dotted where concealed
- Hinge zone trace of upright syncline – Dotted where concealed
- Lacustrine shorelines – Major shorelines of the Bonneville lake cycle, Gilbert-episode lake, and Great Salt Lake. Mapped at the upper nick point of wave-cut bench for erosional shorelines and the top of constructional bars and barrier beaches; may coincide with geologic contacts
  - B — Bonneville shoreline of Lake Bonneville – Dashed where approximately located
  - t — Transgressive shorelines of Lake Bonneville (present above the Provo shoreline)
  - P — Provo shoreline of Lake Bonneville – Dashed where approximately located
  - r — Regressive shorelines of Lake Bonneville (present below the Provo shoreline)
  - G — Gilbert shoreline – Dashed where approximately located
  - Great Salt Lake Holocene intermediate shoreline
  - H — Great Salt Lake late Holocene highstand shoreline
  - h — Great Salt Lake historic highstand shoreline
  - Crest of lacustrine barrier bar or spit
- Landslide scarp – Hachures on down-dropped side, dashed where approximately located
- Outline of aggregate sand and gravel pit operations, contact based on 2011 orthophotography (Utah Automated Geographic Reference Center, 2011b), Qh mapped within outlines represent extent of the pit operations from 1980 USDA Forest Service aerial photography or 1998 USGS topographic basemap
- A——A' Line of cross section
- Line of type section, Perry Canyon Formation, see Balgord and others (2013)
- Fuchsitic quartzite of the Facer Formation (YXffq)
- Carbonate beds of the Maple Canyon Fm (Zmcl)
- Carbonate beds of the Perry Canyon Fm (Zpl)
- Structural measurements – red symbols and text are from Crittenden and Sorenson (1985a)
  - 21 21 — Strike and dip of inclined bedding
  - Strike of vertical bedding
  - 35 — Strike and dip of overturned bedding
  - 65 65 — Strike and dip of metamorphic foliation
  - 32 — Strike and dip of cleavage
  - 55 55 — Bearing and plunge of lineation
  - 36 36 — Minor fold axis, showing plunge
- Sand and gravel pit
- Mine or quarry
- Adit
- Prospect
- Spring
- Water well (selected)
- Oil and gas exploration well, plugged and abandoned
- 36EAB09 — Rock sample location and number for geochronology analysis (Balgord [2011] and Balgord and others [2013])
- Paleoseismic trench (DuRoss and others, 2012)
- Qlgb/Xfc — Stacked unit – Denotes thin cover of first unit overlying second unit

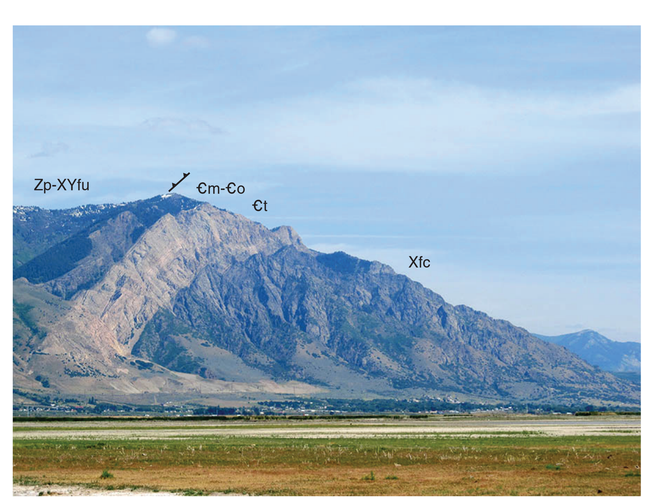

View of the August 13, 1923, Willard flood debris from August 14, 1923. Photo credit Weber State University, Stewart Library Special Collections.


Photo taken September 1, 1925, of debris left by August 13, 1923, Willard flood, note man for scale. Largest boulder measures about 8 x 12 x 20 feet [~2.5 x 3.6 x 6 m]. Photo credit U.S. Geological Survey, photo by William Clinton Alden.


View to the east of Willard Canyon taken September 1, 1925, of debris left by August 13, 1923, Willard flood, note man for scale. Photo credit U.S. Geological Survey, photo by William Clinton Alden.


Ptygmatically folded pegmatite vein with darker edges in the granitic gneiss of the Farmington Canyon Complex.

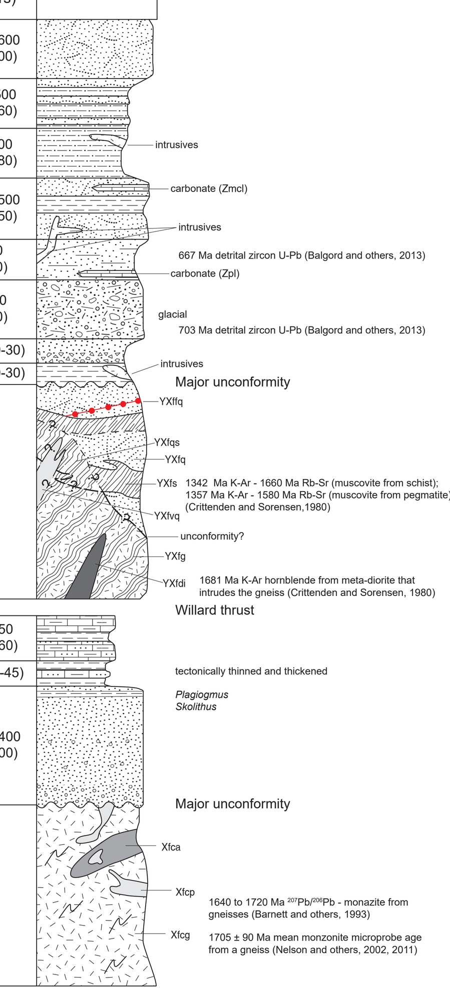

View to the northwest of a large rock avalanche (Qms) in the Facer Formation in Willard Canyon, approximately 1.5 miles (2.5 km) east of the Willard debris basin.



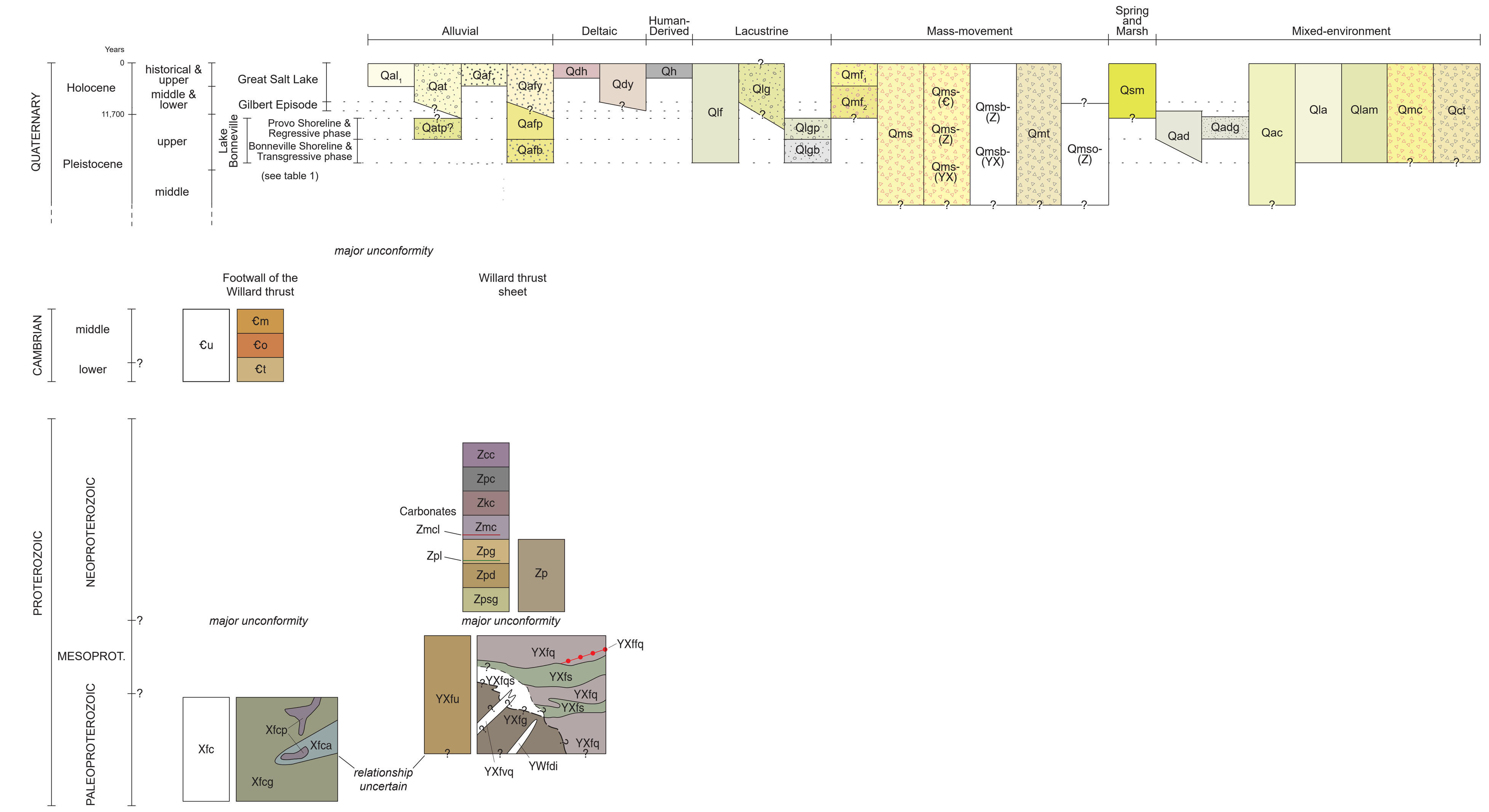
View to the southeast of the Wasatch Range with the Farmington Canyon Complex below the unconformably overlying dipping tan cliffs of Cambrian Tintic Quartzite. Above the Tintic is an attenuation fault that thins and thickens the overlying gray beds of Ophir Shale and Maxfield Limestone. The Cretaceous Willard thrust (top left corner of photograph above dark-green vegetated dip slope of Maxfield Limestone) placed the Paleoproterozoic to Mesoproterozoic Facer Formation and unconformably overlying Neoproterozoic strata over the Cambrian strata. Compare to northeast end of cross section B-B'.

