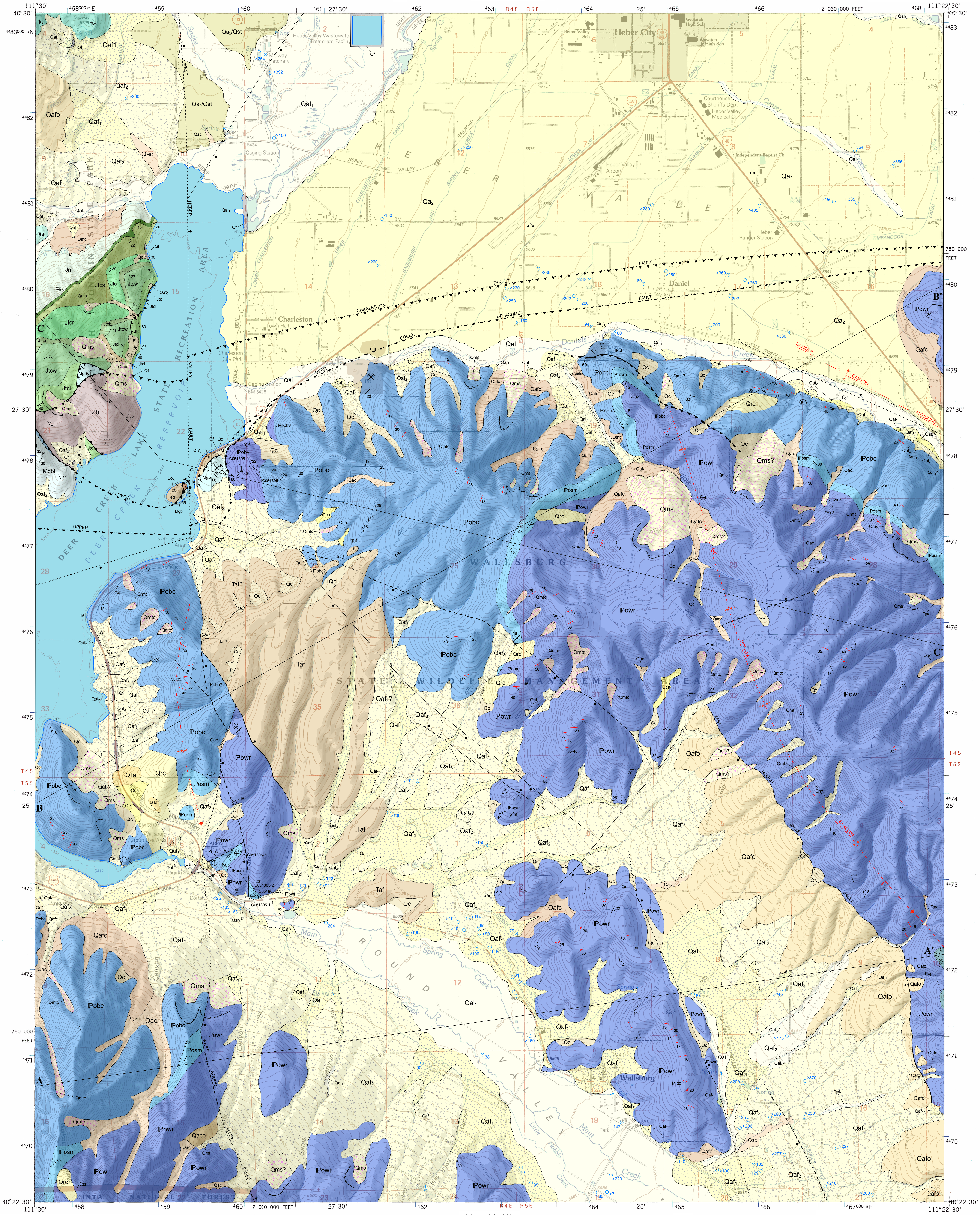


This geologic map was funded by the Utah Geological Survey and the U.S. Geological Survey, National Cooperative Geologic Mapping Program through USGS STATEMAP award number 04HQAG0040. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

UTAH
QUADRANGLE LOCATION

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 40 FEET

GEOLOGIC MAP OF THE CHARLESTON QUADRANGLE, WASATCH COUNTY, UTAH

by

Robert F. Biek and Mike Lowe

2009

12°09'
TRUE NORTH
MAGNETIC NORTH
APPROXIMATE MEAN DECLINATION, 2009

Base from USGS Charleston 7.5' Quadrangle (1993)
Projection: UTM Zone 12
Datum: NAD 1927
Spheroid: Clarke 1886

Project Manager: Jon K. King
GIS and Cartography: Kent D. Brown, Jay Hill, and James Parker
ISBN 1-55791-815-5

Utah Geological Survey
1594 West North Temple, Suite 3110
P.O. Box 146100, Salt Lake City, UT 84114-6100
(801) 537-3300
geology.utah.gov

1	2	3
4		5
6	7	8

1.Brighton
2.Heber City
3.Francis
4.Aspen Grove
5.Center Creek
6.Bridal Veil Falls
7.Wallsburg Ridge
8.Twin Peaks

ADJOINING 7.5' QUADRANGLE NAMES

UTAH GEOLOGICAL SURVEY
a division of
Utah Department of Natural Resources

DESCRIPTIONS OF MAP UNITS

QUATERNARY

Alluvial deposits

Qal₁ — **Alluvial deposits** (Holocene) – Moderately to well-sorted sand, silt, clay, and pebble to boulder gravel; includes river- and stream-channel and floodplain deposits, and terraces as much as 10 feet (3 m) above current stream level; locally includes small alluvial-fan and colluvial deposits; extent is poorly constrained along Center Creek due to subtle geomorphology and modification by agriculture; locally underlain by and interbedded with calcareous tufa in the Snake Creek and Midway fish hatchery areas; 0 to about 30 feet (0-9 m) thick.

Qat_2, Qat_3 — **Stream-terrace deposits** (lower Holocene to upper Pleistocene) – Moderately to well-sorted sand, silt, clay, and pebble to boulder gravel that forms level to gently sloping surfaces above modern drainages; deposited principally in river channels and floodplains; subscript denotes relative age and height above modern drainage with level 2 deposits about 10 to 20 feet (3-6 m) and level 3 deposits about 30 feet (9 m) above modern drainages; mapped along Daniels Creek east of Big Hollow and in an isolated deposit along the west side of Deer Creek Reservoir; the deposit near Deer Creek Reservoir is about 45 feet (12 m) above the level of the now inundated Provo River; 0 to about 30 feet (0-9 m) thick.

Qa_2 — **Valley-fill deposits** (Holocene to upper Pleistocene) – Moderately sorted sand, silt, and pebble to boulder gravel that forms broad, planar, gently west-sloping surface of Heber Valley; has moderately well-developed secondary calcium carbonate in upper part of deposit (Stage II to II+ carbonate of Birkeland and others, 1991) and is locally blanketed by loess veneer; deposited as glacial outwash in braided-stream channels and is thus principally late Pleistocene in age, but may locally include veneer of Holocene alluvial deposits; probably less than 100 feet (30 m) thick; these deposits form the upper part of basin-fill deposits of southern Heber Valley that locally exceed 450 feet (140 m) thick, based on drillers logs of water wells; based on a gravity survey, Peterson (1970) estimated slightly more than 800 feet (245 m) of basin fill in the southwest part of Heber Valley.

Qaf_1 — **Level-1 alluvial-fan deposits** (Holocene) – Poorly to moderately sorted, weakly to non-stratified, clay- to boulder-size sediment deposited principally by debris flows and debris floods at the mouths of active drainages; upper parts typically characterized by abundant boulders and debris-flow levees that radiate away from fan apex; probably less than 40 feet (12 m) thick.

Qaf_2 — **Level-2 alluvial-fan deposits** (upper Pleistocene) – Similar to level-1 alluvial-fan deposits, but incised by modern drainages and are thus typically inactive; characterized by moderately well-developed secondary calcium carbonate in upper part of deposit (Stage II to III carbonate development of Birkeland and others, 1991); Qaf_2 deposits may be cut by a previously unrecognized, down-to-the-west fault that trends parallel to the Boren ditch in the southeastern part of the quadrangle; soils differ across the inferred fault (Woodward and others, 1976), further suggesting a possible fault; Sullivan and Nelson (1983) and Sullivan and others (1988) assigned a latest Pleistocene age to level-2 alluvial-fan deposits at the mouth of Big Hollow, based on soil profile development; Qaf_2 deposits are truncated by Qa_2 deposits in the adjacent Center Creek quadrangle (Biek and others, 2003); 0 to about 50 feet (0-15 m) thick.

Qaf_3 — **Level-3 alluvial-fan deposits** (upper Pleistocene) – Similar to level-2 alluvial-fan deposits, but mapped near the northwest end of Round Valley where deposits stand at an elevation intermediate between adjacent Qaf_2 and Taf deposits; characterized by well-developed secondary calcium-carbonate in upper part of deposit (Stage III carbonate development of Birkeland and others, 1991); query indicates uncertain designation; Qaf_3 deposits appear to be cut by a previously unrecognized, down-to-the-east fault that trends northwest through section 36, T. 4 S., R. 4 E.; 0 to about 50 feet (0-15 m) thick.

Qafo — **Older alluvial-fan deposits** (Pleistocene) – Poorly to moderately sorted, weakly to non-stratified, clay- to boulder-size sediment deeply incised by modern drainages; characterized by well-developed secondary calcium carbonate in upper part of deposit (Stage III+ to IV carbonate development of Birkeland and others, 1991); mapped north of Soldiers Hollow and along the east side of Round Valley; cut by the east Round Valley fault in the SE1/4 section 9, T. 5 S., R. 5 E. and likely to be in fault contact with Wallsburg Ridge strata elsewhere along the trace of the fault in this quadrangle; Qafo deposits are also cut by the Round Valley fault in the adjacent Center Creek quadrangle (Biek and others, 2003); 0 to at least 370 feet (0-110+ m) thick.

Artificial deposits

Qf — **Artificial fill** (Historical) – Fill used to create road and railroad beds; consists principally of local borrow material; although only larger fill deposits are mapped, fill of variable composition may be present in any developed area; variable thickness up to about 30 feet (9 m).

Colluvial deposits

Qc — **Colluvial deposits** (Holocene to upper Pleistocene) – Poorly to moderately sorted, clay- to boulder-size, locally derived sediment deposited on moderate slopes and in shallow depressions by slope wash and soil creep; locally includes talus and mixed alluvial and colluvial deposits too small to map separately; locally grades downslope into alluvial deposits; because most bedrock in the quadrangle is covered by at least a veneer of colluvium, only the larger, thicker deposits are mapped; 0 to about 30 feet (0-9 m) thick.

Mass-movement deposits

Qms — **Landslide deposits** (Holocene to upper Pleistocene) – Landslide deposits are very poorly sorted, clay- to boulder- to large block-size, locally derived sediment deposited principally by rotational and translational movement; characterized by hummocky topography, numerous internal scarps, and chaotic bedding; basal slip surfaces most commonly form in regolithic and colluvial debris that conceals underlying, highly fractured Oquirrh Formation sandstone; large landslides are also mapped on the Twin Creek Limestone and Big Cottonwood Formation; query indicates uncertain designation; thickness variable, but many landslides may be as much as 100 feet (30 m) thick, and the large landslide at the head of Big Hollow, which involves both Wallsburg Ridge bedrock and overlying colluvial and regolithic debris, may exceed 300 feet (100 m) in thickness. Although most landslides in this quadrangle are characterized by slightly to moderately subdued landslide features suggesting they are perhaps older and may not have experienced significant large displacement recently, all landslides may have historical movement; age and stability determinations of landslides require detailed geotechnical investigations; most mapped landslides are newly recognized, but occur on slopes previously mapped as having a moderate landslide-hazard potential (Hylland and Lowe, 1995; Hylland and others, 1995).

Qmt — **Talus deposits** (Holocene to upper Pleistocene) – Very poorly sorted, locally derived, angular, boulder-size and lesser fine-grained interstitial sediment deposited by rock fall on and at the base of steep slopes; typically mapped where it partly fills the uppermost reaches of small drainages; characterized by angular boulder fields that lack vegetation; about 0 to 30 feet (0-9 m) thick.

Mixed-environment deposits

Qac — **Alluvial and colluvial deposits** (Holocene) – Poorly to moderately sorted, generally poorly stratified, clay- to boulder-size, locally derived sediment deposited in swales, small drainages, and the upper reaches of larger ephemeral streams by fluvial, slope-wash, and creep processes; generally less than 30 feet (9 m) thick.

Qaco — **Older alluvial and colluvial deposits** (Holocene to upper Pleistocene) – Similar to younger alluvial and colluvial deposits (Qac), but forms incised, inactive surfaces several tens of feet above modern drainages; mapped in Owens Canyon in the southwest part of the quadrangle and west of Deer Creek Reservoir; 0 to about 50 feet (0-15 m) thick.

Qafc — **Alluvial-fan and colluvial deposits** (Holocene to upper Pleistocene) – Poorly to moderately sorted, weakly to non-stratified, clay- to boulder-size sediment deposited principally by debris flows and debris floods at the mouths of active drainages, but includes significant colluvial sediment shed from adjacent slopes; upper parts typically characterized by abundant boulders and debris-flow levies that radiate away from fan apices; equivalent to level-1 and level-2 alluvial-fan deposits; probably less than 50 feet (15 m) thick, but deposits at Soldier Hollow form a thinner mantle over Nugget Sandstone.