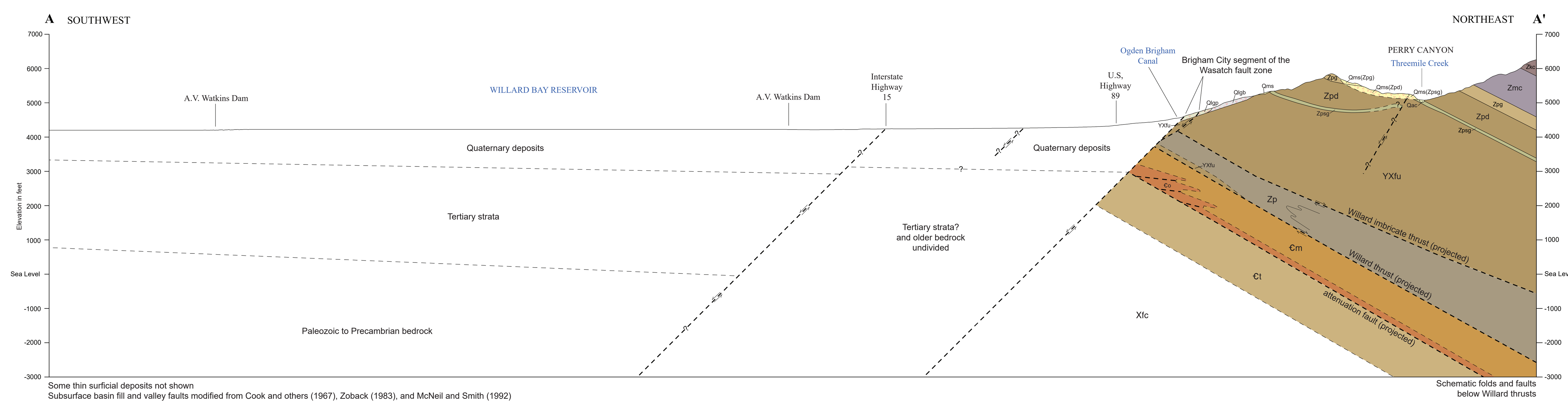
LITHOLOGIC COLUMN

AGE		FORMATION - MEMBER		MAP UNIT SYMBOL		THICKNESS Feet (Meters)
Proterozoic	Neoproterozoic	Caddy Canyon Quartzite		Zcc		1300-1600 (400-500)
		Papoose Creek Formation		Zpc		900-1500 (275-460)
		Kelley Canyon Formation		Zkc		500-600 (150-180)
		Maple Canyon Formation		Zmc		1200-1500 (350-450)
		Perry Canyon Formation	Graywacke member	Zp	Zpg	~650 (~200)
			Diamictite member		Zpd	~1000 (~300)
			Greenstone member		Zpsg	0-100 (0-30)
			Slate member			0-100 (0-30)
	Mesoproterozoic ? Paleoproterozoic	Facer Formation	Fuchsitic quartzite	YXfu	YXffq	
			Quartzite		YXfq	
			Schist and phyllite		YXfs	
			Vein quartz		YXfvq	
			Quartz-muscovite schist		YXfqs	
			Diorite		YXfdi	
			Gneiss		YXfg	
Cambrian	Middle	Maxfield Limestone		Ꞓm		400-850 (120-260)
		Ophir Formation		Ꞓo		0-150 (0-45)
	? Lower	Tintic Quartzite		Ꞓt		1200-1400 (360-400)
Proterozoic	Paleoproterozoic	Farmington Canyon Complex	Pegmatite	Xfc	Xfcp	
			Amphibolite		Xfca	
			Granitic gneiss		Xfcg	



CORRELATION CHART





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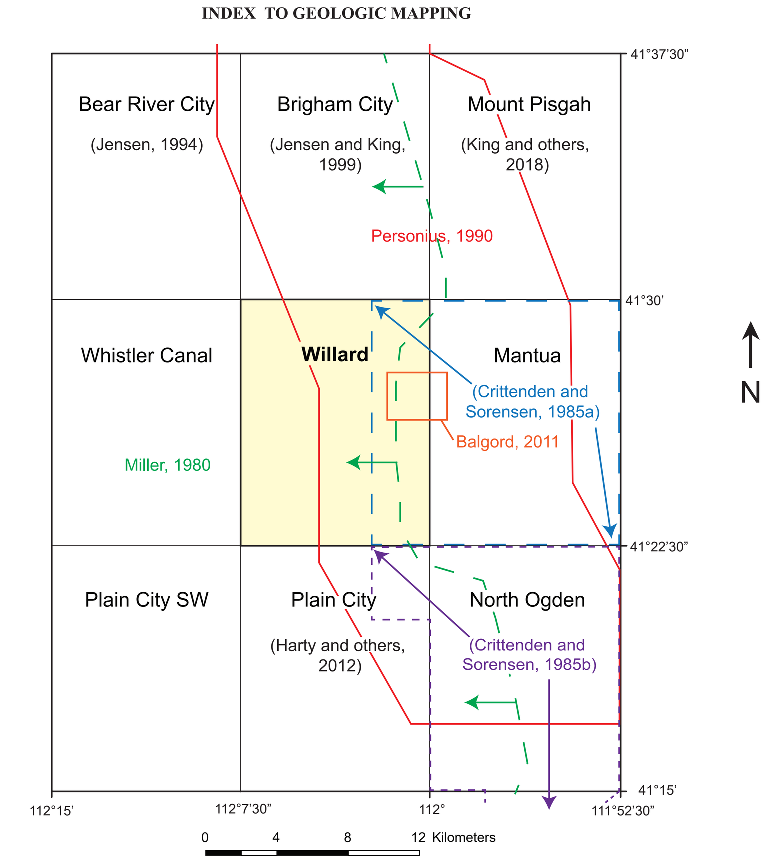

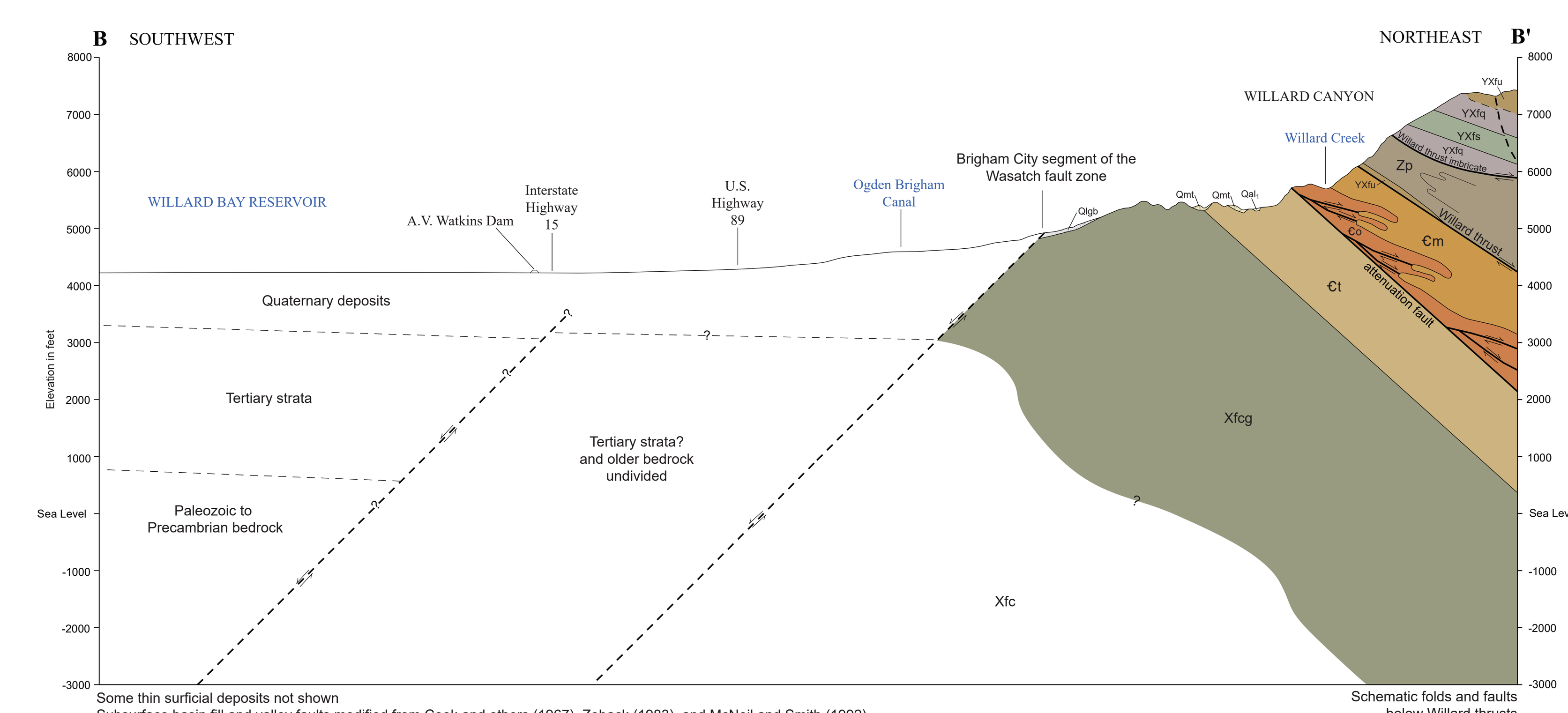

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by Adam P. McKean [1], Elizabeth A. Balgord [2], W. Adolph Yonkee [2], and Adam I. Hiscock [1]

[1]Utah Geological Survey, P.O. Box 146100, Salt Lake City, UT 84114-6100
[2]Department of Geosciences, Weber State University, Ogden, UT 84408

SCALE: 1:24,000

Cover photo: *View to the east of the Wasatch Range within the Willard quadrangle and a desiccated mudflat on the valley floor in mixed marsh, alluvial, and lacustrine wetlands (*Qlam*). The rounded mountains in the center and left of the photo are the less resistant and prone-to-landsliding Paleoproterozoic to Mesoproterozoic Facer Formation and Neoproterozoic strata, all of the Willard thrust sheet. The center of the three mountains on the photo contains a large (approximately 1.6 mi^2 [~4 km^2]) landslide complex near Facer Creek. The more resistant mountain on the right is the footwall of the Willard thrust.*

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INTRODUCTION

The Willard 7.5-minute quadrangle is located in Box Elder County of northern Utah. The eastern part of the quadrangle contains the mountain front of the Wasatch Range. Separating the valley floor from the mountain range is the Brigham City segment of the Wasatch fault zone. The valley floor contains the Bear River delta to the north, Willard Bay (an arm of Great Salt Lake), and Willard Bay Reservoir to the south. Much of the delta is managed by the Bear River National Migratory Bird Refuge, and the Willard Bay Reservoir is part of Willard Bay State Park. The quadrangle contains the towns of Perry, Willard, and part of Brigham City.

Bedrock exposed in the Wasatch Range is cut by the Willard thrust fault. The footwall consists of igneous and metamorphic rocks (granitic gneiss, amphibolite, and pegmatite) of the Paleoproterozoic Farmington Canyon Complex and unconformably overlying Cambrian sedimentary rocks of the Tintic Quartzite, Ophir Formation, and Maxfield Limestone. The hanging wall of the Willard thrust includes metamorphic and igneous rocks (gneiss, schist, quartzite, phyllite, minor pegmatite, and minor meta-diorite) of the Paleoproterozoic to Mesoproterozoic Facer Formation and unconformably overlying Neoproterozoic strata of the Perry Canyon, Maple Canyon, Kelley Canyon, Papoose Creek, and Caddy Canyon Formations. The Perry Canyon Formation contains (from bottom to top) slate, meta-greenstone (metamorphosed mafic igneous rock), meta-diamictite, and meta-graywacke members that are interpreted as the products of Neoproterozoic early Rodina rifting and glaciation during the Cryogenian Period (850–635 Ma) (Balgord and others, 2013). The map area is within the Cretaceous and Tertiary Sevier fold-thrust belt; the Willard thrust sheet had an estimated 40 miles (60 km) of top-to-the-east slip during the Cretaceous (Yonkee and others, 2013). An imbricate of the Willard thrust placed the Facer Formation over the Perry Canyon Formation in the quadrangle. Eastward tilting of the Willard thrust and imbricates, and hanging-wall and footwall rocks, is due to the Wasatch culmination (stacked thrust splays known as an anticlinorium) with pulses of uplift between 90 and 50 Ma (Cretaceous and Tertiary) (Yonkee and Weil, 2011). Attenuation faults in the Cambrian rocks likely formed during these uplift pulses. The culmination is cut by the Brigham City segment of the Wasatch fault zone, a mid-Miocene and younger basin-and-range normal fault. In the quadrangle, the Brigham City segment displays Holocene fault scarps and dips to the west. We estimate 4.5 miles (7 km) of vertical displacement (see cross section A–A′). Normal faulting of the Wasatch fault zone resulted in relative footwall uplift and exhumation of the bedrock of the Wasatch Range. In the north half of the quadrangle normal faults in the bedrock footwall of the Wasatch fault zone are seen in arcuate faults and zones of weakness in the Neoproterozoic units and Perry Canyon Formation. These faults and weak zones have likely resulted in numerous landslides.