Qca — **Colluvial and alluvial deposits** (Holocene to upper Pleistocene) – Poorly to moderately sorted, clay- to boulder-size, locally derived sediment deposited in swales and small drainages; similar to mixed alluvial and colluvial deposits (Qac), but with a more significant component of colluvium; generally less than 20 feet (6 m) thick.

Qrc — **Residual and colluvial deposits** (Holocene to upper Pleistocene) – Poorly exposed, poorly to moderately sorted, clay- to boulder-size, locally derived sediment; mapped principally on north-facing slopes where it supports dense vegetation and obscures bedrock contacts; also mapped near Highway 189 just north of Main Creek where it may contain reworked finer grained alluvial and loess deposits; 0 to about 20 feet (0-6 m) thick.

Qmtc — **Talus and colluvial deposits** (Holocene to upper Pleistocene) – Very poorly sorted, angular to subangular, cobble- to boulder-size and finer grained interstitial sediment deposited principally by rock fall and slope wash in steep washes throughout the quadrangle; includes minor alluvial sediment at the bottom of the washes; generally less than 40 feet (12 m) thick.

Stacked-unit deposits

Qa_2/Qst — **Valley-fill deposits over calcareous spring tufa deposits** (Holocene to upper Pleistocene/Holocene to Pleistocene) – Valley-fill deposits derived principally from mountains west and northwest of Heber Valley that form a veneer over and interfinger with calcareous spring tufa deposits; tufa is pale grayish yellow, weathers light brown, and is highly porous and vuggy; tufa is exposed at and near mapped springs and likely underlies much of the surrounding surface where it is concealed beneath tilled valley fill deposits; tufa, interbedded with valley-fill, is reported to depths of nearly 170 feet (52 m) in monitoring wells (Wallace, 2005) and to 392 feet (120 m) in a water well (Mayo and others, 2005) near the Midway fish hatchery.

unconformity

QUATERNARY AND TERTIARY

QTa — **Older alluvial deposits** (lower Pleistocene to Pliocene?) – Unconsolidated, moderately sorted, fine- to medium-grained sand and silt with lenses of pebble- to small-cobble-size gravel; clasts are subrounded to rounded sandstone and limestone of inferred Pennsylvanian affinity, and minor andestitic volcanic clasts likely derived from the Keetley Volcanics that border the east part of Heber Valley; likely represents ancestral Provo River deposits preserved in a cutoff meander now occupied by Highway 189, nearly 300 feet (90 m) above the Provo River prior to inundation by Deer Creek Reservoir; first recognized by Sullivan and others (1988) who suggested that these deposits are greater than 730,000 years old, based on paleomagnetic analysis of overlying finer-grained colluvium; 0 to about 30 feet (0-9 m) thick.

unconformity

TERTIARY

Taf — **Alluvial-fan deposits** (Pliocene?) – Poorly to moderately sorted, clay- to boulder-size sediment preserved in a graben at the northwest end of Round Valley; query indicates uncertain designation; neither Taf nor Taf? deposits are well exposed, but clasts weathering out of both consist of subangular sandstone, orthoquartzite, and minor limestone derived from the adjacent Oquirrh Formation; Taf forms deeply incised, westward sloping surface within the graben, where it overlies queried alluvial-fan deposits (Taf?); Taf? deposits may be Pennsylvanian Bear Canyon Member concealed by a veneer of colluvium and regolithic debris; contact between Taf and Taf? deposits corresponds to an abrupt break in slope that may reflect better cementation of Taf versus Taf?; Taf deposits within the graben likely exceed 300 feet (90 m) thick in the southern part of section 35, T. 4 S., R. 4 E., but are about 40 to 80 feet (12-24 m) thick where they overlie Taf?; Taf? strata exceed 450 feet (135 m) in thickness.

unconformity

PARAUTOCHTHONOUS STRATA

Twin Creek Limestone (Middle Jurassic, Callovian to middle Bajocian) – Consists of seven members, the oldest six of which are exposed below the Charleston thrust fault west of Deer Creek Reservoir (the Giraffe Creek Member is likely not exposed); thicknesses in this quadrangle are calculated from the map; thicknesses reported from the adjacent Center Creek quadrangle (Biek and others, 2003) were measured by Doug Sprinkel and Hellmut Doelling (UGS unpublished data, June 22, 1999); deposited in warm, shallow, inland sea that occupied a broad backbulge basin that developed in front of the Sevier orogenic belt (Imlay, 1967, 1980).

Jtc — **Twin Creek Limestone, undivided** – Parts of the Rich, Boundary Ridge, Watton Canyon, and Leeds Creek Members that are undivided due to map scale and structural complexity; exposed in the upper plate of a small thrust fault west of Deer Creek Reservoir; exposure in the SE1/4 section 21, T. 4 S., R. 4 E. likely consists of Leeds Creek or possibly Giraffe Creek strata; also used on cross section for entire formation.

Jtcl — **Leeds Creek Member** – Light-gray, splintery, thin-bedded to laminated, slope-forming, argillaceous limestone; incomplete section of about 400 feet (120 m) exposed beneath the Charleston thrust fault; member is 776 feet (235 m) thick about 20 miles (32 km) to the northeast near Peoa (Imlay, 1967); however, Constenius and others (2006) reported that the combined Leeds Creek and Giraffe Creek Members is only about 500 feet (150 m) thick on the southwest flank of the Uinta Mountains.

Jtcw — **Watton Canyon Member** – Yellowish-gray to medium-gray, thin- to thick-bedded, ledge-forming, oolitic limestone, and dense, very fine grained limestone commonly with a conchoidal or rectilinear fracture; locally exhibits well-developed stylolites; upper contact is gradational and is placed at a change from ledge-forming dense limestone to slope-forming argillaceous limestone; about 250 feet (75 m) thick.

Jtcb — **Boundary Ridge Member** – Reddish-brown mudstone, siltstone, and fine-grained sandstone that weathers to form poorly exposed saddles and slopes between more resistant enclosing limestone members; thin bedded to laminated; upper contact is sharp and corresponds to a change from reddish-brown siltstone slopes to gray limestone ledges; about 120 feet (35 m) thick; 145 feet (44 m) thick in adjacent Center Creek quadrangle.

Jtcr — **Rich Member** – Medium-gray, thin- to medium-bedded, finely crystalline, ledge- and slope-forming limestone and argillaceous limestone that weathers to pencil-like fragments and small chips, and very light gray, very fine grained calcareous sandstone with ripple marks; upper gradational contact placed at a change from ledgy slopes of grayish, argillaceous limestone to reddish-brown siltstone slopes; about 160 feet (50 m) thick; 116 feet (35 m) thick in adjacent Center Creek quadrangle.

Jtcs — **Sliderock Member** – Brownish-gray, light-gray-weathering, slope- and ledge-forming, thin- to medium-bedded, dense limestone with a conchoidal fracture, light-gray micritic limestone that weathers to pencil-like fragments, and medium-gray, dense, finely crystalline to very fine grained limestone with *Isocrinus* sp. crinoid columnals and fossil hash near the top; upper gradational contact corresponds to a break in slope between more resistant Sliderock limestone and less resistant, lower part of the argillaceous Rich limestone; about 200 feet (60 m) thick; 209 feet (64 m) thick in adjacent Center Creek quadrangle.

Jtcg — **Gypsum Spring Member** – Slope-forming, dark-reddish-brown, sandy, calcareous siltstone, minor jasperoid, pinkish-brown sideritic limestone, and brown to gray, dense, very fine grained limestone with a conchoidal fracture; weathers to poorly exposed recess between resistant slopes of Nugget Sandstone and Sliderock limestone; upper contact is sharp and marks a change from dominantly reddish-brown siltstone slopes to gray, ledgy limestone; about 60 feet (18 m) thick; 83 feet (25 m) thick in adjacent Center Creek quadrangle.

unconformity (J-1)

Jn — **Nugget Sandstone** (Lower Jurassic) – Moderate-reddish-orange to moderate-orange-pink, massively cross-bedded, moderately well-cemented quartz sandstone composed of well-rounded, fine- to medium-grained, frosted quartz grains; uppermost part is generally white to very pale orange; only upper part exposed, where it forms ledgy slopes west of Deer Creek Reservoir; upper unconformable contact – the J-1 unconformity of Pipiringos and O'Sullivan (1978) – is sharp and planar and corresponds to a prominent lithologic and topographic change, with ledge-forming, massively cross-bedded sandstone below and slope-forming, dark-reddish-brown siltstone above; deposited principally by north winds in a vast coastal and inland dune field (Kocurek and Dott, 1983; Blakey, 1994; Marzolf, 1994; Peterson, 1994); lower part may be Upper Triassic; about 900 to 1000 feet (275-300 m) thick on the saddle west of Soldier Hollow, and about 1260 feet (385 m) thick in West Daniels Land #1 well (Biek and others, 2003).

unconformity (J-0)

TRIASSIC

ℜa — **Ankareh Formation** (Upper and Middle Triassic) – Reddish-brown mudstone, siltstone, and very fine to fine-grained sandstone that weathers to poorly exposed slopes; regionally consists of three members – with a major regional unconformity, the TR-3 unconformity of Pipiringos and O'Sullivan (1978), separating the middle and lower members – that are not mapped separately in this quadrangle due to limited, poor exposure; middle and upper members deposited in fluvial, flood-plain, and lacustrine environments of an interior basin drained by north- and northwest-flowing rivers (Stewart and others, 1972); only about 300 feet (90 m) exposed in this quadrangle, but the Ankareh Formation is 1485 feet (453 m) thick immediately west of the quadrangle (Baker, 1964).

ℜt — **Thaynes Formation** (Lower Triassic) – Incompletely exposed in the extreme northwest corner of the quadrangle; the following description is from Baker (1964): brown-weathering, gray, cherty, locally fossiliferous limestone with some interbedded red-brown to light-brown calcareous sandstone and red shale; deposited in a warm, shallow sea (Blakey and Gubitosa, 1983); only a few hundred feet exposed in this quadrangle, but the formation is 950 feet (290 m) thick to the west in the Aspen Grove quadrangle (Baker, 1964; see also Smith, 1969).

ℜw — **Woodside Shale** (Lower Triassic) – Not exposed; 315 feet (95 m) thick in the adjacent Aspen Grove quadrangle (Baker, 1964), but may be tectonically thinned from 420 to 600 feet (130-180 m) (Constenius and others, 2006).

unconformity

PERMIAN

Ppc — **Park City and Phosphoria Formations** (Upper Permian) – Not exposed; 870 feet (265 m) thick north and west of the Charleston quadrangle (Baker, 1964).

unconformity

STRATA OF THE CHARLESTON THRUST PLATE

PERMIAN TO MISSISSIPPIAN

Oquirrh Formation (Lower Permian to Pennsylvanian) – Divided into, in ascending order, the Bridal Veil Limestone, Bear Canyon, Shingle Mill Limestone, Wallsburg Ridge, and the Granger Mountain Members (Baker and Crittenden, 1961; Baker, 1972, 1976); elevated to group status in the Oquirrh Mountains and other western mountain ranges where the Oquirrh Group consists of the West Canyon Limestone (Lower Pennsylvanian), Butterfield Peaks Formation (Middle Pennsylvanian), and Bingham Mine Formation (Upper Pennsylvanian) (Tooker and Roberts, 1970), but conferred the rank of formation in the Wasatch Range by Baker and Crittenden (1961) and Baker (1964, 1972, 1976); the Oquirrh Formation is about 25,000 feet (7600 m) thick in this area (Baker, 1964; 1972); deposited in the Oquirrh marine basin of north-central Utah and southern Idaho with fine arkosic sand derived principally from the Weber shelf and Uncompahgre Uplift (Welsh and Bissell, 1979).

Pogl — **Granger Mountain Member, lower unit** (Lower Permian, Wolfcampian) – Only lowermost part exposed in the southeast part of the quadrangle, but member consists of two limestone intervals of medium- to very thick bedded, medium-gray, ledge-forming, fossiliferous limestone with few thin beds and nodules of black chert that are separated by a slope-forming, yellowish-brown, calcareous siltstone with few thin limestone interbeds; abundant *Schwagerina*-type fusulinids, locally common rugose and *Syringoporid*-type corals, bryozoans, and crinoid stems; 300 to 500 feet (90-150 m) thick (Biek and others, 2003).

ℙowr — **Wallsburg Ridge Member** (Upper Pennsylvanian, Virgilian and Missourian) – Thick- to very thick bedded, yellowish-brown, siliceous or locally calcareous, feldspathic sandstone; common conchoidal fracture and so weathers like orthoquartzite; locally laminated to cross-bedded; exceptionally poorly exposed and where outcrops are present, bedding commonly difficult to determine due to massive and highly fractured nature of strata; includes rare, thin, silty and sandy limestone interbeds; upper contact corresponds to a change from poorly exposed, slope-forming, yellowish-brown, very fine grained calcareous sandstone to ledge-forming gray fossiliferous limestone; together with the underlying Shingle Mill Limestone, is correlative to the Bingham Mine Formation of the Oquirrh Mountains (John E. Welsh, unpublished notes, 1980-81); about 3700 to 3900 feet (1130-1190 m) thick in adjacent Center Creek quadrangle (Biek and others, 2003).

ℙosm — **Shingle Mill Limestone Member** (Upper Pennsylvanian, Missourian) – Consists of two limestone intervals separated by several tens of feet of thin- to very thick bedded, yellowish-brown to light-olive-gray, very fine to medium-grained, commonly calcareous, slightly feldspathic quartz sandstone with low-angle cross-bedding; limestone is typically sandy and silty in thin to very thick beds, medium to dark gray, with black chert stringers and nodules, and contains uncommon crinoid stems, solitary corals, brachiopods, and thin stringers of fossil hash, but locally, as in the SW1/4SW1/4 section 2, T. 5 S., R. 4 E., contains abundant, partially articulated crinoid stems, bryozoans, solitary and colonial corals, brachiopods, and echinoderm fragments; lower, thinner limestone interval commonly poorly exposed, and in the southwest part of the quadrangle is not mapped; upper, apparently conformable contact corresponds to a change from ledge-forming, gray cherty limestone to slope-forming, poorly exposed, very fine grained, calcareous and silicious sandstone; conodont fauna (table 1) indicates a Missourian age; may be correlative to the Jordan and Commercial Limestones of the Oquirrh Mountains (John E. Welsh, unpublished notes, 1980-81); about 300 to 500 feet (90-150 m) thick.

ℙobc — **Bear Canyon Member** (Middle and Lower Pennsylvanian, Desmoinesian to uppermost Morrowan) – Sandstone with lesser interbedded limestone that is divisible into three informal parts not mapped separately: upper 2000 feet (600 m) is entirely very fine grained sandstone, lower 1000 feet (300 m) is mostly very fine grained sandstone with rare thin limestone intervals, whereas middle part contains several limestone intervals each about 20 to 100 feet (6-30 m) thick; sandstone is yellowish brown, very fine grained, feldspathic, finely laminated in thick to very thick beds, with a siliceous or calcareous cement; limestone is thin to thick bedded, commonly sandy or argillaceous, medium gray with local black chert nodules and stringers and local crinoid stems, bryozoans, and brachiopods; locally, as in the State Highway 189 road cut in SE1/4 section 28, T. 4 S., R.4 E., chert forms spherical nodules similar to those of the "billard-ball limestone" of the Butterfield Peaks Formation at Lake Mountain (Biek, 2004); queried exposure east of Deer Creek Reservoir may be Wallsburg Ridge strata; upper, apparently conformable contact marks a change from yellowish-brown sandstone below to gray cherty limestone above; correlative to the Butterfield Peaks Formation of the Oquirrh Mountains (John E. Welsh, unpublished notes, 1980-81); Shoore (2005) reported latest Morrowan conodonts from the lower few meters of the member (which he called Butterfield Peaks Formation) at Cascade Mountain; best exposures are on the ridgeline in the south part of sections 23 and 24, T. 4 S., R. 4 E. where Welsh (unpublished data, 1981) measured about 4560 feet (1390 m) of Bear Canyon strata; the member is also about 4600 feet (1400 m) thick in the nearby West Daniels Land #1 well (Biek and others, 2003).

ℙobv — **Bridal Veil Limestone Member** (Lower Pennsylvanian, Morrowan) – Medium- to dark-gray, thin- to medium-bedded, rarely thick-bedded, fine- to medium-grained limestone; variably sandy and silty and locally with black or light-gray chert nodules; weathers to ledgy slopes characterized by cyclically interbedded limestone packages composed of slope-forming, thin-bedded, silty limestone capped by ledge-forming fossiliferous limestone with brachiopods and crinoid stems; typically sparse macrofossils include brachiopods, bryozoans, crinoid stems, and trilobites and more commonly thin fossil hash stringers; upper contact placed at the top of the stratigraphically highest limestone ledge, which is overlain by feldspathic sandstone of the Bear Canyon Formation; Shoore (2005; see also Shoore and Ritter, 2007) recognized 21 sequence boundaries within the member caused by glacio-eustatic sea-level fluctuations and reasoned that the member was deposited in cool, shallow-marine water and shows evidence of shoaling and steady progradation of the Weber shelf; the member is largely Morrowan (Lower Pennsylvanian) in age (Baker, 1964; Webster, 1984; Davis and others, 1994); Welsh (unpublished data, 1981) measured an incomplete section of about 800 feet (245 m) at the boundary of sections 22 and 23, T. 4 S., R. 4 E., which we reassign to the Bridal Veil Limestone; 1312 feet (400 m) thick at Squaw Creek Gully on the south side of Mount Timpanogos (Shoore, 2005), similar to the 1245 feet (380 m) that Baker (1972) measured near Bridal Veil Falls in Provo Canyon.

disconformity

PENNSYLVANIAN AND MISSISSIPPIAN

ℙMmc — **Manning Canyon Shale** (lowest Pennsylvanian and Upper Mississippian) – Only exposed as a thin sliver of fault gouge, thus not mapped; served as one of several regional detachment horizons for Cretaceous to early Tertiary contractional and extensional deformation (Paulsen and Marshak, 1998, 1999; Constenius and others, 2003); a thin sliver of dense, black, graphitic clay fault gouge, sharply overlain by very pale orange to grayish orange clay fault gouge, is exposed in a new U.S. Highway 189 road cut about 500 feet (150 m) west of State Highway 113, and this sliver is all that remains of the Manning Canyon Shale along this part of the upper Deer Creek detachment; mostly Upper Mississippian, but contains earliest Pennsylvanian conodonts near the top of the formation (Webster and others, 1984; Shoore and Ritter, 2007); the Manning Canyon Shale is about 1650 feet (500 m) thick in the nearby Bridal Veil Falls quadrangle (Baker, 1972).

Great Blue Limestone (Upper Mississippian, Chesterian) − Regionally divided into three members, ascending: lower limestone member; middle shale member (called the Long Trail Shale Member west of Utah Lake); and upper limestone member; only the lower limestone member (Mgbl) is mapped separately, north of Deer Creek Reservoir; strata exposed at and both northeast and northwest of Deer Creek Island are undivided due to structural complications and limited exposure; age from Gordon and others (2000); deposited in a shallow-marine back-bulge basin of the Antler orogenic belt (Silberling and others, 1997); about 2800 feet (850 m) thick in Rock Canyon in the nearby Bridal Veil Falls quadrangle (Baker, 1972).

Mgb — **Great Blue Limestone, undivided** – Dark-bluish-gray limestone in laminated, thin to medium beds; locally cherty and fossiliferous with brachiopods, corals, and bryozoans; platy weathering; typically forms ledges and cliffs, but weathers to ledgy slopes in this quadrangle due to extensive fracturing and proximity to Charleston thrust fault and Deer Creek detachment fault; contains abundant, calcite-filled fractures; upper contact with Manning Canyon Shale is not exposed, but regionally marks a prominent change from cliff-forming limestone to slope-forming shale; probably less than 150 feet (45 m) of Great Blue strata is exposed in the vicinity of Deer Creek Island; also used on cross section for entire formation.

Mgbl — **Lower limestone member** − Thin- to medium-bedded, light-gray to bluish-gray limestone and fossiliferous limestone with locally abundant bryozoans; upper contact not exposed, but is gradational and corresponds to the first thick interval of slope-forming, grayish, carbonaceous shale; only the lower few hundred feet is poorly exposed in section 21, T. 4 S., R. 4 E.; the member is about 700 to 850 feet (210-260 m) thick in the southern Oquirrh Mountains (Gordon and others, 2000; Constenius and others, 2006).

Mh — **Humbug Formation** (Upper Mississippian) − Only a few tens of feet is exposed immediately above the lower Deer Creek detachment fault where it consists of thin- to medium-bedded, pale-yellowish-brown to olive-gray, variably calcareous or siliceous, fine-grained quartz sandstone; upper contact is conformable and gradational and represents a change from sandstone to limestone; age from Morris and Lovering (1961); cyclic sandstone and limestone represent shallow-marine deposits likely influenced by glacio-eustatic sea-level fluctuations (Veevers and Powell, 1987); the formation is about 520 feet (160 m) thick at Rock Canyon near Provo (Baker, 1972).

CAMBRIAN

Co — **Ophir Formation** (Middle Cambrian) – Yellowish-brown weathering, olive-green micaceous shale and minor gray, thin-bedded, fine-grained limestone believed to be part of the Ophir Formation; incomplete section is folded and faulted as a fault sliver along the lower Deer Creek detachment fault; only a few tens of feet is exposed on the northeast side of Deer Creek Island at low lake levels; complete formation is about 510 feet (155 m) thick to the west in American Fork Canyon (Baker, 1964).

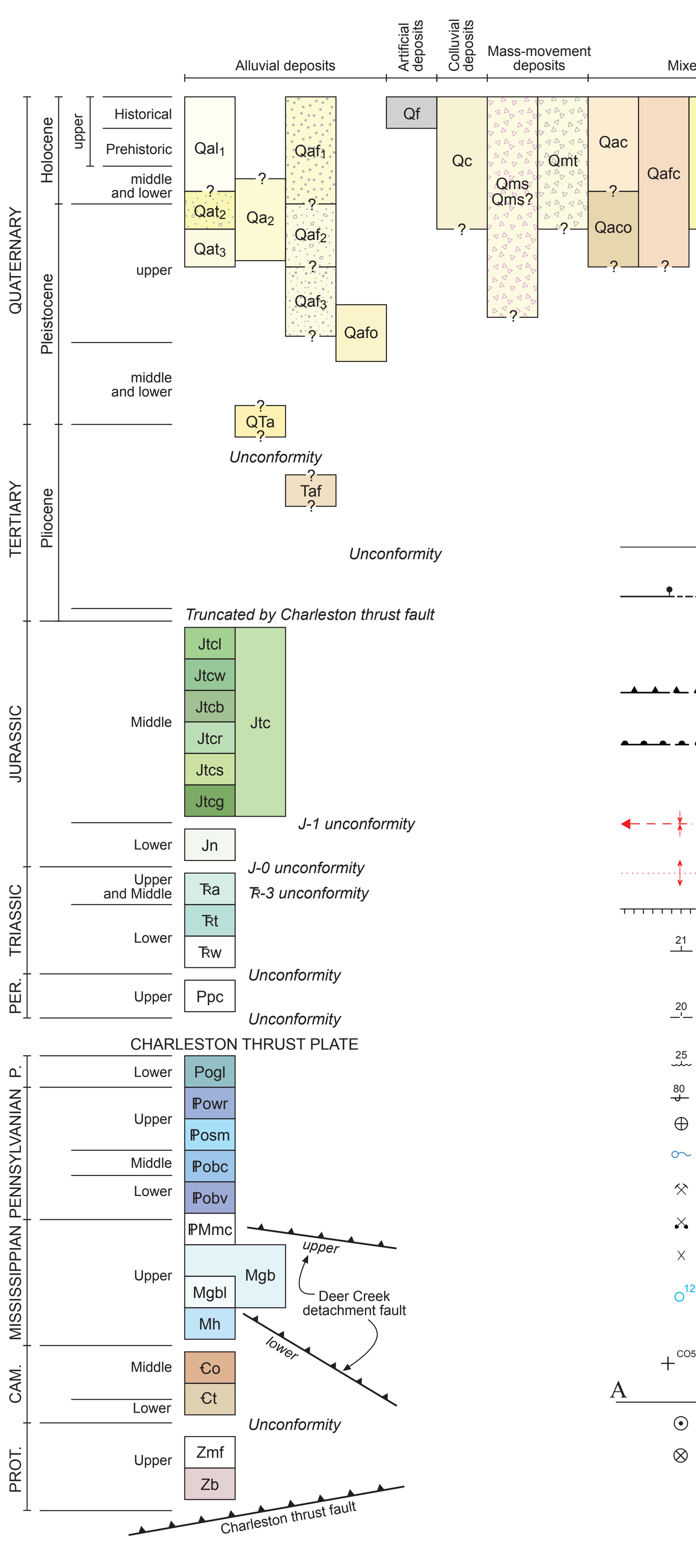
Ct — **Tintic Quartzite** (Middle and Lower Cambrian) – White, light-gray, and light-brown, fine- to medium-grained orthoquartzite in medium to very thick beds with low-angle cross-stratification; locally medium to coarse grained with rounded white quartz pebbles; fracture surfaces commonly stained rusty brown and yellowish brown by iron oxides and hydroxides; forms ledgy slopes at Deer Creek Island where it is in fault contact with Great Blue Limestone; east of Deer Creek Reservoir, exposures along Highway 189 are very light gray to very pale orange, fine-grained or rarely coarse-grained, highly fractured orthoquartzite with low-angle cross-stratification, but lack quartzite pebbles typical of Tintic at Deer Creek Isalnd; query indicates uncertain correlation of these Highway 189 exposures; age from Baker (1964); deposited in beach and coastal-plain environments (Calkins and others, 1943); incomplete section is about 150 feet (45 m) thick, but the formation is 1170 feet (357 m) thick in Slate Canyon near Provo (Baker, 1972).