Surficial deposits are mapped mainly to the west of the Wasatch fault zone and bedrock to the east. The valley floor is covered by Quaternary lacustrine, deltaic, alluvial, and marsh deposits. Lacustrine and deltaic sediments were deposited during late Pleistocene Lake Bonneville (30 to 13 ka), the Gilbert-episode lake (~11.5 ka), and Holocene Great Salt Lake (since ~11 ka) (see table 1; all ages in this section are in calibrated years). Following Oviatt (2014), the Gilbert-episode lake is regarded as a separate lake rather than a phase of the Bonneville or Great Salt Lake cycles. The Gilbert-episode shoreline in this quadrangle is poorly exposed at an elevation of about 4250 feet (~1295 m), with no evidence of Gilbert-episode shorelines above that elevation, which is consistent with Oviatt (2014). Alluvial deposits are mostly range-front alluvial fans and fan-deltas. Mass-movement deposits in the range include a large (approximately 1.6 mi^2 [~4 km^2]) landslide complex near Facer Creek and a rock avalanche in Willard Canyon.

PREVIOUS WORK

Previous geologic maps in and near the Willard quadrangle, shown on figure 1 (plate 2), include (1) the regional surficial geologic map by Miller (1980) at 1:100,000 scale and the surficial geologic map along the Wasatch fault zone by Personius (1990) at 1:50,000 scale, and (2) bedrock geologic maps of the bedrock part of the Willard quadrangle at 1:24,000 scale by Crittenden and Sorensen (1985a), and of the Perry Canyon area (Willard and Mantua quadrangles) at approximately 1:24,000 scale by Balgord (2011). Detailed geologic maps of adjacent areas include the Mantua (Crittenden and Sorensen, 1985a), North Ogden (Crittenden and Sorensen, 1985b), Bear River City (Jensen, 1994), Brigham City (Jensen and King, 1999), Plain City (Harty and others,

Table 1. *Ages of major shoreline occupations of Lake Bonneville, Gilbert episode, and Great Salt Lake with shoreline elevations in the Willard quadrangle.*

Lake Cycle and Phase	Shoreline (map symbol)	Age radiocarbon years (^{14}C yr B.P.)	Age calibrated years (cal yr B.P.)[1]	Shoreline Elevation feet (meters)
Lake Bonneville				
Transgressive phase	Stansbury shorelines	22,000–20,000[2]	26,000–24,000	Not recognized[3]
	Bonneville (B)	~15,200–15,000[4]	~18,500–18,000	5180–5200 (1580–1585)
Overflowing phase	Provo (P)	15,000–12,600[5]	18,000–15,000	4820–4860 (1470–1482)
Regressive phase	Regressive shorelines (r)	12,600–11,500[5]	15,000–13,000	4380–4820 (1335–1470)
Gilbert episode	Gilbert (G)	10,000[6]	11,500	~4250 (1295)
Great Salt Lake				
	early Holocene highstand	9700–9400[7]	11,000–10,500	Not recognized
	late Holocene highstand (H)	4200–2100[8]	5000–2000	4217–4221 (1285–1287)
	Historical highstand (h)		late 1860s to early 1870s and 1986–87[9]	4212 (1284)

[1] All calibrations made using OxCal ^{14}C calibration and analysis software (version 4.3.2; Bronk Ramsey, 2009; using the IntCal13 calibration curve of Reimer and others, 2013), rounded to the nearest 500 years.
[2] Oviatt and others (1990)
[3] The Stansbury shoreline formed at elevations of about 4440 to 4450 feet (1350-1360 m), which are present in the quadrangle, but the shoreline was either weakly developed or poorly preserved and cannot be identified.
[4] Oviatt (2015), Miller (2016), and references therein
[5] Godsey and others (2005, 2011), Oviatt (2015), Miller (2016) for the timing of the occupation of the Provo shoreline and subsequent regression of Lake Bonneville to near Great Salt Lake level. Alternatively, data in Godsey and others (2005) may suggest that regression began earlier, shortly after 16.5 cal ka (see sample Beta-153158, with an age of 13,660 ± 50 ^{14}C yr B.P. [16.5 cal ka] from 1.5 m below the Provo shoreline). Also, lacustrine carbonate deposits in caves reported by McGee and others (2012) seem to support an earlier Lake Bonneville regression beginning around 16.4 cal ka.
[6] Gilbert-episode highstand may have been very short lived; age represents lake culmination (Oviatt and others, 2005; Oviatt, 2014).
[7] Murchison (1989), Currey and James (1982)
[8] Miller and others (2005)
[9] Arnow and Stephens (1990)

2012), and Mount Pisgah (King and others, in preparation) 7.5-minute quadrangles; these maps provided geologic context for this project.

While mapping, a few edge mismatches with adjacent mapping became apparent. Jensen and King's (1999) deltaic-plain deposits (Qdp) include channel deposits of the Bear River and other alluvial channels, whereas we depict channel deposits of the Reeder Overflow as a separate unit (Qal_1). Deposits equivalent to Jensen and King's (1999) lacustrine silt deposits (Qli) are included in our lacustrine fine-grained deposits (Qlf). At the mouth of the unnamed canyon south of Pearsons Canyon on the southern quadrangle boundary, one older alluvial-fan deposit (Qaf_2) mapped by Harty and others (2012) was combined into our younger alluvial-fan deposits (Qafy). Crittenden and Sorensen (1985a) mapped a number of short faults in the Farmington Canyon Complex granitic gneiss, some of which we choose not to include based on limited offset and interpretation as small hematized fractures in the footwall damage zone (Evans and Langrock, 1994; Ault and others, 2015). When compared with the mapping of Personius (1990), we combined some of his stream alluvium (alp) deposited as topset beds over his deltaic deposits related to the Provo shoreline (lpd) into our fan-delta deposits (Qad).

METHODS

Mapping of surficial deposits by the Utah Geological Survey Geologic Mapping Program is based on age and depositional environment or origin. The letters of the map units in order indicate (1) age (geologic period, e.g., Q for Quaternary), (2) primary depositional environment or origin, usually determined from setting, landform or morphology, (3) grain size(s), bedding, or other distinctive characteristics of the deposits, and (4) additional significant information, such as tighter age constraints (Doelling and Willis, 1995) as related to the phases of Lake Bonneville or numbered with 1 being the youngest. For example, unit Qaf_1 is a Quaternary surficial deposit of alluvial-fan origin (af), and the number one indicates it is young and potentially historically active.

Bedrock geologic mapping was revised from previous mapping by Crittenden and Sorensen (1985a) and Balgord (2011). Contacts and units were field checked and changed where needed based on field observations and interpretation. Description of map units for the Perry Canyon Formation is from our field mapping and Balgord and others (2013).

Mapping for the project used stereographic pairs of aerial photographs from the following sources: (1) 1937 black-and-white aerial photographs (approximately 1:20,000 scale) from the U.S. Department of Agriculture (USDA) Agricultural Adjustment Administration, 1965 USDA Agricultural Stabilization and Conservation Service, and 1959 USDA Commodity Stabilization Service; (2) 1980 color aerial photographs (approximately 1:12,000 scale) from USDA Forest Service; and (3) black-and-white oblique aerial photography (approximately 1:12,000 scale) from the Woodward-Lundgren & Associates Wasatch fault investigation (Cluff and others, 1970, available in Bowman and others, 2015). Some features are too small to show at map scale.

The geologic map was made by transferring the geology from the aerial photographs to a geographic information system (GIS) database using the programs ESRI ArcGIS, computer-aided design (CAD) Cardinal Systems VR1, and VR2 (digital stereographic mapping) for a target scale of 1:24,000. McKean mapped some contacts and faults using lidar elevation data (1-meter data available from Utah Automated Geographic Reference Center (AGRC) [2011a], and 0.5-meter data from AGRC [2013–2014]). Some contacts were revised using 2011 orthophotography (AGRC, 2011b). Digital U.S. Natural Resources Conservation Service (NRCS) (2011) soil data and maps were also used to delineate some surficial deposits. Some features and units were not mapped, because they were too small to map at a scale of 1:24,000. Aerial-photographic and field mapping of the Willard quadrangle was completed in 2011 and 2012.

Geologic cross sections A–A′ and B–B′ were created by combining available surface mapping, gravity data, and well data. Gravity data came from Zoback (1983) and McNeil and Smith (1992), the Pan-American Center for Earth and Environmental Studies (PACES) (2012) gravity database, and newly acquired Utah Geological Survey (UGS) gravity data, as well as seismic and gravity data from Cook and others (1967). Geophysical and lithologic well logs from oil and gas exploration wells (see table 2), well data from Case (1985), and other information from the UGS deep-basin-structure database (UGS, undated) were used to estimate the subsurface contacts between Quaternary deposits (unconsolidated sediments), Tertiary strata (semiconsolidated to consolidated strata), and Paleozoic to Precambrian strata (bedrock). The Quaternary deposits and Tertiary strata contact is not well constrained by well data near the Wasatch fault and is shown as slightly inclined but may be flatter.

GEOLOGIC HAZARDS

The quadrangle was mapped to help identify and delimit potential geologic hazards along the populous Wasatch Front. The surficial deposits in the entire quadrangle had not been mapped previously at a detailed scale of 1:24,000. Geologic hazards related to features on the geologic map include surface fault rupture along the Brigham City segment of the Wasatch fault zone; mass movements including debris flows ($Qmf_{1\text{-}2}$), landslides (Qms), and rockfalls (Qmt); flooding in alluvial channels (Qal_1); flooding and debris flows on alluvial fans ($Qaf_{1\text{-}2}$ and Qafy); and flooding by Great Salt Lake (see its mapped historic highstand “h” on plate 1, at about 4212 feet [1284 m] elevation). Other potential problem units include springs and marshes (Qsm) indicative of shallow groundwater and clay-rich unconsolidated deposits on the valley floor (Qlf and Qlam). The combination of shallow groundwater and fine-grained sediments on the valley floor are a potential risk for liquefaction during an earthquake event. Below is a brief discussion of the surface fault rupture, flooding, and debris flow hazard in the quadrangle. See the unit descriptions and geologic map for more information and locations of these hazards and problem deposits. See the UGS website (geology.utah.gov) for additional information on these and other geologic hazards.

Table 2. *Selected wildcat exploration drill holes in and near the Willard quadrangle used for cross sections.*

API Well Number	Well Name	Latitude	Longitude	Total Depth (ft)	Completion Date	7.5′ Quadrangle	Notes
43-003-10978	RHINE PETROLEUM 1	41.48548	-112.11592	–	4/3/1958	Willard	Plugged and abandoned
43-003-20059	CHRISTENSEN 1-23	41.49865	-112.04399	100	1/18/1994	Willard	Plugged and abandoned
43-003-30021	CHRISTENSEN 1-9	41.50050	-112.12449	6000	8/4/1981	Brigham City	Plugged and abandoned Electronic logs available
43-003-30023	CHESAPEAKE ENERGY CO 1A	41.48626	-112.17496	4610	9/2/1981	Whistler Canal	Plugged and abandoned Electronic logs available
43-057-30001	BASIN INVESTMENT CO 1	41.29175	-112.15854	4817	8/27/1981	Plain City SW	Plugged and abandoned Electronic logs available

Source:
Utah Division of Oil, Gas and Mining; http://oilgas.ogm.utah.gov/Data_Center/LiveData_Search/well_data_lookup.cfm, accessed March 6, 2012, and September 15, 2016
Location data based on NAD83, UTM Zone 12N

Surface Fault Rupture

Paleoseismic investigations in the quadrangle near Pearsons Canyon (see trench location near the southern quadrangle boundary on plate 1) by DuRoss and others (2012) revealed that an earthquake on the Weber segment of the Wasatch fault zone likely ruptured across the Weber-Brigham City segment boundary onto the southern part of the Brigham City segment of the Wasatch fault zone about 1200 years ago. A 3- to 6-foot (1–2 m) vertical surface offset from this rupture is preserved almost as far north as Cook Canyon (DuRoss and others, 2012). Fault scarps up to 65 feet (20 m) high, undoubtedly from several earthquakes, are present along the entire length of the Brigham City segment of the Wasatch fault zone in the quadrangle, including the southern part of the map area. Areas near specific geologic hazards require comprehensive site-specific geotechnical and geologic hazard investigation; all parts of the quadrangle are expected to experience extensive ground shaking during major earthquakes.

Several scarps 3 to 6 feet (1–2 m) high are mapped on the valley floor northwest and southwest of Perry. The scarps form small grabens about 1 mile (1.5 km) west of the main Wasatch fault trace. A similar graben also exists in Brigham City (Personius, 1990; Jensen and King, 1999). Personius (1990) identified these features as possible tectonic fault scarps or liquefaction-induced lateral-spread failures. Personius (1990) positively identified west-facing fault scarps 1.5 miles (2.5 km) northwest of Willard that offset Bonneville-lake-cycle gravels (Qla) 4 inches to 3 feet (0.1–1 m) in a gravel pit. These faults were subsequently covered by fill used for Interstate Highway 15. The small-offset scarp identified by Personius (1990) as a tectonic fault coincides with a change in gradient in the gravity data (Zoback, 1983; McNeil and Smith, 1992; PACES, 2012; unpublished UGS gravity data collected for this report) that likely represents a down-to-the-west normal fault (see cross section A–A′, plate 2). However, uncertainty remains concerning the scarps mapped west of the main Wasatch fault zone from Willard to Brigham City—these sag pond-like features may be earthquake-induced lateral spread features or tectonic fault scarps (Personius, 1990). More work is needed to determine their origin.

Flooding and Debris Flows

The town of Willard has a history of damaging alluvial-fan flooding and debris flows. On August 13, 1923, a debris flow moved down Willard Creek and caused widespread damage to the town (Woolley, 1946). The Willard debris basin was subsequently constructed at the mouth of the canyon but a July 1936 flood diverted around the structure and damaged property (Wolley, 1946; Croft, 1967). After the 1936, flood the Town of Willard, State of Utah, and Box Elder County purchased the Willard Basin drainage basin and turned fire-damaged and overgrazed land over to the U.S. Forest Service for protection and management (from U.S. Forest Service information sign at the rim of Willard Basin). Mitigation work by the U.S. Soil Conservation Service and Civilian Conservation Corps began in 1936 to rehabilitate the basin (from U.S. Forest Service information sign at the rim of Willard Basin). Much of the significant hazard has likely been mitigated by debris basin construction and land rehabilitation. However, because the Willard Basin drainage basin is large, the potential for damaging floods and debris flows remains. Significant loose material exists in the channel and side slopes to source debris flows, including steep exposed bedrock in Willard Canyon and a large rock avalanche (Qms) approximately 1.5 miles (2.5 km) east of the Willard debris basin up Willard Canyon. The approximate extent of Holocene and historical debris-flood deposits from Willard Creek are mapped in the town of Willard as debris-flow deposits (Qmf_1). Other flood and debris-flow hazard areas include, but are not limited to, flooding in alluvial channels (Qal_1) and the steep alluvial fans of the Willard area (Qaf_1 and Qafy).

The historic highstand of Great Salt Lake occurred in the late 1860s to early 1870s and again in 1986 to 1987 at an elevation of 4212 feet (1284 m) (Arnow and Stephens, 1990). As mapped on plate 1, this historic highstand ("h" shoreline on map), if reoccupied, could flood much of the low-elevation valley floor west of Interstate Highway 15 and elevate shallow groundwater upslope. For planning and building purposes, land at and below an elevation of 4212 feet (1284 m) should not be developed without significant mitigation of a reoccupation of the historic-highstand shoreline by Great Salt Lake. Land above an elevation of 4212 feet (1284 m) could still be affected by elevated shallow groundwater levels in the event of a lake-level rise greater than the historic high, and potential storm wave run-up along the shoreline during high water years (Atwood and Mabey, 1995; Atwood, 2006).

MAP UNIT DESCRIPTIONS

QUATERNARY

Alluvial deposits

Qal_1 **Modern stream deposits** (upper Holocene) – Poorly to moderately sorted pebble and cobble gravel with a matrix of sand, silt, and minor clay, locally bouldery; contains thin discontinuous sand lenses; subangular to rounded clasts; thin to medium bedded; mapped along Willard and Threemile Creeks and in the Reeder Overflow and Black Slough of the Bear River National Migratory Bird Refuge; mapped in active channels and floodplains, and on minor terraces less than 15 to 20 feet (5–8 m) above active channels; locally includes minor colluvial deposits along steep stream embankments; some stream deposits are channelized and include channel embankments; exposed thickness less than 15 feet (5 m).

Qat **Stream terrace deposits** (Holocene to upper Pleistocene?) – Moderately to poorly sorted pebble and cobble gravel with a matrix of sand, silt, and minor clay; contains thin discontinuous sand lenses; subangular to rounded clasts; mapped below the Provo shoreline on a terrace 15 to 25 feet (5–8 m) above Threemile Creek at the mouth of Perry Canyon; may include minor alluvial and colluvial deposits from nearby slopes; likely above the floodplain; exposed thickness less than 15 feet (5 m).

Qatp? **Stream terrace deposits related to regressive phase of Lake Bonneville** (upper Pleistocene) – Moderately to poorly sorted pebble and cobble gravel with a matrix of sand, silt, and minor clay; contains thin discontinuous sand lenses; subangular to rounded clasts; mapped on a terrace 20 to 30 feet (6–9 m) above Willard Creek near the mouth of Willard Canyon; terrace appears related to the Provo shoreline; time equivalent to part of Qafp; exposed thickness less than 15 feet (5 m).

Qaf_1 **Modern alluvial-fan deposits** (upper Holocene) – Poorly to moderately sorted, weakly to non-stratified, pebble to cobble gravel, in a matrix of sand, silt, and clay, with boulders near bedrock sources; clasts commonly angular to subangular; deposited by debris flows, debris floods, and streams at the mouths of several canyons and extending onto valley floor along the base of the Wasatch Range; younger part of younger alluvial-fan deposits (Qafy) but differentiated because Qaf_1 are not incised by younger channels and can be mapped separately; no Lake Bonneville shorelines are found on these alluvial fans; exposed thickness less than 50 feet (15 m).

Qafy **Younger alluvial-fan deposits, undivided** (Holocene to upper Pleistocene) – Poorly to moderately sorted, pebble to cobble gravel in a matrix of sand, silt, and clay, with boulders near bedrock sources, and grading to mixtures of sand, silt, and clay on gentler slopes; deposited by debris flows, debris floods, and streams at the mouths of mountain canyons; mapped between drainages and their younger alluvial-fan deposits (Qaf_1) along the mountain front; mapped where upper Holocene and older alluvial-fan deposits cannot be differentiated because of map scale or where the specific age of Holocene deposits cannot be determined; likely postdates most of the regression of Lake Bonneville from the Provo shoreline; no Lake Bonneville shorelines are found on these alluvial fans; thickness variable, probably less than 50 feet (15 m).

Qafp, Qafp?

Alluvial-fan deposits related to Provo shoreline and regressive phase of Lake Bonneville (middle Holocene? to upper Pleistocene) – Poorly to moderately sorted, pebble to cobble gravel, locally bouldery, in a matrix of sand, silt, and minor clay; clasts typically angular but well-rounded where derived from Lake Bonneville gravel; deposited by debris flows, debris floods, and stream flow along the Wasatch Range and downslope graded to the Provo and regressive lower shorelines of Lake Bonneville; queried northwest of Willard where alluvial fans are far below mapped regressive shorelines of Lake Bonneville, and are near the Gilbert shoreline; deposited in the Gilbert-episode lake or are regressive-phase fans modified later by the Gilbert shoreline; incised and overlain by modern and younger alluvial-fan deposits (Qaf_1 and Qafy); exposed thickness less than 50 feet (15 m).

Qafb **Alluvial-fan deposits related to transgressive phase of Lake Bonneville** (upper Pleistocene) – Poorly to moderately sorted, pebble to cobble gravel, locally bouldery, in a matrix of sand, silt, and minor clay; clasts subangular to angular; deposited by debris flows, debris floods, and stream flow along the Wasatch Range, grade downslope to the Bonneville shoreline; locally may include interbeds of minor sand, silt, and clay of younger alluvial, colluvial, and lagoon-fill deposits behind barrier bars at the Bonneville shoreline at Perry Basin 0.7 mile (1.1 km) north of Perry Canyon and 1.1 miles (1.8 km) south of Perry Canyon near Facer Creek; exposed thickness less than 50 feet (15 m).

Deltaic deposits

Qdh **Historical deltaic deposits** (historical) – Moderately sorted, fine sand, silt, and clay; sand grains are well rounded; deposited in Bear River National Migratory Bird Refuge by the Reeder Overflow of the Bear River into impounded water and wetlands that are maintained by dikes and other water-control structures; subaqueous to subaerially exposed depending on Great Salt Lake water elevation and water control actions of the Bear River National Migratory Bird Refuge; includes deposits in marshes, channels, crevasse splays and natural levees; estimated thickness 15 feet (5 m).

Qdy **Deltaic deposits** (Holocene?) – Moderately sorted silt, clay, and fine sand, contains some organic-rich fines with gastropods and other shell hash; deposited in the Bear River delta in overbank settings as fines with sand interbeds; sand grains are subrounded to well rounded; likely postdates the Holocene highstand but may include older Gilbert deposits, hence the age query; distinguished from undivided lacustrine and alluvial mud-flat and marsh deposits (Qlam) on aerial photography by the presence of distributary channels, abandoned channels, point bars, oxbow lakes, crevasse splays, and natural levees; subaqueous to subaerially exposed depending on Great Salt Lake water elevation and water-control actions of the Bear River National Migratory Bird Refuge and wetlands mitigation; exposed thickness less than 15 feet (5 m).

Human-derived

Qh **Fill and disturbed land** (historical) – Undifferentiated fill and disturbed land related to sand and gravel extraction, sewage disposal ponds, land disturbed by borrow pits, and disturbed land and fill used for construction of Interstate Highway 15, the Willard Bay Arthur V. Watkins dam, the Bear River dike and water-control structures, and small dams for livestock watering; the outlines of artificial fill and disturbed land are shown with a hachured outline; mapped from 2011 orthophotography (Utah Automated Geographic Reference Center, 2011b); only the larger areas of disturbed land are mapped; many sites have been graded and developed such that unmapped fill is locally present in most developed areas; smaller fill areas and disturbed lands are not mapped due to map-scale limitations; thickness variable.