PRECAMBRIAN

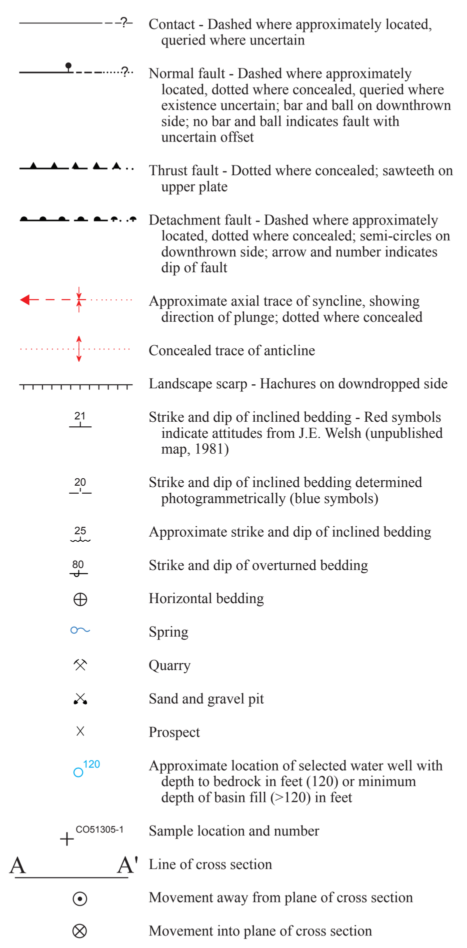
Zmf — **Mineral Fork Tillite** (Upper Proterozoic) – Not exposed, due to truncation by the Deer Creek detachment fault; at least 200 feet (60 m) thick in the Bridal Veil Falls quadrangle, but pinches out southward (Constenius and others, 2006).

Zb — **Big Cottonwood Formation** (Upper Proterozoic) – Exposed west of Deer Creek Reservoir where it consists of moderate- to dark-reddish-brown to grayish-purple, fine- to coarse-grained quartzite; locally contains very coarse grained thin gritstone beds; southernmost outcrops north of the reservoir are commonly white to very light gray with iron-stained fractures and so appear similar to the Tintic Quartzite, and were mapped as Tintic by Reiss (1985), but lack pebbles to boulders typical of basal Tintic strata elsewhere in the region; beds are very thick to massive, fractured, and it is thus difficult to determine bedding attitudes; contains minor micaceous, moderate- to dark-reddish-brown argillite interbeds and in the SW1/4NE1/4 section 21, T. 4 S., R. 4 E., a slope-forming interval several tens of feet thick of grayish-brown to greenish-brown micaceous argillite, siltstone, and very fine grained sandstone that may be a fault sliver of the Ophir Formation (Baker, 1976). New detrital zircon geochronology shows that the formation may be no more than about 770 million years old (Kingsbury and others, 2008); deposited in equatorial tidal and estuarine environments of an east-trending rift valley (Chan and others, 1994; Ehlers and others, 1997); incomplete thickness of about 400 feet (120 m) exposed west of the reservoir, but regionally the formation is about 16,000 feet (5000 m) thick (Crittenden and others, 1952; James, 1979; Bryant, 1992).

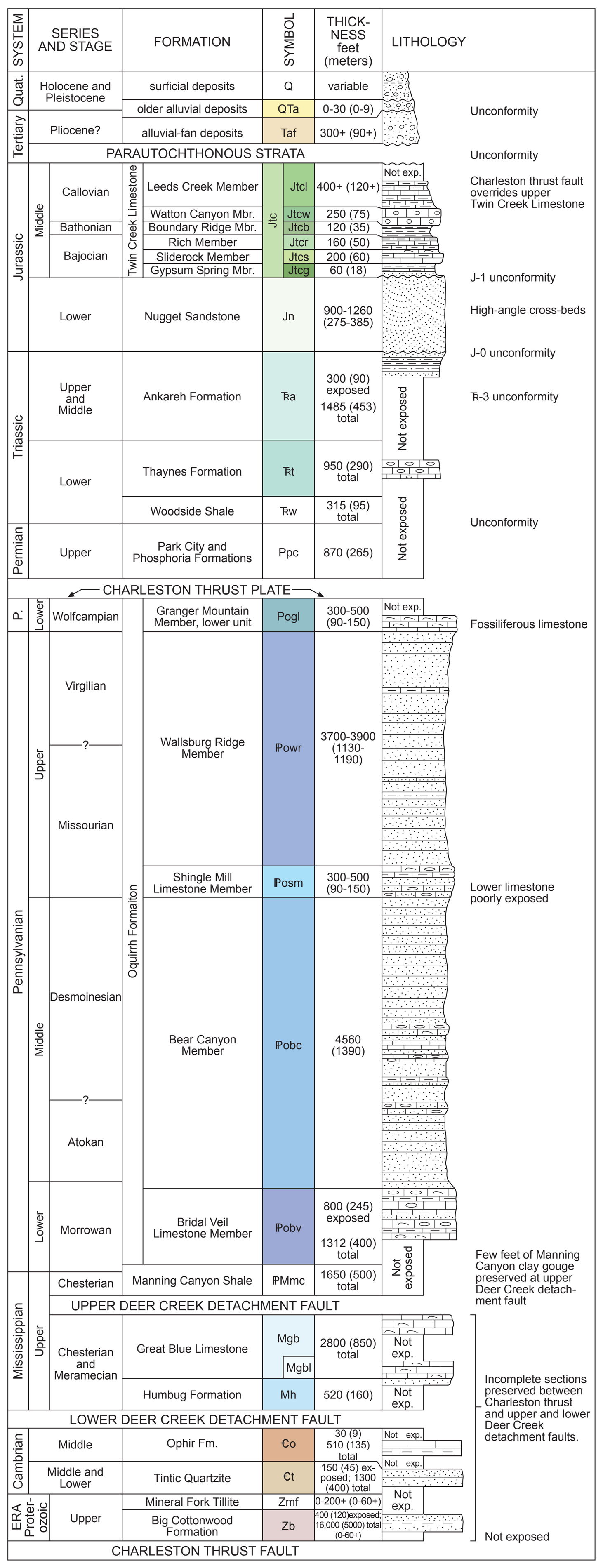
CORRELATION OF GEOLOGIC UNITS

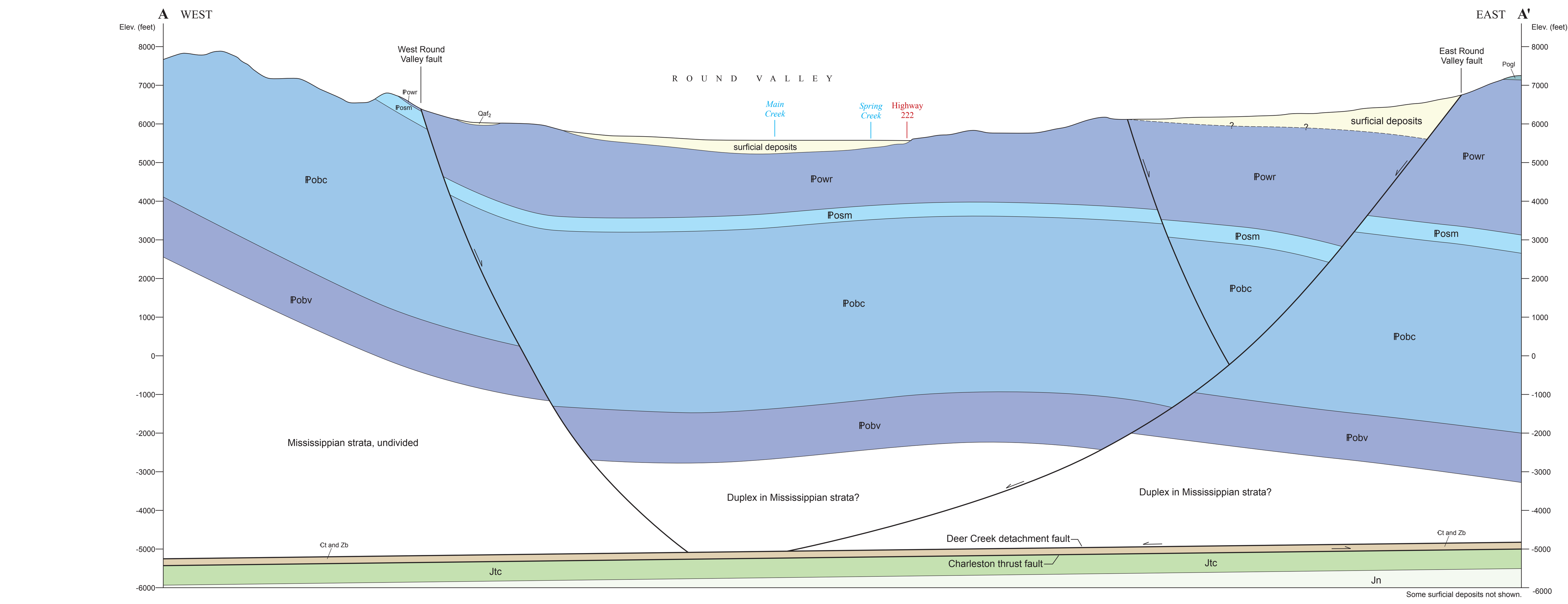


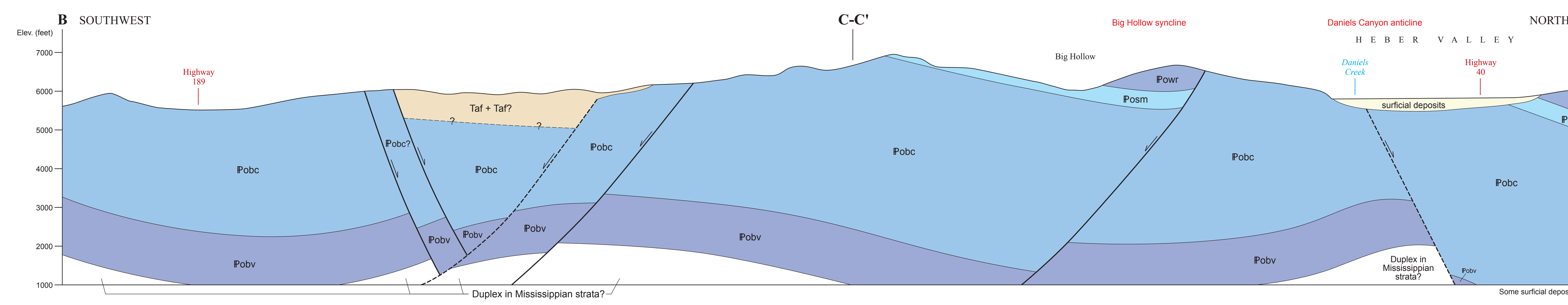
GEOLOGIC SYMBOLS

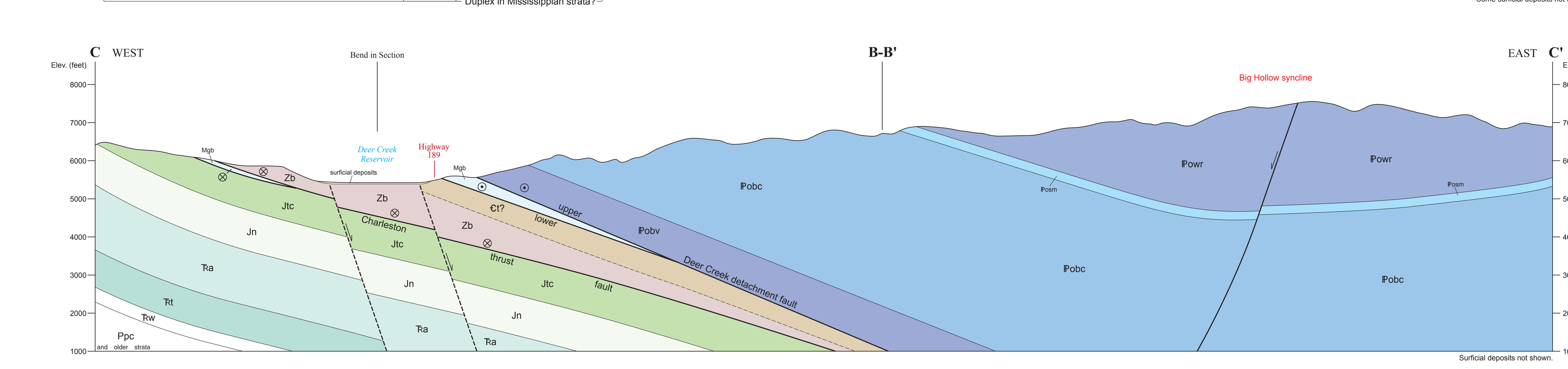


LITHOLOGIC COLUMN









GEOLOGIC MAP OF THE CHARLESTON QUADRANGLE, WASATCH COUNTY, UTAH

by Robert F. Biek and Mike Lowe

UTAH DNR GEOLOGICAL SURVEY

MAP 236
UTAH GEOLOGICAL SURVEY
a division of
UTAH DEPARTMENT OF NATURAL RESOURCES
in cooperation with
U.S. GEOLOGICAL SURVEY
2009

Utah Geological Survey 60 years 1949 2009 Excellence, Integrity, and Objectivity

GEOLOGIC MAP OF THE CHARLESTON QUADRANGLE, WASATCH COUNTY, UTAH

by Robert F. Biek and Mike Lowe

ISBN 1-55791-815-5

UTAH DNR
GEOLOGICAL SURVEY

MAP 236
UTAH GEOLOGICAL SURVEY
a division of
UTAH DEPARTMENT OF NATURAL RESOURCES
in cooperation with
U.S. GEOLOGICAL SURVEY
2009