Lacustrine deposits

Qlf **Lacustrine fine-grained deposits** (Holocene to upper Pleistocene) – Interbedded deposits of moderately sorted silt, clay, and minor fine sand; angular to rounded sand grains; typically thin bedded; deposits include those of Lake Bonneville transgression and regression, the Gilbert inundation, and the late Holocene inundation; mapped downslope from areas of mixed lacustrine and alluvial deposits (Qla); distinguished from Qla by the presence of less sand as noted in the NRCS soil maps (2011); interbedded or laterally gradational with areas of mixed lacustrine and alluvial deposits (Qla); estimated thickness 15 feet (5 m).

Qlg **Lacustrine gravel and sand** (Holocene? to upper Pleistocene?) – Moderately to poorly sorted, pebble to cobble gravel and pebbly sand with minor silt and clay matrix; gravel is subrounded to rounded; well bedded with thin bedding; includes transgressive and/or regressive deposits of Lake Bonneville; located near the intersection of Willard Creek and the Gilbert shoreline, likely related to Gilbert inundation; also mapped above the Gilbert shoreline along Threemile Creek where it might be related to regressive phase of Lake Bonneville; distinguished on aerial photography by elevated mounds above the other alluvial and lacustrine deposits and by the presence of gravelly sandy loam as noted in the NRCS soil maps (2011); estimated thickness 20 feet (6 m).

Deposits of the Provo shoreline and regressive phase of the Bonneville lake cycle: Only mapped below the Provo shoreline ("P" shoreline on map) at elevations of about 4820 to 4860 feet (1470–1482 m) and minor regressive shorelines ("r" shoreline on map) at elevations of about 4380 to 4820 feet (1335–1470 m) in the Willard quadrangle (table 1). In some locations movement on the Brigham City segment of the Wasatch fault zone has displaced shorelines of the Provo and regressive phase of the Bonneville lake cycle. Shorelines are shifted relatively upward in the footwall and downward in the hanging wall.

Qlgp **Lacustrine gravel and sand** (upper Pleistocene) – Moderately to well-sorted, pebble to cobble gravel and pebbly sand and silt, with boulders near bedrock sources; gravel locally cemented with calcium carbonate (tufa); subrounded to rounded gravel; thin to thick bedded; mostly veneers over bedrock and possibly over older alluvial-fan deposits on mountain front slopes; typically partly covered by colluvium; interbedded with or laterally gradational to mixed lacustrine and alluvial deposits (Qla); thickness 3 to 50 feet (1–15 m).

Deposits of Bonneville shoreline and transgressive phase of the Bonneville lake cycle: Mapped below the Bonneville shoreline and above the Provo shoreline. The highest Bonneville shoreline ("B" shoreline on map) is at elevations of about 5180 to 5200 feet (1580–1585 m) (table 1) and minor transgressive shorelines ("t" shoreline on map) are at elevations of about 4860 to 5180 feet (1482–1580 m) in the Willard quadrangle (table 1). Most of the Bonneville shorelines are in the footwall of the Wasatch fault zone. In one location (section 36, T. 9 N., R. 2 W., Salt Lake Base Line and Meridian) the Brigham City segment of the Wasatch fault zone has displaced the Bonneville shoreline, giving it a lower elevation than average in the hanging wall.

Qlgb **Lacustrine gravel and sand** (upper Pleistocene) – Moderately to well-sorted, pebble to cobble gravel in a matrix of sand and silt, with boulders near bedrock sources; locally interbedded with silt and pebbly sand; clasts commonly subrounded to rounded, but some deposits consist of poorly sorted, angular gravel derived from nearby bedrock outcrops; a few gravels are locally cemented with calcium carbonate (tufa); thin to thick bedded; forms veneers over bedrock mountain front slopes, typically below wave-cut benches at the Bonneville shoreline; commonly partly covered by colluvium on these slopes and benches; locally includes barrier bar deposits along the Bonneville shoreline, including at the mouth of Perry Canyon, 0.7 mile (1 km) north of Perry Canyon at Perry Basin, and 1.2 miles (2 km) south of Perry Canyon; thickness 3 to 50 feet (1–15 m).

Mass-movement deposits

Qmf_1 **Debris-flow deposits** (upper Holocene) – Poorly sorted pebble to boulder deposits, in a matrix of sand, silt, and clay; boulders are 3 to 6 feet (1–2 m) and greater in diameter; subangular to angular clasts; thin to thick bedded; some clasts are imbricated in the downstream direction; deposited by debris flows and debris floods from Willard Canyon; distinguished from modern alluvial-fan deposits (Qaf_1) on aerial photography by a rougher texture; includes historical deposits from a major flood event on August 13, 1923, and other historical floods between 1906 and 1936 (Woolley, 1946); same debris flow as cd1 unit of Personius (1990); similar debris flows in modern alluvial-fan deposits are too small to show at map scale; estimated thickness 3 to 10 feet (1–3 m).

Qmf_2 **Older debris-flow deposits** (middle Holocene?) – Poorly sorted pebble to boulder deposits in a matrix of sand, silt, and clay; subangular to angular clasts; deposited by prehistoric debris flows and floods from Holmes Canyon and incised by modern alluvial-fan deposits (Qaf_1); offset across the Brigham City segment of the Wasatch fault zone; Lake Bonneville regressional shorelines are covered by these deposits; same as debris flow unit cd2 mapped by Personius (1990); thickness 20 to 30 feet (7–10 m).

Qms **Landslide deposits** (Holocene to middle Pleistocene?) – Poorly sorted clay- to boulder-sized material in slides, slumps, and minor flows; grain size varies with the properties of the source material; characterized by hummocky topography, main and internal scarps, and chaotic bedding in displaced bedrock; mapped separately from landslides in which the bedrock unit is identifiable, mapped as Qms(Ꞓu, Zp, Zpg, Zpd, Zpsg, or YXfu), and from identifiable bedrock blocks with bedding that have moved downslope, mapped as Qmsb(Zp, Zpd, Zpsg, YXfvq, YXfdi, YXfqs, or YXfg); a large landslide and rock fall are mapped at the quadrangle boundary in Willard Canyon and other smaller landslides exist along the Wasatch Range and in Lake Bonneville lacustrine gravel and sand deposits (Qlgb and Qlgp); slopewash and soil-creep deposits grade into landslide deposits in areas of subdued morphology; two large landslide complexes are mapped in which the bedrock is displaced or appears to be displaced—see Qms(unit) and Qmsb(unit), one on the south side of Perry Canyon and the other on the hummocky topography north of Willard Canyon, including the Facer Creek drainage and White Rock area; not divided by age because landslides with subdued morphology (suggesting that they are older, weathered, and have not moved recently) may continue to exhibit slow creep or are capable of renewed movement if stability thresholds are exceeded (Ashland, 2003); age and stability determinations require detailed geotechnical investigations; smaller landslides are not mapped due to map scale limitations; thickness highly variable.

Qms(Ꞓu), Qms(Zp), Qms(Zpg), Qms(Zpd), Qms(Zpsg), Qms(YXfu)

Landslide with identifiable bedrock fragments (Holocene to middle Pleistocene?) – Landslides where the bedrock is identifiable and dominated by one unit, mapped as Qms(unit); bedrock can typically be identified in fragments in the landslide; unit has characteristic landslide features of hummocky topography, slumps, scarps, and chaotic bedding in displaced bedrock; distinguished from landslides deposits (Qms) by the identification of bedrock fragments, and distinguished from landslide bedrock blocks Qmsb(unit) by the characteristic landslide traits listed above; descriptions of bedrock units are in the geologic unit description; previously mapped as bedrock and landslides by Crittenden and Sorensen (1985a); not divided by age because landslides with subdued morphology (suggesting that they are older, weathered, and have not moved recently) may continue to exhibit slow creep or are capable of renewed movement if stability thresholds are exceeded (Ashland, 2003); age and stability determinations require detailed geotechnical investigations; thickness highly variable.

Qmsb(Zp), Qmsb(Zpd), Qmsb(Zpsg), Qmsb(YXfvq), Qmsb(YXfdi), Qmsb(YXfqs), Qmsb(YXfg)

Landslide bedrock blocks (Holocene to middle Pleistocene?) – Blocks of bedrock that have moved downslope in landslides are mapped as Qmsb(unit); distinguished from other landslide units Qms(unit) and Qms by the largely intact nature of the blocks, and the lack of hummocky topography, slumps, or scarps in the block; blocks are typically surrounded by landslides with these features; unit typically contains identifiable bedding; see geologic unit description for lithologic descriptions of bedrock units; previously mapped as faulted blocks of bedrock in a landslide complex and in-place bedrock by Crittenden and Sorensen (1985a); not divided by age because landslides with subdued morphology (suggesting that they are older, weathered, and have not moved recently) may continue to exhibit slow creep or are capable of renewed movement if stability thresholds are exceeded (Ashland, 2003); age and stability determinations require detailed geotechnical investigations; thickness highly variable.

Qmt **Talus deposits** (Holocene to middle Pleistocene?) – Poorly sorted pebble- to boulder-sized material;

subangular to angular; composed of locally derived clasts; deposits typically present above and below the Bonneville shoreline along the Wasatch Range; other small and thin talus deposits are not mapped due to map-scale limitations; includes fresh, potentially active rockfall to partially vegetated and stabilized talus slopes; thickness 3 to 15 feet (1–5 m).

Qmso(Zcc), Qmso(Zpc), Qmso(Zkc)

Older landslide, with identifiable bedrock fragments and blocks (Holocene? to middle Pleistocene?) – Poorly sorted colluvium, and clay to boulder-sized debris with angular pieces of bedrock (Zcc, Zpc, and Zkc); characterized by eroded scarps, elevated flank margins, internal offset of bedrock units, and lack of hummocky topography and toe thrust(s); appear to be older landslides because most characteristic geomorphic features of landslides are not present and could have been removed by erosion; may have failed on fault planes in the footwall of the Wasatch fault zone; Crittenden and Sorensen (1985a) mapped the margins and scarps of these landslides as faults, Coogan and King (2016) mapped them as landslide bedrock blocks with no age connotation; landslides with subdued morphology (suggesting that they are older, weathered, and have not moved recently) may continue to exhibit slow creep or are capable of renewed movement if stability thresholds are exceeded (Ashland, 2003); age and stability determinations require detailed geotechnical investigations; thickness unknown.

Spring and marsh deposits

Qsm **Spring and marsh deposits** (Holocene to upper Pleistocene?) – Fine-grained, organic-rich sediment associated with springs, ponds, seeps, and wetlands; mostly wet, but seasonally dry; may locally contain peat deposits; overlie lacustrine fine-grained deposits (Qlf) and grade laterally into undivided lacustrine and alluvial deposits (Qla); distinguished from undivided lacustrine and alluvial mud-flat and marsh deposits (Qlam) by the presence of wetlands and the lack of alluvial deposits; mapped where the water table is high in the lowlands in the Bear River delta and east of Interstate Highway 15; supports the growth of tall reeds, which aid mapping on aerial photographs; some marsh deposits in the Bear River delta may be the result of impounded water and wetlands controlled by dikes and water-control actions of the Bear River National Migratory Bird Refuge and other wetlands mitigation; smaller spring and marsh deposits are not mapped due to map-scale limitations; estimated thickness less than 10 feet (3 m).