Utah Geological Survey
60 years
1949 2009
Excellence, Integrity, and Objectivity

STATE OF UTAH
Jon Huntsman, Jr., Governor

DEPARTMENT OF NATURAL RESOURCES
Michael Styler, Executive Director

UTAH GEOLOGICAL SURVEY
Richard G. Allis, Director

PUBLICATIONS
contact
Natural Resources Map & Bookstore
1594 W. North Temple
Salt Lake City, UT 84116
telephone: 801-537-3320
toll-free: 1-888-UTAH MAP
Web site: mapstore.utah.gov
email: geostore@utah.gov

UTAH GEOLOGICAL SURVEY
contact
1594 W. North Temple, Suite 3110
Salt Lake City, UT 84116
telephone: 801-537-3300
Web site: geology.utah.gov

This geologic map was funded by the Utah Geological Survey and the U.S. Geological Survey, National Cooperative Geologic Mapping Program through USGS STATEMAP award number 04HQAG0040. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

CONTENTS

FIGURES

TABLE

GEOLOGIC MAP OF THE CHARLESTON QUADRANGLE, WASATCH COUNTY, UTAH

by Robert F. Biek and Mike Lowe

ABSTRACT

The Charleston quadrangle lies on the south edge of a structural and topographic saddle between the Wasatch Range and Uinta Mountains. The quadrangle includes the southern part of Heber City and Heber Valley and the northern half of Round Valley, as well as parts of Deer Creek Reservoir and Wasatch Mountain State Park; the small communities of Charleston, Daniel, and Wallsburg are also in the quadrangle. The quadrangle also straddles the north edge of the Charleston-Nebo thrust sheet, and thus includes three distinct groups of rocks: (1) a nearly complete section of allochthonous Pennsylvanian rocks of the Oquirrh Formation that comprises the Charleston thrust plate; (2) para-autochthonous, southeast-dipping Jurassic and Triassic strata (Thaynes Limestone, Ankareh Formation, Nugget Sandstone, and Twin Creek Limestone) below the Charleston thrust; and (3) parts of the Big Cottonwood Formation (Upper Proterozoic), Tintic Quartzite (Middle to Lower Cambrian), and the Great Blue Limestone and Humbug Formation (Upper Mississippian), which are exposed in a structurally complicated zone between the Charleston thrust and Deer Creek detachment faults.

The Charleston thrust fault bounds the northern edge of the Charleston-Nebo salient of the Sevier orogenic belt. Previous research shows that the northern part of this salient (the Charleston allochthon) was transported eastward about 30 to 60 miles (50–100 km) during the late Early Cretaceous and early Late Cretaceous at the height of the Sevier orogeny in central Utah. Thrusting resulted in juxtaposition of a 9- to 10-mile-thick (14.5–16.5 km) section of Proterozoic to Lower Cretaceous, mostly miogeoclinal strata against a cratonic shelf section of the same age that is only about one-third as thick. The Sevier orogenic belt collapsed westward during a late Eocene to early Miocene episode of crustal extension. Mostly westward slip on low-angle normal faults, including the Deer Creek detachment fault, produced grabens superimposed on the Charleston-Nebo thrust sheet, and shows that 3 to 4 miles (5–7 km) of extension occurred on the sole thrust during the late Eocene to early Miocene. The Round Valley graben lacks mid-Tertiary deposits, and so likely developed after this period of extensional collapse of the Sevier orogenic belt.

Our mapping refines the structure and stratigraphy of the highland area between Heber and Round Valleys. A nearly complete section of the Pennsylvanian part of the Oquirrh Formation is present on this ridge in this quadrangle, beginning with newly identified Bridal Veil Limestone immediately east of Deer Creek Reservoir and continuing upsection on the west limb of the Big Hollow syncline through the Bear Canyon Member, Shingle Mill Limestone Member, Wallsburg Ridge Member, and up to the Lower Permian lower limestone unit of the Granger Mountain Member. The basal part of the Bridal Veil Limestone Member is cut out by the Deer Creek detachment fault, which is spectacularly exposed in a new Highway 189 road cut immediately west of State Route 113. We report the Morrowan conodonts *Rhachistognathus* sp. and *Adetognathodus lautus* from the Bridal Veil Limestone, and the lower Missourian conodont *Idiognathodus sagittalis(?)* from the Shingle Mill Limestone near the northwest end of Round Valley.

The principal economic resources of the quadrangle are aggregate, particularly crushed quartzite from the Bear Canyon and Wallsburg Ridge Members of the Oquirrh Formation, and sand and gravel, particularly from valley-fill deposits in southwest Heber Valley. Numerous springs and streams in the quadrangle, and ground water from southern Heber Valley and the northern end of Round Valley provide water for domestic use and irrigation.

Geologic hazards in the Charleston quadrangle include landslides, flooding, debris flows, shallow ground water, problem soil and rock, earthquakes, and radon. We mapped numerous landslides in the quadrangle, many of which were previously unrecognized; they typically involve the Pennsylvanian Oquirrh Formation and Jurassic Twin Creek Limestone, and colluvial and residual deposits derived from these units.

INTRODUCTION

The Charleston quadrangle lies about 30 miles (50 km) southeast of Salt Lake City, on the south side of a structural and topographic saddle between the Wasatch Range and Uinta Mountains. The quadrangle includes the southern part of Heber City and Heber Valley and the northern half of Round Valley, as well as parts of Deer Creek Reservoir and Wasatch Mountain State Park; the small communities of Charleston, Daniel, and Wallsburg are also in the quadrangle (figure 1). Heber Valley and Round Valley are two of Utah's scenic "back valleys," and both are experiencing significant population growth. The 2000 U.S. Census listed the population of Wasatch County as 15,215, and in 2006 listed an estimated population of 22,215, a 33.1% increase in just six years. Most residents in the county live in the Heber Valley and Round Valley areas. Geologic hazards associated with landslides, earthquakes, flooding, problem soils, and other factors are known in the quadrangle and surrounding area. This geologic map and report provide basic geologic information necessary to further evaluate geologic hazards and resources in the area, and to gain an understanding of the geology upon which this landscape developed.

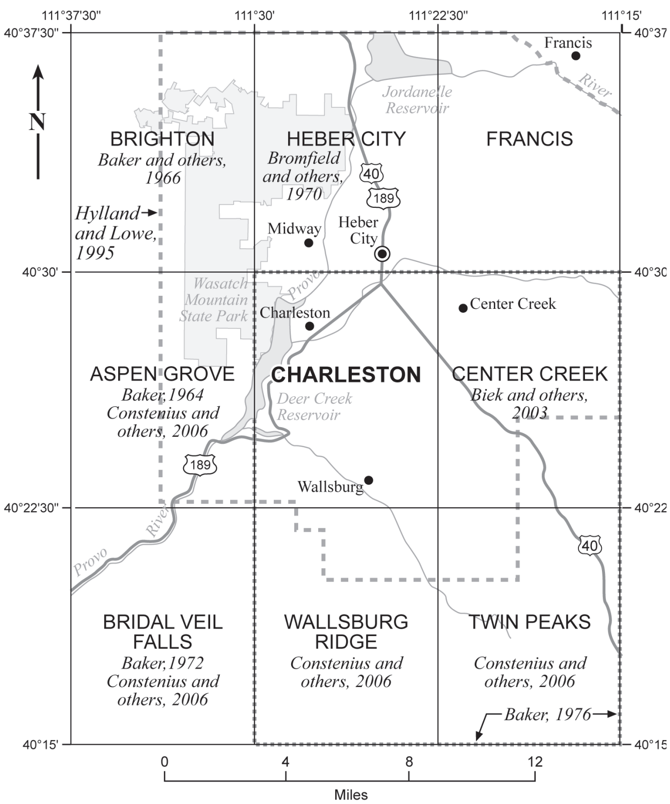


Figure 1. *Index map showing the Charleston quadrangle and surrounding area. Geologic maps of adjacent areas are also shown; Bryant's (1992) 1:125,000-scale geologic map of the Salt Lake City 1° x 2° quadrangle covers all of these quadrangles. Constenius and others (2006) provided a 1:62,500-scale geologic map of the east half of the Provo 30'x 60' quadrangle, and they are now working to complete the entire sheet.*

The Charleston quadrangle lies in what Stokes (1986) referred to as the Wasatch Hinterlands portion of the Middle Rocky Mountains physiographic province. Heber Valley is drained by the Provo River, whereas Main Creek drains lower Round Valley; each stream now terminates at Deer Creek Reservoir, focal point of the Deer Creek Lake State Recreation Area and an important part of the water supply for Wasatch Front communities. Part of Wasatch Mountain State Park, including the Soldier Hollow cross country ski area, occupy the northwest part of the quadrangle. U.S. Highway 189, which links Heber Valley with Provo, skirts the east shore of Deer Creek Reservoir; U.S. Highway 40 enters the valley through the lower reaches of Daniels Canyon. Elevations in the quadrangle range from 5417 feet (1652 m) at Deer Creek Reservoir to 8800 feet (2680 m) on Wallsburg Ridge in the southwest part of the quadrangle. Apart from the state park and recreation area, most of the land in the quadrangle is privately owned. Much of the area between Heber Valley and Round Valley is managed as the Wallsburg Unit of the Heber Wildlife Management Area.

The scenic and rugged Uinta Mountains and Wasatch Range have been the focus of numerous geologic investigations. In contrast, the geology of the Charleston quadrangle has not been widely studied, principally due to poor and limited bedrock exposures. Baker (1947, 1959) summarized the regional stratigraphy and structure, respectively, and later published several maps of areas immediately west of the Charleston quadrangle (figure 1). He later mapped the Charleston quadrangle at a scale of 1:63,360 as part of the west half of the Strawberry Valley (30') quadrangle (Baker, 1976). In his unpublished 1980–81 study of the stratigraphy and structure of Permian and Pennsylvanian strata of part of the Charleston allochthon, John Welsh mapped most of the Charleston and adjacent Center Creek, Co-op Creek, and Twin Peaks quadrangles at a scale of 1:24,000. Riess (1985) mapped part of the Charleston thrust fault west of Deer Creek Reservoir. Bryant (1992) completed a 1:125,000-scale geologic map of the Salt Lake City 1° x 2° quadrangle. Hylland and others (1995) produced an engineering geology and geologic hazards map folio of western Wasatch County, which includes most of the Charleston quadrangle. Constenius and others (2006) produced a 1:62,500-scale geologic map of the east part of the Provo 30' x 60' quadrangle, and are now working to complete the full sheet. Selected geologic maps of adjacent areas are shown in figure 1.

STRATIGRAPHY

Because the Charleston quadrangle straddles the northern edge of the Charleston-Nebo thrust plate, this area includes three distinct groups of rocks: (1) allochthonous Pennsylvanian rocks of the Oquirrh Formation that comprise the Charleston thrust plate; (2) para-autochthonous, southeast-dipping Triassic and Jurassic strata (Thaynes Limestone, Ankareh Formation, Nugget Sandstone, and Twin Creek Limestone) below the Charleston thrust; and (3) parts of the Big Cottonwood Formation (Upper Proterozoic), Tintic Quartzite (Middle to Lower Cambrian), and the Great Blue Limestone and Humbug Formation (Upper Mississippian), which are exposed in a structurally complicated zone between the Charleston thrust and Deer Creek detachment faults. A variety of late Tertiary and Quaternary deposits, including high-level alluvial-fan deposits at the north end of Round Valley and glacial outwash deposits in Heber Valley, record the evolution of the present landscape.

Unlike areas to the south and east near the Strawberry and Nebo thrusts, no coarse, middle to late Cretaceous synorogenic strata are exposed in front (north) of the Charleston thrust in this or adjacent quadrangles. Such sediments were certainly shed from the northern part of the Charleston-Nebo salient as they were to the south and east, but were likely eroded during later uplift of the Uinta Mountains and Cottonwood arch. Alternatively, some synorogenic deposits could be preserved beneath a cover of Keetley Volcanics in the structural saddle between the Uinta Mountains and Wasatch Range.

Precambrian

Big Cottonwood Formation (Zb)

Incomplete, fault-bounded parts of the Big Cottonwood Formation that total just several hundred feet thick are exposed at the base of the Charleston allochthon on the west side of Deer Creek Reservoir. There, the Big Cottonwood Formation is thrust over the Twin Creek Limestone and truncated by the lower Deer Creek detachment fault. The Big Cottonwood Formation consists mostly of moderate- to dark-reddish-brown to grayish-purple, fine- to coarse-grained quartzite with rare, thin, very coarse grained gritstone beds. Minor micaceous, moderate- to dark-reddish-brown argillite interbeds—and in the SW1/4NE1/4 section 21, T. 4 S., R. 4 E., a slope-forming interval several tens of feet thick of grayish-brown to greenish-brown micaceous argillite, siltstone, and very fine grained sandstone—are also present. Baker (1976) suggested that these argillite beds may be a fault sliver of the Ophir Formation. The southernmost outcrops of Big Cottonwood Formation immediately north of the reservoir are commonly white to very light gray with iron-stained fractures and so appear similar to the Tintic Quartzite, and were so mapped as Tintic by Riess (1985), but the outcrops lack pebbles to boulders typical of basal Tintic strata elsewhere in the region. It is difficult to determine bedding attitudes in the quartzite intervals because the quartzite is very thick to massive and beds are highly fractured. These exposures total about 400 feet (120 m) thick.

The Big Cottonwood Formation is a tremendously thick succession of alternating quartzite and argillite that may be as much as 16,000 feet (5000 m) thick in Big Cottonwood Canyon, its type locality in the Wasatch Range (Crittenden and others, 1952; James, 1979; Bryant, 1992). It was deposited in an equatorial macro-tidal estuarine environment of an east-trending rift valley and contains the oldest known tidal rhythmites (Chan and others, 1994; Ehlers and others, 1997). New detrital zirocon geochronology shows that the formation may be no more than about 770 million years old (Kingsbury and others, 2008). Previously, the age of the formation was only broadly constrained between about 850 and 1000 Ma (Link and others, 1993); regardless, it is early Late Proterozoic in age.

Mineral Fork Tillite (Zmf)

Not exposed in this quadrangle—likely due to truncation by the Deer Creek detachment fault—but regionally overlying the Big Cottonwood Formation is a gray to brown, unstratified, very poorly sorted micaeous siltstone with matrix-supported clasts, which records sediments deposited from continental glaciers as they melted in a shallow ocean (Christie-Blick, 1983; Crittenden and others, 1983). It is at least 200 feet (60 m) thick in the Bridal Veil Falls quadrangle, but pinches out southward (Constenius and others, 2006).

Cambrian

Tintic Quartzite (Ꞓt,Ꞓt?)

The Tintic Quartzite is exposed on an island in Deer Creek Reservoir (referred to herein as "Deer Creek island"), where it forms ledgy slopes and is overlain by fault-bounded blocks of the Ophir Formation and Great Blue Limestone. The Tintic consists of white, light-gray, and light-brown, fine- to medium-grained orthoquartzite in medium to very thick beds having low-angle cross-stratification. Locally, it is medium to coarse grained with rounded white quartz pebbles. Fracture surfaces are commonly stained rusty brown and yellowish brown by iron oxides and hydroxides. Immediately to the northeast, we mapped the Tintic as queried due to uncertain identification of these outcrops. There, it consists of very light gray to very pale orange, fine-grained or rarely coarse-grained, highly fractured quartzite with low-angle cross-stratification. These beds lack pebbles characteristic of the Tintic on Deer Creek island, and instead look similar to the Big Cottonwood Formation exposed on the west side of the reservoir. Structural relationships in the footwall of the Deer Creek detachment fault, however, suggest that these beds are indeed Tintic as suggested by Baker, 1976) and Welsh (unpublished mapping, 1980–81). The Tintic and queried Tintic exposures are part of the lower plate of the lower Deer Creek detachment fault; a similar relationship is present in the nearby Placid West Daniels Land #1 well.

The Tintic Quartzite is Middle and Early Cambrian in age (Baker, 1964) and was deposited in beach and coastal-plain environments (Calkins and others, 1943). The incomplete section at Deer Creek island is about 150 feet (45 m) thick, but the formation is about 1300 feet (400 m) thick 10 miles (16 km) west of the quadrangle in American Fork Canyon (Baker and Crittenden, 1961) and 1170 feet (357 m) thick in Slate Canyon near Provo (Baker, 1972).

Ophir Formation (Ꞓo)

At low lake levels, a few tens of feet of yellowish-brown weathering, olive-green micaceous shale and minor gray, thin-bedded, fine-grained limestone is exposed on the northeast side of Deer Creek island. These beds are folded into an overturned syncline with a vertical to overturned southeast limb and a gently southeast-dipping northwest limb. These beds are believed to be part of the Ophir Formation, which here is highly attenuated and preserved as a fault sliver along the lower Deer Creek detachment fault. The complete formation is about 510 feet (155 m) thick to the west in American Fork Canyon and is Middle Cambrian in age (Baker, 1964).

Mississippian

Humbug Formation (Mh)

Only a few tens of feet of the Humbug Formation are exposed immediately above the lower Deer Creek detachment fault at the west edge of the quadrangle. The Humbug consists of thin- to medium-bedded, pale-yellowish-brown to olive-gray, variably calcareous or siliceous, fine-grained quartz sandstone. The upper contact with the Great Blue Formation is conformable and gradational and represents a change from sandstone to limestone. The Humbug Formation is Upper Mississippian (Morris and Lovering, 1961), and its cyclic sandstone and limestone represent shallow-marine deposits likely influenced by glacio-eustatic sea-level fluctuations (Veevers and Powell, 1987). The formation is about 800 feet (245 m) thick in American Fork Canyon, about 10 miles (16 km) west of the quadrangle (Baker and Crittenden, 1961), and about 520 feet (160 m) thick at Rock Canyon near Provo (Baker, 1972).

Great Blue Limestone

Parts of the Great Blue Limestone are exposed at the base of the Charleston allochthon and as fault slivers between the upper and lower Deer Creek detachment faults along both sides of Deer Creek Reservoir. Regionally, the Great Blue Limestone is divided into three members, ascending: lower limestone member (Mgbl), middle shale member (called the Long Trail Shale west of Utah Lake), and upper limestone member. Only the lower limestone member is mapped separately, north of Deer Creek Reservoir. Elsewhere, strata are undivided due to structural complications and limited exposure. The Great Blue Limestone is Upper Mississippian (Chesterian) (Gordon and others, 2000), and was deposited in a shallow-marine back-bulge basin of the Antler orogenic belt (Silberling and others, 1997). The Great Blue Limestone is about 2800 feet (850 m) thick in Rock Canyon in the nearby Bridal Veil Falls quadrangle (Baker, 1972).

Great Blue Limestone, undivided (Mgb): The Great Blue Limestone is undivided at and east of Deer Creek island, and in a fault sliver west of the reservoir, due to limited exposure. It consists of thin- to medium-bedded, locally laminated, dark-bluish-gray limestone, locally with irregular black chert nodules and brachiopod, coral, and bryozoan fossils. The Great Blue typically forms ledges and cliffs, but here weathers to ledgy slopes due to extensive fracturing, likely due to proximity to the Charleston thrust fault and Deer Creek detachment fault. The upper contact with the Manning Canyon Shale is not exposed, but regionally marks a prominent change from cliff-forming limestone to slope-forming shale. Less than about 150 feet (45 m) of Great Blue strata is exposed in the vicinity of Deer Creek island.

Lower limestone member (Mgbl): Part of the lower limestone member is recognized west of Deer Creek Reservoir due to its position above the Humbug Formation. There, the lower limestone member is thin- to medium-bedded, light-gray to bluish-gray limestone and fossiliferous limestone with locally abundant bryozoans. The upper contact is not exposed in this quadrangle, but regionally is gradational and corresponds to the first thick interval of slope-forming, grayish, carbonaceous shale. Only the lower few hundred feet is poorly exposed in section 21, T. 4 S., R. 4 E., but the member is about 850 feet (260 m) thick in the southern Oquirrh Mountains (Gordon and others, 2000) and about 700 feet (210 m) thick in the Wasatch Range (Constenius and others, 2006).

Mississippian to Pennsylvanian

Manning Canyon Shale

The Manning Canyon Shale is about 1650 feet (500 m) thick in the adjacent Bridal Veil Falls quadrangle (Baker, 1972), but is not present in this quadrangle because it has been cut out by the upper Deer Creek detachment fault. It is mostly Upper Mississippian, but contains earliest Pennsylvanian conodonts near the top of the formation (Webster and others, 1984; Shoore and Ritter, 2007). The Manning Canyon Shale served as one of several regional detachment horizons for Cretaceous to early Tertiary contractional and extensional deformation (Paulsen and Marshak, 1998, 1999; Constenius and others, 2003).

During this mapping project, the upper splay of the Deer Creek detachment fault was exposed in a new U.S. Highway 189 road cut about 500 feet (150 m) west of State Highway 113 (see figures 3a and 3b). The fault places the Bridal Veil Limestone Member of the Oquirrh Formation on top of the Great Blue Formation; parts of those formations are cut out, as is all of the intervening Manning Canyon Shale. All that remains of the Manning Canyon Shale in this outcrop is a thin sliver of dense, black, graphitic clay fault gouge. The fault gouge displays prominent, highly polished surfaces.

Pennsylvanian

Oquirrh Formation

Oquirrh strata consist of as much as 25,000 feet (7600 m) of

Lower Permian to Lower Pennsylvanian sandstone, orthoquartzite, shale, and limestone deposited in the Oquirrh marine basin of north-central Utah and southern Idaho, with fine arkosic sand derived principally from the Weber shelf and Uncompahgre uplift (Welsh and Bissell, 1979). The Oquirrh is elevated to group status in the Oquirrh Mountains and other mountain ranges west of Utah Lake, where it consists of the West Canyon Limestone (Lower Pennsylvanian), Butterfield Peaks Formation (Middle Pennsylvanian), and Bingham Mine Formation (Upper Pennsylvanian) (Tooker and Roberts, 1970), but in the Wasatch Range it was conferred the rank of formation by Baker and Crittenden (1961) and Baker (1964, 1972, 1976). In the Wasatch Range, the Oquirrh Formation is divided into five members: in ascending order these are the Bridal Veil Limestone, Bear Canyon, Shingle Mill Limestone, Wallsburg Ridge, and Granger Mountain Members. The Charleston quadrangle contains just over 10,000 feet (3050 m) of Oquirrh Formation strata, missing only the lower part of the Bridal Veil Limestone and most of the Granger Mountain Members. Regional correlations of member and formational names were summarized by Baker (1976) and Welsh and Bissell (1979). The Oquirrh Formation typically weathers to steep, colluvium-covered slopes; good exposures are uncommon and tend to be restricted to the crests of ridges.

Bridal Veil Limestone Member (IPobv): The Bridal Veil Limestone consists almost entirely of medium- to dark-gray, fine- to medium-grained, variably sandy and silty limestone. The member weathers to ledgy slopes characterized by cyclically interbedded limestone packages composed of slope-forming, thin-bedded, silty limestone capped by ledge-forming, thicker bedded fossiliferous limestone. Typically sparse macrofossils include brachiopods, bryozoans, crinoid stems, and trilobites and more commonly thin fossil hash stringers. Locally, black or light-gray chert nodules are common.

In the Charleston quadrangle, the Bridal Veil Limestone is only exposed near Deer Creek Reservoir, south of Charleston. There, Welsh (unpublished data, 1981) measured an incomplete section of about 800 feet (245 m) at the boundary of sections 22 and 23, T. 4 S., R. 4 E., which we reassign to the Bridal Veil Limestone (the member had not previously been recognized in this area). Baker (1972) measured a complete section of 1245 feet (380 m) of Bridal Veil Limestone near Bridal Veil Falls in Provo Canyon. At Squaw Creek Gully on the south side of Mount Timpanogos, Shoore (2005) reported the member is 1312 feet (400 m) thick.

Shoore (2005; see also Shoore and Ritter, 2007) recognized 21 sequence boundaries within the Bridal Veil Limestone Member caused by glacio-eustatic sea-level fluctuations, and reasoned that the member was deposited in cool, shallow-marine water and shows evidence of shoaling and steady progradation of the Weber shelf. The member is largely Morrowan (Early Pennsylvanian) in age (Baker, 1964; Webster, 1984; Davis and others, 1994). We recovered the Morrowan conodonts *Rhachistognathus* sp. and *Adetognathodus lautus* (table 1) from the Bridal Veil Limestone Member immediately south of

Table 1. *Oquirrh Formation conodont fossils in the Charleston quadrangle.*

Sample #	Latitude	Longitude	Conodont	Age	Formation
051305-1	40° 24' 26.0"	111° 28' 14.4"	indeterminate juvenile *Streptognathodus*	Missourian	Shingle Mill Ls.
051305-2	40° 24' 24.9"	111° 28' 15.4"	indeterminate juvenile *Streptognathodus*	Missourian	Shingle Mill Ls.
051905-2.3	40° 24' 25.5”	111° 28' 14.0”	*Idiognathodus sagittalis*?	Lower Missourian	Shingle Mill Ls.
051305-3	40° 24' 42.2"	111° 28' 21.2"	indeterminate juvenile *Streptognathodus*	Missourian?	Shingle Mill Ls.
051305-4	40° 27' 06.5"	111° 28' 19.4"	*Rhachistognathus* sp.	Morrowan	Bridal Veil Ls.
051305-4	40° 27’ 06.5”	111° 28’ 19.4”	*Adetognathodus lautus*	Morrowan	Bridal Veil Ls.
051305-5	40° 27' 08.2"	111° 28' 13.6"	*Adetognathodus lautus*	Morrowan	Bridal Veil Ls.

Note: Identifications by Scott Ritter, Brigham Young University, May 2005.

Charleston. The Bridal Veil Limestone is largely equivalent to the West Canyon Limestone of the Oquirrh and Lake Mountains (John E. Welsh, unpublished notes, 1980-81).

Bear Canyon Member (IPobc): The Bear Canyon Member consists of mostly sandstone with lesser interbedded limestone. A complete section of Bear Canyon strata is exposed along the ridge crest between Big Hollow and Deer Creek Reservoir, in the south part of sections 23 and 24, and the northeast corner of section 25, T. 4 S., R. 4 E. There, the member is divisible into three informal parts not mapped separately: (1) the lower 1000 feet (300 m) is mostly very fine grained sandstone with rare thin limestone intervals, (2) the middle part, about 1600 feet (490 m) thick, contains several limestone intervals each about 20 to 100 feet (6–30 m) thick, and (3) the upper 2000 feet (600 m) is entirely very fine grained sandstone.

Bear Canyon sandstone is typically yellowish brown, very fine grained, feldspathic, finely laminated in thick to very thick beds, and is well indurated with a siliceous, or less commonly, calcareous cement. Most sandstone beds are resistant and commonly display a prominent conchoidal fracture. The sandstones commonly have a light-yellow goethetic stain from a trace of pyrite.