Mixed-environment deposits

Qad **Fan-delta deposits** (upper Pleistocene) – Poorly to moderately sorted sand and gravel; very coarse to coarse sand, pebble, cobble, and boulder clasts; rounded to angular clasts, includes reworked Lake Bonneville gravels; thin to medium bedded; some beds appear to be repeating coarsening upward sequences, while others are unbedded, poorly sorted gravels; locally gravel-poor and sand-rich in parts of the Willard Canyon deposits; mapped at the mouth of Box Elder Canyon where regressive-phase alluvial fans entered Lake Bonneville; also mapped at Perry and Willard Canyons where deposits include Lake Bonneville transgressive and regressive alluvial-fan and deltaic deposits; includes both fan and deltaic deposits, typically with fan over delta; exposed thickness approximately 200 to 300 feet (60–90 m).

Qadg **Deltaic and alluvial gravel deposits** (upper Pleistocene) – Moderately to poorly sorted gravel and sand in a matrix of fine sand and silt; pebble and cobble gravels are clast supported and are subrounded to rounded; deposited in deltaic foreset and alluvial topset beds at the mouth of Box Elder Canyon during the occupation of the Provo shoreline of Lake Bonneville (Personius, 1990; Jensen and King, 1999); most exposures of the unit in the northeast corner of the quadrangle have been extensively excavated during aggregate (gravel and sand) operations; estimated thickness is up to 250 feet (75 m) (Jensen and King, 1999); Smith and Jol (1992) imply the deposits are up to 400 feet (120 m) thick.

Qac **Alluvial and colluvial deposits, undivided** (Holocene to middle Pleistocene?) – Poorly to moderately sorted, generally poorly stratified, clay- to boulder-size, locally derived sediment; can contain recycled deposits of Lake Bonneville; deposited by streams and slope wash and soil creep; typically mapped in drainages that are cut in bedrock or are underlain by bedrock at shallow depths; also mapped in Perry and Holmes Canyon where deposits of alluvium, slope wash, and soil creep grade into one another, mapped along the Provo shoreline (“P” shoreline on map) where the shoreline is partially concealed by the deposits; small, thin unmapped deposits are likely in most small drainages and along many Lake Bonneville shorelines; thickness less than 15 feet (5 m).

Qla **Lacustrine and alluvial deposits, undivided** (Holocene to upper Pleistocene) – Poorly to moderately sorted pebble to cobble gravel, sand, silt, and clay; deposits are undifferentiated because the materials grade imperceptibly into one another; subangular to rounded clasts; mapped downslope from alluvial fans and where Willard Creek emptied into Willard Bay; obscured by construction of the Willard Bay Reservoir; typically coarse grained upslope, transitioning to finer grained downslope; locally contains more gravel near the intersection of Willard Creek and Willard Bay; distinguished from lacustrine fine-grained deposits (Qlf) by the presence of more gravel and sand as noted in the NRCS soil maps (2011), and by the change in slope from alluvial-fan surface to flatter valley floor; estimated thickness 15 to 45 feet (5–14 m).

Qlam **Lacustrine, alluvial, mud-flat, and marsh deposits, undivided** (Holocene to upper Pleistocene) – Moderately to well-sorted silt, clay, and minor sand and pebbles; subrounded to well-rounded clasts; mapped where marsh, alluvial, and lacustrine deposits cannot be distinguished from one another and are so intermixed that they cannot be shown separately at map scale; mapped east of the Bear River deltaic plain where deposits lack scars from meandering alluvial channels but may contain small alluvial deposits; subaqueous to subaerially exposed depending on Great Salt Lake water elevation and water-control actions of the Bear River National Migratory Bird Refuge and other wetlands mitigation actions; estimated thickness greater than 15 feet (5 m).

Qmc **Landslide and colluvium deposits, undivided** (Holocene to upper Pleistocene?) – Poorly sorted clay- to boulder-size debris; deposits of landslides, slope wash, and soil creep that grade into one another in areas where mapping colluvium separately from landslides is not possible at map scale; mapped near the mouth of Perry Canyon where Lake Bonneville gravels are slumping and hummocky in a steep bank cut by Threemile Creek; thickness 0 to greater than 30 feet (0–9+ m).

Stacked-unit deposits

Stacked units are a thin covering of one unit over another, which is shown by the upper map unit (listed first) then a slash, then an underlying unit (for example Qct/Xfc). The upper unit is a surficial deposit while most lower units are bedrock. We map the stacked unit where it is important to show both units. The upper unit is typically thin (around 6 to 10 ft [2–3 m] thick) and partially conceals but does not obscure the lower unit.

Qlgp/Qms, Qlgp/Zpc, Qlgp/Zkc, Qlgp/YXfg, Qlgp/Xfc

Lacustrine gravel and sand (regressive phase) over landslide deposits or bedrock (see each unit for age) – A veneer of moderately to well-sorted lacustrine gravel, sand, and silt, related to the Provo shoreline and regressive phase of Lake Bonneville, that partially conceals landslide deposits (Qms), or bedrock (Zpc, Zkc, YXfg, or Xfc); some parts of Qlgp/Qms have hummocky topography where lacustrine deposits and underlying (older) landslide deposits are displaced and tilted by reactivated landsliding; occurs below the Provo shoreline along the base of the Wasatch Range; deposits on bedrock slopes and shoreline benches are 3 to 40 feet (1–12 m) thick.

Qlgb/Qms, Qlgb/Zkc, Qlgb/Zpd, Qlgb/YXfg, Qlgb/Xfc

Lacustrine gravel and sand (transgressive phase) over landslide deposits or bedrock (see each unit for age) – A veneer of moderately to well-sorted lacustrine gravel, sand, and silt, related to the Bonneville shoreline and transgressive phase of Lake Bonneville, partially conceals landslide deposits (Qms) or bedrock (Zkc, Zpd, Xfc, or YXfg); some parts of Qlgb/Qms have hummocky topography where lacustrine deposits and underlying (older) landslide deposits are displaced and tilted by reactivated landsliding; typically on wave-cut benches close to the Bonneville shoreline along the base of the Wasatch Range; commonly partly covered by colluvium derived from adjacent oversteepened slopes; deposits on bedrock slopes and shoreline bench deposits are 3 to 30 feet (1–10 m) thick.

Qct/Xfc **Colluvium and talus over Farmington Canyon Complex bedrock** (Holocene to upper Pleistocene?/ Paleoproterozoic) – Deposits of poorly sorted sand- to boulder-sized clasts of angular to subangular colluvium and talus that partially conceal gneiss and amphibolite bedrock of the Farmington Canyon Complex along the Bonneville shoreline at the mountain front; clasts are local Farmington Canyon Complex bedrock; differentiated from talus deposits (Qmt) by the addition of colluvium; only mapped south of Willard Canyon; mapped as Qmtc/Xfcg in the Plain City quadrangle (Harty and others, 2012); thickness about 0 to 10 feet (0–3 m).

Unconformity

WILLARD THRUST SHEET

NEOPROTEROZOIC

Neoproterozoic age assignment for Caddy Canyon Quartzite, Papoose Creek Formation, Kelley Canyon Formation, and Maple Canyon Formation is based on a hornblende K-Ar age of 570 Ma in the overlying Browns Hole Formation noted in Crittenden and Sorenson (1985a) and detrital zircon U-Pb age of 667 ± 5 Ma in the underlying graywacke of the Perry Canyon Formation (Balgord and others, 2013).

Zcc **Caddy Canyon Quartzite** (Neoproterozoic) – Vitreous quartzite; variable colors that include white, pale yellowish brown, pale olive, greenish gray, dark gray, and grayish purple; fine to medium grained; moderate to well sorted; low- to high-angle cross-bedding, with medium to thick bedding; includes minor interbedded argillite layers and pebble conglomerate lenses; ledge forming; mapped north of Perry Canyon; the contact between the base of the Caddy Canyon Formation and Papoose Creek Formation is gradational and placed where interbedded argillite beds diminish and quartzite beds dominate; incomplete thickness of about 1300 to 1600 feet (~400–500 m) exposed in the quadrangle; total thickness is 1000 to 1600 feet (300–500 m) in the adjacent Mantua, North Ogden, and Plain City quadrangles (Crittenden and Sorenson, 1985a, 1985b).

Zpc **Papoose Creek Formation** (Neoproterozoic) – Interbedded, olive-gray argillite and dark-yellowish-brown to pinkish-gray quartzite; argillite is thin bedded to thinly laminated to wavy bedded; quartzite is thin to medium bedded with soft sediment deformation, syneresis cracks (mud cracks), and ripple marks; quartzite is fine to medium grained; the Papoose Creek Formation is a gradational lithology from the fine-grained Kelly Canyon Formation below to the Caddy Canyon Quartzite above; interbeds of argillite and quartzite are slope and ledge formers, respectively; mapped north of Perry Canyon; the base of the Papoose Creek Formation was mapped at the first thick quartzite bed above the fine-grained Kelley Canyon Formation; estimated thickness 900 to 1500 feet (275–460 m); thickness of the unit in the Mantua quadrangle is 750 to 1000 feet (230–300 m) (Coogan and King, 2016), difference in thickness may be due to difficulty picking top and basal contacts.

Zkc **Kelley Canyon Formation** (Neoproterozoic) – Gray to olive-gray weathering, slope-forming argillite to slate to phyllite with minor layers of fine-grained quartzite; micaceous to graphitic; alternating yellowish-gray to greenish-gray silt and dark-gray to olive-gray, fine-grained laminations; locally contains mafic and ultramafic intrusive rocks (Balgord and others, 2013); mapped north of Perry Canyon, with one small outcrop at the intersection of U.S. Highway 89/91 within the quadrangle boundary; the base of the Kelley Canyon Formation was mapped where argillite is dominant above quartzite beds of the Maple Canyon Formation; estimated thickness is 500 to 600 feet (150–180 m) in map area; Crittenden and Sorenson (1985a) report a thickness of the unit in the Mantua and Willard quadrangles of 600 feet (180 m); Coogan and King (2016) reported 1000 feet (300 m) thick in the Mantua quadrangle.

Zmc, Zmcl

Maple Canyon Formation (Neoproterozoic) – White to pinkish-gray to yellowish-gray to light-green quartzite and minor quartz-pebble meta-conglomerate, with intervals of yellowish-gray to dusky yellow meta-limestone and greenish-gray argillite; quartzite is fine to very coarse grained, quartzose to subarkosic, and contains mostly sub-rounded to rounded grains; the meta-limestone is a minor component, mapped as marker unit Zmcl where possible, and is laminated, contains sandstone lenses, and is interbedded with the greenish-gray meta-siltstone; the argillite is thinly laminated; the unit is a ledge- to slope-former; mapped north of Threemile Creek in Perry Canyon; locally contains mafic and ultramafic intrusive rocks (Balgord and others, 2013) that were not noted by previous workers (see Crittenden and others, 1971; Sorensen and Crittenden, 1979; Crittenden and Sorenson, 1985a, 1985b); when compared with the Maple Canyon Formation to the east in the Ogden 30′ x 60′ quadrangle (Coogan and King, 2016) our unit has more quartzite and no upper conglomerate; the contact of the Maple Canyon Formation with the underlying graywacke-argillite member of the Perry Canyon Formation is gradational to intercalated, and our contact is placed at a different stratigraphic position than in the previous map of the area (Crittenden and Sorenson, 1985a); for this map, the contact is placed at the top of the uppermost thick argillite interval of the Perry Canyon Formation, whereas Balgord and others (2013) placed the contact at the base of the lowermost thick quartzite interval of the Maple Canyon Formation; detrital zircon U-Pb age spectra from the Maple Canyon Formation record Archean grains and lack the Neoproterozoic grains of the older Perry Canyon Formation (Balgord and others, 2013; sample 18JK08, table 3 and plate 1); estimated thickness is 1200 to 1500 feet (350–450 m).