Bear Canyon limestone is typically medium gray, thin to thick bedded, commonly sandy or argillaceous, with local black chert nodules and stringers. Crinoid stem, fenestrae bryozoan, and small brachiopod fossils are locally common in these beds. Locally, as in the U.S. Highway 189 road cut in SE1/4 section 28, T. 4 S., R.4 E., chert forms spherical nodules similar to those of the "billard-ball limestone" of the Butterfield Peaks Formation at the Lake Mountains (Biek, 2004).

The Bear Canyon Member is about 4560 feet (1390 m) thick just east of Deer Creek Reservoir, in sections 23 and 24, T. 4 S., R. 4 E. (Welsh, unpublished notes, 1980–81). In the West Daniels Land #1 well, immediately east of the Charleston quadrangle (south of Daniels Canyon in section 11, T. 5 S., R. 5 E.), the Bear Canyon Member is also probably about 4600 feet (1400 m) thick (Welsh, unpublished data, 1980–81; Sprinkel, 1994; Biek and others, 2003). Baker (1972) reported that the Bear Canyon strata are about 4000 to 8350 feet (1200–2550 m) thick in the Bridal Veil Falls quadrangle, but reinterpretation of his measured section suggests that the member is actually about 5500 feet (1675 m) thick (Jon King, Utah Geological Survey, written communication, February, 2008). At the west end of Wallsburg Ridge, immediately west of the southwest corner of the Charleston quadrangle, John Welsh reported Bear Canyon strata to be about 9200 feet (2800 m) thick (John E. Welsh, unpublished notes, 1980–81). However, Welsh's line of section crosses a significant normal fault and steeper dips he noted in Bear Canyon strata there are not reflected in much less steeply dipping enclosing carbonates of the Bridal Veil and Shingle Mill Limestone Members (Constenius and others, 2006); thus, in our minds, Welsh's 9200 feet (2800 m) of Bear Canyon strata, though comparable in thickness to the Butterfield Peaks Formation, its correlative in the Oquirrh Mountains, is likely too thick.

Fusulinid zones of *Fusulinella*, *Wedekindellina*, and *Fusulina* place the Bear Canyon Member in the Atokan and Desmoinesian stages (Middle Pennsylvanian) (John E. Welsh, unpublished notes, 1980–81). The same fusulinid zones are present in the correlative Butterfield Peaks Formation (Welsh and Bissell, 1979; Webster, 1984; Davis and others, 1994). Shoore (2005) reported latest Morrowan conodonts from the lower few meters of the member (which he called Butterfield Peaks Formation) at Cascade Mountain. As discussed by Welsh and Bissell (1979), the lithologies and fauna indicate that the Bear Canyon Member was deposited in a moderately deep shelf or shallow-marine basin. Konopka (1999) studied cyclic patterns observed in Butterfield Peaks and Bear Canyon strata and reasoned that sedimentation was partly controlled by glacio-eustatic sea level rise. Limestone muds, common in the middle part of the member, were deposited in quiet water with a sparse fauna of benthic bryozoa, few fusulinids, and chonetid and productid brachiopods. Periodically the lime muds were overwhelmed by influxes of arkosic sand from the Uncompahgre uplift and, to a lesser extent, by coarse carbonate debris and rounded quartz grains from sources outside or marginal to the basin. The carbonate debris probably washed in from the shallow Callville platform that covered the Emery High to the south and southeast. The Bear Canyon Member is largely correlative to the Butterfield Peaks Formation of the Oquirrh Mountains (John E. Welsh, unpublished notes, 1980–81).

Shingle Mill Limestone Member (IPosm): The Shingle Mill Limestone Member forms an important marker between the thick, similar sandstones of the Bear Canyon and Wallsburg Ridge Members. The Shingle Mill Limestone Member forms ledgy outcrops in Big Hollow where it helps define the Big Hollow syncline, and is also exposed in the southwest part of the quadrangle. Like Welsh (unpublished map, 1980–81), we also mapped the member at the north end of Round Valley, where it forms the exposed core of a small syncline and is cut by the West Round Valley and subsidiary faults. Our mapping differs from Baker (1976) and Welsh (unpublished map, 1980–81) along the east shore of Deer Creek Reservoir; the limestone interval they mapped as Shingle Mill we reinterpret as one of many limestone intervals in the middle Bear Canyon Member. The Shingle Mill Limestone Member consists of two thick limestone intervals separated by several tens of feet of sandstone. The lower, thinner limestone interval is commonly poorly exposed, and in the southwest part of the quadrangle is not mapped.

Limestone of the Shingle Mill is typically medium to dark gray, sandy and silty in thin to very thick beds, commonly with black chert stringers and nodules. Most exposures are only sparsely fossiliferous with uncommon crinoid stems, solitary corals, brachiopods, and thin stringers of fossil hash. But locally, as in the SW1/4SW1/4 section 2, T. 5 S., R. 4

E. at the northwest end of Round Valley, fossils are abundant and include partially articulated crinoid stems, bryozoans, solitary and colonial corals, brachiopods, and echinoderm fragments. Welsh (unpublished notes, 1980–81) noted that the upper limestone interval at Wallsburg Ridge contains a benthic fauna of *Chonetes*, *Marginifera*, *Dictyoclostus*, rhynchonellids, bryozoa, crinoids, and trochoid gastropods. The intervening sandstone is poorly exposed, thin- to very thick bedded, yellowish-brown to light-olive-gray, very fine- to medium-grained, commonly calacreous, slightly feldspathic quartz sandstone with low-angle cross-bedding.

Baker (1976) included only the upper limestone interval in the Shingle Mill Limestone in the Daniels Canyon and Wallsburg Ridge area. We include both limestone intervals in the Shingle Mill Limestone Member based on Welsh's (unpublished notes, 1980–81) correlation that shows the lower and upper limestone intervals are equivalent to the Jordan and Commercial Limestones, respectively, of the Oquirrh Mountains. The *Eowaeringella* fusulinid zone is in the basal part of the lower limestone, the same position in which it is found at Middle Canyon in the Oquirrh Mountains and at South Mountain (Welsh, unpublished notes, 1980–81). In the adjacent Center Creek quadrangle, *Eowaeringella* sp. was collected from beds near the center of section 26, T. 4 S., R. 5 E. No fusulinids have been found in the upper limestone interval or in the Commercial Limestone. However, 225 feet (69 m) above this limestone interval at Wallsburg Ridge, Welsh (unpublished notes, 1980–81) recovered the Missourian fusulinid *Triticites* from lower Wallsburg Ridge Member strata. Baker (1976) collected fusulinids from Shingle Mill strata on the west side of Wallsburg Ridge, in section 5, T. 6 S., R. 4 E., that were initially misidentified as Desmoinesian in age, but that were later reclassified as earliest Missourian (Raymond C. Douglass, U.S. Geological Survey, written communication to John Welsh, January 28, 1981). Scott Ritter recovered the lower Missourian conodont *Idiognathodus sagittalis*(?) (table 1) from the Shingle Mill Limestone near the northwest end of Round Valley.

In an unpublished measured section at Wallsburg Ridge, immediately southeast of the Charleston quadrangle, Welsh measured about 1145 feet (349 m) of Shingle Mill strata; his line of section crosses a significant normal fault (Constenius and others, 2006) so this thickness may be suspect. There, Welsh found the lower limestone is about 230 feet (70 m) thick, the middle sandstone unit about 500 feet (150 m) thick, and the upper limestone interval about 385 feet (117 m) thick. In the West Daniels Land #1 well, Welsh (unpublished notes, 1980–81) assigned about 110 feet (34 m) to the lower limestone, 140 feet (43 m) to the middle sandstone, and 260 feet (79 m) to the upper limestone. We estimate that the member is about 300 to 500 feet (90–150 m) thick near Big Hollow.

Wallsburg Ridge Member (IPowr): The Wallsburg Ridge Member was named by Baker (1976) for a thick section of siliceous, slightly feldspathic sandstone strata exposed along the crest of Wallsburg Ridge, just south of the Charleston quadrangle. In the Charleston quadrangle, the Wallsburg Ridge Member forms steep, colluvium-covered slopes bordering Round Valley. Exposures, however, are few, and decent marker beds nonexistent, so that mapping of Wallsburg Ridge strata is mostly limited to measuring bedding attitudes.

The Wallsburg Ridge Member consists of a monotonous mass of yellowish-brown, fine- to medium-grained, well-indurated, siliceous sandstone (orthoquartzite) that typically contain 2 to 5 percent feldspar. The sandstones are commonly finely laminated and cross-laminated in thick to very thick beds, and are barren except for uncommon trace fossils on some bedding planes. These sandstones are highly fractured nearly everywhere, and brecciated near faults, so that bedding is difficult to determine and attitudes surprisingly difficult to obtain. Low-angle cross-laminae commonly form large wedge-shaped sets up to tens of feet in length. Combined with poor exposures, measurements on such beds can easily give erroneous strikes and dips. The sandstones commonly have a conchoidal fracture.

Interbedded with these feldspathic sandstones are a few thin silty and sandy limestones. Welsh noted five such beds in his unpublished measured section of Wallsburg Ridge, and over 30 such beds in correlative strata of the Bingham Mine Formation in the Oquirrh Mountains. These calcareous beds contain a benthic fauna of *Caninia* (rugosa) and syringoporid corals, fusulinids, and disarticulated crinoid columns.

In his unpublished measured section at Wallsburg Ridge, about 8 miles (13 km) west of Daniels Canyon, Welsh measured about 5200 feet (1580 m) of Wallsburg Ridge strata, but noted that due to difficulty in obtaining accurate strike and dip measurements, the section thickness may be off by 10 percent. The West Daniels Land #1 well penetrated a nearly complete section of 4150 feet (1265 m) of the Wallsburg Ridge Member; however, strata there dip about 25 degrees southwest so that the actual thickness of the member is about 3700 to 3900 feet (1130–1190 m). Correlative strata in the Oquirrh Mountains are approximately 6500 feet (2000 m) thick, again illustrating the thinning of strata towards the eastern margin of the Oquirrh basin. Baker (1976) collected Missourian to Virgilian (Late Pennsylvanian) fusulinids from Wallsburg strata at Wallsburg Ridge.

Permian

Granger Mountain Member: The Granger Mountain Member can be divided into two informal map units: (1) a lower unit of limestone and siltstone, and (2) an upper, much thicker unit of interbedded sandstone and siltstone (the Freeman Mountain sandstone facies and Curry Peak siltstone facies). Only the lower few tens of feet of the lower limestone unit is exposed in the Charleston quadrangle, east of Round Valley, along the axis of the Big Hollow syncline.

Granger Mountain Member, lower unit (Pogl): The lower unit consists of two ledge- and cliff-forming limestone intervals of about equal thickness separated by a middle, somewhat thicker, slope-forming siltstone interval. Like the Shingle Mill Limestone, these limestone packages form an important marker in a vast thickness of Oquirrh sandstone and siltstone. The limestone is medium to very thick bedded, medium gray, fossiliferous, and contains a few thin, discontinuous beds and nodules of black chert. It also contains abundant *Schwagerina*-type fusulinids characteristic of the Early Permian (Wolfcampian), common bryozoans and rugose and syringoporid corals, and uncommon crinoid stems and brachiopods. The middle siltstone interval consists of yellowish-brown calcareous siltstone with few thin limestone interbeds.

Map patterns indicate that the lower Wolfcampian limestone unit thins to the west, from about 500 feet (150 m) thick at Parker Canyon on the east limb of the Big Hollow syncline to about 300 feet (90 m) thick on the west limb (Biek and others, 2003). This limestone interval is apparently not present at Wallsburg Ridge about 5 miles (8 km) to the southwest (John E. Welsh, unpublished notes, 1980–81; Constenius and others, 2006).

Park City and Phosphoria Formations, undivided (Ppc)

This map unit consists of upper (Franson Member of the Park City Formation), middle (Meade Peak Phosphatic Member of the Phosphoria Formation), and lower (Grandeur Member of the Park City Formation) units. It is not exposed, but is shown on cross section C–C', in the footwall of the Charleston-Nebo thrust system.

Triassic

Woodside Shale (ꞦW)

The Woodside Shale consists of reddish-brown shale and siltstone that weathers to form strike valleys. It is not exposed, but is shown on cross section C–C’, in the footwall of the Charleston-Nebo thrust system.

Thaynes Formation (Ꞧt)

Part of the Thaynes Formation is exposed in the extreme northwest corner of the quadrangle. There, the Thaynes is a brown-weathering, gray, thin- to thick-bedded, cherty, locally fossiliferous limestone with some interbedded red-brown to light-brown calcareous sandstone and red shale (Baker, 1964). The formation is 950 feet (290 m) thick immediately west of the quadrangle near Cascade Springs and contains locally abundant Early Triassic shallow-marine fossils (Baker, 1964; Smith 1969). The Thaynes Limestone was deposited in a warm, shallow sea that transgressed over tidal-flat deposits of the underlying Woodside Formation (Blakey and Gubitosa, 1983).