Perry Canyon Formation – This burial-metamorphosed formation was divided into seven informal members by Balgord and others (2013), from top to bottom: (1) graywacke, (2) diamictite, (3) mafic volcanic and intrusive rocks (greenstone), (4) slate, (5) pebbly slate, (6) quartzite-grit, and (7) arkosic grit; in the following descriptions, the prefix meta- that signifies their metamorphic origin has been omitted for simplicity. The upper four members are present in the Willard quadrangle and the slate and volcanic members are thin and mapped together as a single unit. The type section for the Perry Canyon Formation is located north of Facer Creek and south of Perry Canyon; see plate 1 for location and Balgord and others (2013) for description. Due to an unconformity with the Facer Formation at the type locality, the three lower units are likely missing. The upper contact with the Maple Canyon Formation is uncertain but is likely above the top of their section (Balgord and others, 2013). The composite reference section on Fremont Island also lacks exposed upper and lower contacts (Balgord and others, 2013). Due to rapid lateral and vertical changes in lithology, Coogan and King (2016) placed Balgord and others' (2013) lower four units in an informal "mudstone" member. U-Pb dating of abundant volcaniclastic, euhedral zircon grains yielded a maximum depositional age of 667 ± 5 Ma for the graywacke member (table 3 and plate 1, sample 38EAB09), and a maximum depositional age of 703 ± 6 Ma for the diamictite member (table 3 and plate 1, sample 36EAB09) (Balgord and others, 2013) in the quadrangle.

The Perry Canyon Formation is about 2000 feet (600 m) thick in the quadrangle, but varies regionally, particularly individual members (Balgord and others, 2013). Variation likely due to syndepositional normal faulting and tectonic modification during Cretaceous thrusting (Balgord and others, 2013). Crittenden and Sorenson (1985a) divided the formation into informal mudstone, sandstone, and diamictite members in the Willard and Mantua quadrangles, but failed to recognize that only one diamictite is present (see Crittenden and others, 1983), which is repeated by faulting. They thereby misinterpreted thickness and stratigraphic relationships.

Zp **Perry Canyon Formation, undivided** (Neoproterozoic) – Mapped where informal members cannot be separated because of intense deformation and poor exposures; mapped along the eastern quadrangle boundary and between the main Willard thrust fault and a Willard imbricate thrust fault; cleavage is well developed in this unit.

Zpg **Graywacke member** (Neoproterozoic) – Interlayered olive-gray to medium-gray, moderately to poorly sorted, feldspathic to lithic wacke, and dark-yellowish-brown to olive-gray argillite; locally near base includes a <10-foot- (2-m-) thick interval of thin- to medium-bedded, micritic meta-carbonate (Zpl) with soft sediment deformation and oncoids up to 1 inch (2.5 cm) across; locally intruded by mafic to ultramafic dikes (Balgord, 2011); graywacke and argillite form normally graded beds interpreted to be turbidites (Balgord and others, 2013); graywacke contains subangular to subrounded grains of quartz, feldspar, and volcanic lithics in a micaceous, altered matrix; pyrite cubes up to 0.5 inch (1 cm) across are widespread and typically altered; cleavage is best developed in argillite; the member forms ledges and slopes in Perry Canyon and between Perry Canyon and Facer Creek; the lower contact is mapped above the diamictite outcrop; on north side of Perry Canyon Crittenden and Sorenson (1985a) included part of the graywacke member of the Perry Canyon Formation in their Maple Canyon Formation; member thickness is ~650 feet (~200 m); 1000 feet thick (300 m) in the North Ogden quadrangle (Coogan and King, 2016).

Zpl **Carbonate marker unit** (Neoproterozoic) – Medium-light-gray, thin bed of minor meta-carbonate and medium-gray, laminated siltstone; on the ridge north of Facer Creek minor carbonate is thinly bedded with 3- to 9-foot-thick (1–3 m) lenses, interbedded near the base of the graywacke member; on the north slope of Perry Canyon medium-gray laminated siltstone is interbedded with the graywacke in 1- to 4-foot (0.3–1.2 m) intervals with a total thickness of 20 to 30 feet (6–9 m), and contains stylolites, sandy carbonate (dolomite), soft sediment deformation, and 0.5 to 1 inch (1–3 cm) pisoids and/or oncoids; the carbonate in Perry Canyon is underlain by a medium gray feldspathic sandstone with its base covered by alluvium, making its stratigraphic position uncertain; but the thickness of the overlying graywacke implies that the Perry Canyon carbonate, like the carbonate on the ridge north of Facer Creek, is near the base of the graywacke member; total thickness 3 to 30 feet (1–9 m).

Zpd **Diamictite member** (Neoproterozoic) – Dark-gray diamictite with minor interbedded argillite, graywacke, and conglomerate; diamictite contains subrounded to subangular, pebble to boulder clasts (up to 6 feet [2 m] across) composed of granite and gneiss (~40–70%), quartzite (20–30%), volcanic rocks (5–30%) (including trachyte, rhyolite, and basalt), and sedimentary rocks (<10%), in a micaceous to sandy matrix (Balgord and others, 2013,

Table 3. *Location and zircon U-Pb maximum depositional ages of samples in the Willard quadrangle, in stratigraphic order (see plate 1).*

Sample	Description	Zircon U-Pb ages*	Map unit	Easting	Northing
18JK08	Maple Canyon Formation	No Neoproterozoic grains	Zmc	415604	4589681
38EAB09	Perry Canyon graywacke	667 ± 5 Ma	Zpg	415115	4588459
36EAB09	Perry Canyon diamictite	703 ± 6 Ma	Zpd	414890	4588328
32EAB09	Facer Formation gneiss	1582 ± 5 Ma (youngest grain)	YXfg	414545	4588225

Notes:
Ages and locations from Balgord (2011) and Balgord and others (2013)
Location data based on NAD83, UTM Zone 12N
*U-Pb "best age" chosen from $^{206}Pb/^{238}U$ for samples <~1.5 Ga and $^{207}Pb/^{206}Pb$ for samples >~1.5 Ga (see Spencer and others, 2016)

see figures 6 and 11); source of rhyolite clasts is unknown (no older rhyolite is present in the Ogden 30′ x 60′ quadrangle to the east [Coogan and King, 2016]); diamictite is typically unstratified, but locally displays sandy wisps and crude layering defined by clast-rich zones; the diamictite is interpreted as glacio-marine deposits (Balgord and others, 2013); the member forms rocky ledges and slopes partly covered by unmapped colluvium and talus in Perry Canyon and north of Facer Creek, including along the mountain front; the lower contact with the slate and greenstone members is typically obscured by colluvium; estimated member thickness in the quadrangle is 1000 feet (300 m); regional thicknesses are variable, with a minimum thickness of approximately 1000 feet (~300 m) on Fremont Island (Balgord and others, 2013), but only 200 to 400 feet (60–120 m) thick just to the east in the Ogden 30′ x 60′ quadrangle (Coogan and King, 2016); interpreted as correlative with diamictite of the Mineral Fork Formation exposed on Antelope Island that is in the footwall of the Willard thrust fault (Balgord and others, 2013), where it is 0 to 200 feet (0–60 m) thick (Doelling and others, 1990).

Zpsg **Greenstone and slate members, undivided** (Neoproterozoic) – Dark- to medium-gray, graphitic slate and locally overlying greenstone composed of altered mafic igneous rocks; the slate and greenstone members are combined on the Willard quadrangle map because they are thin above a basal unconformity and the greenstone is locally absent; the slate is highly deformed, lacks quartzite beds, and is intruded by mafic dikes and sills; the greenstone member contains pillow basalts with vesiculated rims and agglomerate intruded by dikes and sills; composed mostly of albite, epidote, actinolite, and chlorite; fine-grained, epidote-rich, altered material between pillows may have been fragmental material; the agglomerate contains basalt fragments 0.25 to 4 inches (0.5–10 cm) across in a green matrix; the contact with the overlying diamictite is locally marked by felsic volcanic clasts in a feldspathic matrix in the greenstone; the slate and greenstone members are poorly exposed north of Facer Creek and along Threemile Creek in Perry Canyon; the lower contact is an unconformity with the Facer Formation; in the map area estimated thickness of the slate member is 0 to 100 feet (0–30 m) and of the greenstone member is 0 to 100 feet (0–30 m); in Willard Basin in the Mantua quadrangle the slate member ("mudstone" member of Coogan and King [2016]) is about 1000 feet (300 m) thick and the greenstone member is not present.

Unconformity

MESOPROTEROZOIC AND PALEOPROTEROZOIC

Facer Formation – As described by Crittenden and Sorensen (1980) the Facer Formation is a collection of metamorphic units including quartzite, pelitic schist and phyllite, quartz-muscovite schist, amphibolite (meta-diorite), gneiss, (meta-) carbonate, (meta-) conglomerate, pegmatite, vein quartz, and minor fuchsite-bearing quartzite and quartz-hematite schist. The meta-carbonate, meta-conglomerate, and quartz-hematite schist units are not found in the Willard quadrangle. The vein quartz, meta-diorite, and quartz-muscovite schist units are not in place in the quadrangle due to landsliding—see Qmsb(YXfvq), Qmsb(YXfdi), and Qmsb(YXfqs). In the Mantua quadrangle, muscovite from a schist yielded a K-Ar age of 1342 ± 10 Ma and a Rb-Sr age of 1660 ± 50 Ma; muscovite from a pegmatite in the upper Facer yielded a K-Ar age of 1357 ± 10 Ma and a Rb-Sr age of 1580 ± 50 Ma from the same sample (Crittenden and Sorensen, 1980). Hornblende from meta-diorite that intrudes the gneiss in the Mantua quadrangle yielded a K-Ar age of 1681 ± 12 Ma (Crittenden and Sorensen, 1980). The wide age range between the K-Ar muscovite and hornblende ages may be due to a younger metamorphism/alteration event, or indicate that the schist and pegmatite are significantly younger than the meta-diorite and gneiss that they intrude. A ^{206}Pb/^{207}Pb age from zircons in a quartzite in the gneiss (sample 32EAB09, see table 3 and plate 1) have a minimum age of 1582 ± 10 Ma and a population of Paleoproterozoic grains (~2000 to 2500 Ma) (Balgord, 2011). A pegmatite sample in the gneiss to the east in the Mantua quadrangle has similar age populations (sample 41EAB09 in Balgord, 2011). Based on the available geochronology the Facer Formation is Mesoproterozoic and Paleoproterozoic age, but further work is needed to constrain the age, geologic history, correlation, and characteristics of the various units within the Facer Formation.

Gneiss and meta-diorite along the Willard-Mantua quadrangle boundary appear to be older Facer Formation that forms a paleotopographic high that is unconformably overlain by upper Facer Formation rocks and Perry Canyon Formation strata that notably thin and lap onto the older Facer gneiss (see plate 1 and Coogan and King [2016]).

YXfu **Facer Formation, undivided** (Mesoproterozoic and Paleoproterozoic) – Quartzite, schist and phyllite, quartz-muscovite schist, pegmatite, vein quartz, meta-diorite, and leucocratic gneiss that is typically brecciated with Facer Formation units grading into each other; ledge to slope forming; mapped north of Willard Canyon and south of Perry Canyon; lower contact is concealed where not truncated by thrust faults; thickness unknown.

YXffq **Fuchsitic quartzite** (Mesoproterozoic and Paleoproterozoic) – Greenish-gray to pale-green quartzite colored by 3- to 6-foot-thick (1–2 m) fuchsite (chromian mica) layers; layers seem to follow low-angle fractures or faults along or near bedding in quartzite unit (YXfq) (Crittenden and Sorensen, 1980), but in Mantua quadrangle mapped along faults at a high angle to bedding (see Crittenden and Sorensen, 1985a); ledge forming; mapped along the ridge and cliffs on the north edge of Willard Canyon; about 3 to 9 feet (1–3 m) thick in the map area and mapped as a single line; reportedly 3 to 6 feet (1–2 m) thick in the Mantua and Willard quadrangles (Crittenden and Sorenson, 1985a).

YXfq **Quartzite** (Mesoproterozoic and Paleoproterozoic) – Light-gray to white quartzite, with minor green phyllite; medium to thick bedded, interbedded with the schist and phyllite unit (YXfs) and locally contains fuchsitic quartzite (YXffq); in most places the quartzite is fractured; cliff former; mapped in three bands along the ridge and cliffs on the north edge of Willard Canyon; lower two bands truncated by a thrust fault; thickness is highly variable; quartzite bands are about 100 to 550 feet (30–160 m) thick in map area.

YXfs **Schist and phyllite** (Mesoproterozoic and Paleoproterozoic) – Greenish-gray to dark-greenish-gray schist and phyllite (meta-siltstone to mudstone); varies from fine-grained phyllite to spotted schist; interbedded with the mapped quartzite (YXfq); slope former; mapped in three bands along the north rim of Willard Canyon; schist and phyllite bands vary from 30 to 350 feet (10–100 m) thick; contains meta-conglomerate and meta-carbonate in the Mantua quadrangle (Crittenden and Sorenson, 1985a).

YXfvq **Vein quartz** (Mesoproterozoic and Paleoproterozoic) – White quartz vein; cliff forming; large blocks within landslides; only mapped at White Rock (NE1/4 section 13, T. 8 N., R. 2 W, Salt Lake Base Line and Meridian), forms an unusually large prominent white boulder in a landslide mass near Facer Creek—mapped as Qmsb(YXfvq); host rock for the vein quartz may be the quartz-muscovite schist unit (YXfqs) or the gneiss (YXfg) but is not in place; White Rock outcrop is approximately 40 to 60 feet (10–20 m) high and 100 to 200 feet (30–70 m) across.

Unconformity?

YXfqs **Quartz-muscovite schist** (Mesoproterozoic and Paleoproterozoic) – Light-gray to greenish-gray quartz muscovite schist; composed mostly of coarse-grained quartz and muscovite (sericite); Crittenden and Sorensen (1980) reported garnet, apatite, zircon, and tourmaline; may be intercalated with the gneiss, and may be the host for the large vein quartz body at White Rock (YXfvq) and unmapped quartz-plagioclase pegmatite veins, however, contacts are not apparent in the landslide; slope forming; mapped near Facer Creek within the landslide complex; only mapped in the quadrangle as block within a landslide Qmsb(YXfqs); bedrock source may be east of quadrangle but not exposed (Crittenden and Sorenson, 1985a); based on float in the landslide the schist could make up much of the undivided landslide deposit Qms(YXfu); block at least 30 feet (10 m) across, total thickness unknown.

YXfdi **Diorite** (Mesoproterozoic and Paleoproterozoic) – Dark-greenish-gray meta-diorite; containing fine- to medium-grained hornblende, biotite, plagioclase, and muscovite; ledge former; only mapped in the quadrangle as block within a landslide Qmsb(YXfdi); bedrock source for blocks located east of quadrangle; to the east in the Mantua quadrangle the diorite intrudes the gneiss (YXfg) and has a K-Ar age of 1681 ± 12 Ma (Crittenden and Sorensen, 1980; Crittenden and Sorenson, 1985a)—that same relationship is seen in the landslide block; block about 80 to 200 feet (25–60 m) across; reported thickness of the unit in the Mantua quadrangle is 30 to 130 feet (10–40 m) (Crittenden and Sorenson, 1985a).

YXfg **Gneiss** (Mesoproterozoic and Paleoproterozoic) – Light-gray to light-brownish-gray leucocratic gneiss; composed of quartz and feldspar with minor chlorite and sericite (Crittenden and Sorensen, 1980); pegmatite veins throughout; highly fractured and brecciated locally; may be the host for the large vein quartz body at White Rock (YXfvq) and is intruded by the meta-diorite (1681 ± 12 Ma) in the Mantua quadrangle; gneiss is likely a para-gneiss based on population of Paleoproterozoic zircon grains (see sample 41EAB09, appendix C in Balgord [2011]); ledge to slope former; larger blocks within landslides mapped as Qmsb(YXfg), and could make up much of the undivided landslide deposit Qms(YXfu); base not exposed; landslide block about 100 to 500 feet (30–150 m) across; exposed thickness is 800 feet (240 m), base is not exposed and top appears to be an unconformity.

Willard Thrust Fault

WILLARD THRUST FOOTWALL

CAMBRIAN

Ꞓu **Cambrian, undivided** (Middle to Lower Cambrian?) – Undivided Maxfield Limestone (Ꞓm), Ophir Formation (Ꞓo), and Tintic Quartzite (Ꞓt); only mapped as a landslide deposit with identifiable bedrock fragments, see unit Qms(Ꞓu).

Ꞓm **Maxfield Limestone** (Middle Cambrian) – Upper part is medium-gray, thin- to thick-bedded, micritic to oolitic limestone and dolomite; middle part is medium- to dark-gray, thin- to medium-bedded, argillaceous limestone with abundant orange-weathering silty stringers and flat-pebble conglomerate; lower part is light- to medium-gray, thin- to medium-bedded, micritic limestone with thin, orange-weathering silty stringers; parts are not mapped separately due to complex folding and faulting that thin, thicken, repeat, and omit parts of the formation; upper part is a cliff former, the middle part forms a slope with thin ledges, and the lower part forms ledges; exposed north and south of Willard Canyon; lower contact with the Ophir Formation is placed above the top of the uppermost thick shale interval, but in places the Maxfield Limestone and Ophir Formation are tightly folded, faulted, and tectonically interleaved such that the mapped Maxfield Limestone may locally include tectonic slices of Ophir Formation; Middle Cambrian age based on *Elrathia* sp. trilobites reported by Rigo (1968) in Ogden Canyon and placed in the Maxfield Limestone by Yonkee and Lowe (2004), but neither study provided a detailed sample location; estimated total thickness is 400 to 850 feet (120–260 m) in map area, and is highly variable due to deformation.

Attenuation fault

Ꞓo **Ophir Formation** (Middle Cambrian) – Upper part is gray-brown shale; middle part is light- to medium-gray, thin- to medium-bedded, micritic limestone with orange-weathering silty stringers; lower part is olive-gray to brown micaceous shale and siltstone with thin quartzite beds; upper and lower shales are slope formers whereas limestone forms ledges; the Ophir Formation is tectonically thickened and thinned by minor folds and faults in the footwall of the Willard thrust; mapped above cliffs in the Tintic Quartzite north and south of Willard Canyon; the lower contact with the Tintic Quartzite is gradational over a few tens of feet with alternating quartzite and shale beds; Middle Cambrian age based on *Ehmaniella* sp. and *Glossopleura* sp. trilobites in Ogden Canyon (Rigo, 1968); in the map area thickness is highly variable, but is estimated to be 0 to 150 feet (0–45 m); where less deformed in the Ogden 7.5-minute quadrangle the total thickness is 300 to 660 feet (90–200 m) (Yonkee and Lowe, 2004).

Attenuation fault

Ꞓt **Tintic Quartzite** (Middle to Lower Cambrian?) – White- to pinkish-gray, dark-yellowish-orange weathering, moderately to well sorted, fine- to coarse-grained, quartzose to feldspathic, well-cemented sandstone (orthoquartzite); thin to thick bedded with widely developed cross-beds; contains lenses of moderately to poorly sorted quartz pebble conglomerate up to 3 feet (1 m) thick and arkosic sandstone in the lower part of the formation, and layers of laminated olive-drab to dark-brown argillite up to 1 foot thick (0.3 m) in the upper part of the formation; trace fossils in the upper part of the formation in Ogden Canyon area include *Skolithus* tubes and *Plagiogmus* traces that indicate Middle Cambrian age (Peterson and Clark, 1974); cliff-forming along the eastern margin of the quadrangle north and south of Willard Canyon; lower contact with the Farmington Canyon Complex is a nonconformity where basal arkose and conglomerate with reworked basement clasts fill erosional depressions up to 10 feet (3 m) deep along the top of the Farmington Canyon Complex; estimated thickness 1200 to 1400 feet (360–400 m) in the map area.

Major unconformity

PALEOPROTEROZOIC

Farmington Canyon Complex – Bryant (1988) divided the complex into four main units: (1) quartz-monzonite gneiss, (2) migmatite, (3) schist and gneiss, and (4) quartzite, gneiss, and schist. Smaller exposures include amphibolite, pegmatite, and mica-rich schist. Yonkee and Lowe (2004) divided the complex into nine mapable units. Of these previously mapped and described units only three are present in the Willard quadrangle: granitic gneiss, amphibolite, and pegmatite. The Farmington Canyon Complex is Paleoproterozoic based on geochronologic data in nearby areas; Barnett and others (1993) report $^{207}Pb/^{206}Pb$ monazite ages from gneisses that range from 1640 to 1720 Ma; Nelson and others (2002, 2011) reported a mean monzonite microprobe age of 1705 ± 90 Ma from a gneiss; Mueller and others (2011) reported a $^{207}Pb/^{206}Pb$ age of 2450 Ma for inherited zircon in the granitic gneiss body and a ~1700 Ma $^{207}Pb/^{206}Pb$ age for metamorphic zircon overgrowths (Nelson and others, 2011; Mueller and others, 2011).

Xfc **Farmington Canyon Complex, undivided** (Paleoproterozoic) – Undivided pegmatite, plagioclase-hornblende amphibolite, and granitic gneiss; shown on cross sections and mapped as a stacked unit with talus and colluvium over Farmington Canyon Complex gneiss (Qct/Xfc); thickness is unknown.

Xfcp **Pegmatite** (Paleoproterozoic) – White to light-gray pegmatite veins and dikes; composed of very coarse grained quartz, K-feldspar, and plagioclase with some biotite that locally forms books up to 6 inches (15 cm) wide; intruded into the granitic gneiss and amphibolite; forms ledges; mapped south of Willard Canyon; dike edges locally are darker than the pegmatite; smaller veins and dikes are not shown due to map-scale limitations; veins and dikes are 1 inch (2 cm) to several tens of feet (~10 m) wide, some thicknesses are exaggerated on plate 1 for visibility.

Xfca **Amphibolite** (Paleoproterozoic) – Medium- to dark-greenish-gray amphibolite pods and dikes composed of fine- to coarse-grained hornblende and plagioclase; ledge to slope former; mapped south of Willard Canyon; intruded into granitic gneiss; smaller veins and dikes are not shown due to map-scale limitations; the largest exposures are about 1500 feet (450 m) long and 500 to 600 feet (150–180 m) wide.

Xfcg **Granitic gneiss** (Paleoproterozoic) – Gray, medium- to coarse-grained gneiss (orthognesis) composed of quartz, plagioclase, K-feldspar, and minor biotite, hornblende, and magnetite; magnetite occurs in mafic clots (or spots) with halos of felsic minerals; faults with small offsets in the gneiss were not shown due to map-scale limitations; forms rugged cliffs; mapped south of Willard Canyon; thickness unknown.

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