Ankareh Formation (Ꞧa)

Only a small part of the Ankareh Formation is exposed at Soldier Hollow at the northwest edge of the quadrangle. Limited exposures there reveal reddish-brown mudstone, siltstone, and very fine to fine-grained sandstone that weather to poorly exposed slopes. Regionally, the formation consists of three members—with a major regional unconformity, the TR-3 unconformity of Pipiringos and O’Sullivan (1978), separating the lower and middle members—that are not mapped separately in this quadrangle due to limited, poor exposure. Baker (1964) showed the thin middle member (Gartra Grit) projecting to the west edge of the Charleston quadrangle at Soldier Hollow, but we found only a fine-grained, ledge-forming sandstone devoid of pebbles or grit typical of this member; the part of the Ankareh Formation mapped in the Charleston quadrangle likely belongs to the upper member.

The Ankareh Formation is 1485 feet (453 m) thick along Decker Creek immediately west of the quadrangle (Baker, 1964); only about 300 feet (90 m) of Ankareh strata are present in the Charleston quadrangle at Soldier Hollow. The Middle and Upper Triassic Ankareh Formation was deposited in fluvial, flood-plain, and lacustrine environments of an interior basin drained by north- and northwest-flowing rivers (Stewart and others, 1972).

Jurassic

Nugget Sandstone (Jn)

The Nugget Sandstone and correlative sandstone formations are renowned as one of the world’s largest coastal and inland paleodune fields, which covered much of what is now Utah and portions of adjacent states in the Early Jurassic (Kocurek and Dott, 1983; Blakey, 1994; Marzolf, 1994; Peterson, 1994). These sandstones are known too for their great thickness and uniformity. Except for a basal transition zone and uncommon, thin, planar interdune deposits, they consist entirely of massively cross-bedded, fine- to medium-grained, commonly bimodal, quartz sandstone that typically weathers to bold, rounded cliffs.

A nearly complete though poorly exposed section of the Nugget Sandstone is present at the northwest edge of the quadrangle near Soldier Hollow. There, the Nugget consists primarily of moderately well-cemented, well-rounded, fine- to medium-grained, frosted quartz grains. It is uniformly colored moderate reddish orange to moderate orange pink, although the uppermost part is generally white to very pale orange. Cementation is variably calcareous or siliceous, but the white upper part is commonly noncalcareous.

Outcrop patterns suggest that the Nugget Sandstone is about 900 to 1000 feet (275–300 m) thick on the saddle west of Soldier Hollow. However, in the West Daniels Land #1 well in the adjacent Center Creek quadrangle, 1306 feet (400 m) of Nugget Sandstone was penetrated; using a 15 degree westerly dip determined from seismic data, the stratigraphic thickness of the Nugget there is about 1260 feet (385 m). Baker (1964, 1976) reported 1500 feet (460 m) of Nugget Sandstone at Decker Creek, just west of Soldier Hollow, but this thickness seems excessive based on map patterns. The Nugget Sandstone thins both to the north and east along the flanks of the Uinta uplift (Bryant, 1992).

The upper contact with the Twin Creek Limestone, the J-1 unconformity of Pipiringos and O'Sullivan (1978), is marked by a prominent change in lithology, with dark-reddish-brown siltstone and jasperoid and brown to gray limestone of the Gypsum Spring Member of the Twin Creek Limestone overlying the planated surface of the white, massively cross-bedded Nugget Sandstone.

Twin Creek Limestone

The Twin Creek Limestone is divided into seven members in northern Utah: in ascending order these are the Gypsum Spring, Sliderock, Rich, Boundary Ridge, Watton Canyon, Leeds Creek, and Giraffe Creek Members (Imlay, 1967). The lower five members are each lithologically consistent and easily recognizable over a wide area. When traced to the south, the upper two members lose identity and grade into the Arapien Shale (Imlay, 1967, 1980; Sprinkel, 1982, 1994). In the Charleston quadrangle, the lower six members are exposed below the Charleston thrust fault west of Deer Creek Reservoir. The uppermost Twin Creek Limestone—part of the Leeds Creek Member and likely all of the Giraffe Creek Member—are cut out by the Charleston thrust fault.

The Twin Creek Limestone is Middle Jurassic (Callovian to middle Bajocian) in age and was deposited in a warm, shallow, inland sea; this shallow sea occupied a broad backbulge basin that developed in front of the Sevier orogenic belt during the first two major Mesozoic transgressive episodes in west-central North America (Imlay, 1967, 1980). Regionally, the Twin Creek Limestone is conformably overlain by the Pruess Sandstone and correlative strata (Imlay, 1980). The incomplete section of Twin Creek Limestone exposed in the Charleston quadrangle is about 1200 feet (365 m) thick.

Twin Creek Limestone, undivided (Jtc): The Twin Creek Limestone is undivided in several exposures along the west shore of Deer Creek Reservoir, in the SW1/4 section 15, T. 4 S., R. 4 E., due to map scale and structural complexity. There, Twin Creek strata likely contain parts of the Rich, Boundary Ridge, Watton Canyon, and Leeds Creek Members in the upper plate of a small thrust fault. The exposure in the SE1/4 section 21, T. 4 S., R. 4 E. likely consists of Leeds Creek or possibly Giraffe Creek strata. The formation is also undivided on cross section C–C'.

Gypsum Spring Member (Jtcg): The Gypsum Spring Member weathers to a poorly exposed recess between resistant slopes of Nugget Sandstone below and Sliderock Member limestone above. Gypsum Spring strata are better exposed in the adjacent Center Creek quadrangle, from which the following description is modified. The base of the member is marked by a 10-foot-thick (3 m), dark-reddish-brown, sandy, calcareous siltstone with thick beds of reddish- and yellowish-brown jasperoid. The jasperoid is overlain by several feet of medium-bedded, pinkish-brown, medium- to coarsely crystalline, sideritic limestone with veinlets of siderite and calcite. The remainder of the member is brown to gray, dense, very fine grained limestone with a conchoidal fracture. The upper contact with the Sliderock Member is gradational and corresponds to the base of more resistant ledgy limestone. The Gypsum Spring Member is about 60 feet (18 m) thick west of Deer Creek Reservoir, and it is 83 feet (25 m) thick in the adjacent Center Creek quadrangle (Biek and others, 2003).

Sliderock Member (Jtcs): The Sliderock Member is mostly thin- to medium-bedded limestone that forms ledges and steep slopes. It consists of light-gray-weathering, brownish-gray, dense limestone with a conchoidal fracture; light-gray micritic limestone that weathers to pencil-like fragments; and medium-gray, dense, finely crystalline to very fine grained limestone with *Isocrinus* sp. crinoid columnals and fossil hash near the top. The upper gradational contact corresponds to a break in slope between more resistant Sliderock limestone and less resistant argillaceous Rich limestone. Based on map patterns, the Sliderock Member is about 200 feet (60 m) thick west of Deer Creek Reservoir; it is 209 feet (64 m) thick in the adjacent Center Creek quadrangle (Biek and others, 2003).

Rich Member (Jtcr): The Rich Member is characterized by medium-gray, thin- to medium-bedded, finely crystalline, ledge- and slope-forming limestone and argillaceous limestone that weathers to pencil-like fragments and small chips. Unlike the Sliderock Member, the Rich Member contains interbeds of very light gray, very fine grained calcareous sandstone with ripple marks. The upper gradational contact corresponds to a change from ledgy slopes of grayish, argillaceous limestone to reddish-brown siltstone slopes of the overlying Boundary Ridge Member. The Rich Member is about 160 feet (50 m) thick based on map patterns west of Deer Creek Reservoir; it is 116 feet (35 m) thick in the adjacent Center Creek quadrangle (Biek and others, 2003).

Boundary Ridge Member (Jtcb): Thin-bedded to laminated, reddish-brown mudstone, siltstone, and fine-grained sandstone characterize the Boundary Ridge Member. The upper part of the member also contains yellowish-brown to olive-gray mudstone and thin limestone beds. This distinctive red-bed interval weathers to form conspicuous but poorly exposed saddles and slopes between more resistant enclosing limestone members; the member is well exposed, however, in a railroad cut in the NW1/4 section 15, T. 4 S., R. 4 E. The upper contact with the overlying Watton Canyon Member is sharp and corresponds to a change from reddish-brown siltstone slopes to gray limestone ledges. The Boundary Ridge Member is about 120 feet (35 m) thick west of Deer Creek Reservoir; it is 145 feet (44 m) thick in the adjacent Center Creek quadrangle (Biek and others, 2003).

Watton Canyon Member (Jtcw): The Watton Canyon Member is noted for yellowish-gray to medium-gray, thin- to thick-bedded, ledge-forming, oolitic limestone, as well as dense, very fine grained limestone that commonly exhibits a conchoidal or rectilinear fracture. Both lithologies locally exhibit well-developed stylolites. The upper contact with the overlying Leeds Creek Member is gradational and is placed at a change from ledge-forming dense limestone to slope-forming argillaceous limestone. Map patterns show that the Watton Canyon Member is about 250 feet (75 m) thick west of Deer Creek Reservoir, comparable to its thickness in the adjacent Center Creek quadrangle (Biek and others, 2003).

Leeds Creek Member (Jtcl): The Leeds Creek Member is incompletely and poorly exposed west of Deer Creek Reservoir, where it is mostly concealed beneath the upper plate of the Charleston thrust fault. The member consists of light-gray, splintery, thin-bedded to laminated, slope-forming, argillaceous limestone. The incomplete section in this quadrangle is about 400 feet (120 m) thick; the complete member is 776 feet (235 m) thick about 20 miles (32 km) to the northeast near Peoa (Imlay, 1967); Constenius and others (2006) reported that the combined Leeds Creek and Giraffe Creek Members are only about 500 feet (150 m) thick on the southwest flank of the Uinta Mountains.

Tertiary

Alluvial-fan deposits (Taf,Taf?)

The northwest end of the Round Valley graben, centered on section 35, T. 4 S., R. 4 E., contains high-level alluvial-fan deposits of uncertain Tertiary age. The deposits form a deeply incised, southwest-sloping surface within the graben, but they retain an alluvial-fan morphology, so we believe they may be Pliocene in age. They overlie Bear Canyon strata on the northeast side of the graben, and appear to be in fault contact with a splay of the West Round Valley fault along the graben's west side. Because the deposits are restricted to the Round Valley graben and retain an alluvial-fan morphology, they are doubtless much younger than the Eocene Uinta Formation, which is present at high elevations on Wallsburg Ridge to the southwest (Biek and others, 2003); the deposits are also much less eroded and not as well cemented as the Miocene to Eocene Tibble Formation, which is present in a graben west of Deer Creek Reservoir (Constenius and others, 2006).

Clasts weathering out of these alluvial-fan deposits consist entirely of subangular sandstone, orthoquartzite, and minor limestone derived from the Oquirrh Formation of Wallsburg Ridge. The deposits are nowhere exposed, but are assumed to be poorly to moderately sorted with clay- to boulder-size sediment. Queried deposits (Taf?) in sections 26 and 27, T. 4 S., R. 4 E., are of uncertain designation. Again, no exposures are present in Taf?, but clasts that are weathering out are identical to Taf deposits and more variable than would be expected if this were simply very poorly exposed Oquirrh bedrock. Still, Taf? may be Pennsylvanian Bear Canyon Member concealed by a veneer of colluvium and regolithic debris. The contact between Taf and Taf? deposits corresponds to an abrupt break in slope that may reflect better cementation of Taf versus Taf?.

Alluvial-fan deposits (Taf) within the graben likely exceed 300 feet (90 m) thick in the southern part of section 35, T. 4 S., R. 4 E., but are only about 40 to 80 feet (12–24 m) thick where they overlie Taf?. Queried alluvial-fan deposits (Taf?) exceed 450 feet (135 m) in thickness.

Quaternary and Tertiary

Older alluvial deposits (QTa)

Older alluvial deposits along Highway 189, just southeast of Deer Creek Reservoir, consist of unconsolidated, moderately sorted, fine- to medium-grained sand and silt with lenses of pebble- to small-cobble-size gravel. The clasts are subrounded to rounded sandstone and limestone of inferred Pennsylvanian Oquirrh Formation affinity, and minor andestitic volcanic clasts likely derived from the late Eocene to early Oligocene Keetley Volcanics that border the east part of Heber Valley. We interpret the deposits as ancestral Provo River deposits preserved in a cutoff meander now occupied by Highway 189, nearly 300 feet (90 m) above the Provo River prior to inundation by Deer Creek Reservoir.

These deposits were first recognized by Sullivan and others (1988), who suggested that they are greater than 730,000 years old based on paleomagnetic analysis of overlying finer-grained colluvium. We infer the deposits to be lower Pleistocene to Pliocene in age based on their elevation above modern drainages. The deposits are as much as about 30 feet (9 m) thick.

Quaternary

Alluvial deposits

Alluvial deposits (Qal_1): Alluvial deposits form the flat valley floor of Round Valley along Main Creek and its tributaries, and are also present along the Provo River, Snake Creek, Lake Creek, and Daniels Creek in Heber Valley. In both valleys, these deposits are marked by conspicuous abandoned meanders and cutoff channels. In the Snake Creek and Midway fish hatchery areas, these deposits are locally underlain by and interbedded with calcareous tufa. Except for the active channels, most of these deposits are cultivated, mostly for alfalfa, and so good exposures are rare and restricted to stream cuts. Alluvial deposits are also mapped in smaller channels across the quadrangle.

Alluvial deposits consist of moderately to well-sorted sand, silt, clay, and pebble to boulder gravel in river and stream channels and flood plains. As mapped, they include low terraces as much as about 10 feet (3 m) above current stream level, and they locally include small alluvial-fan and colluvial deposits. The extent of modern alluvial deposits (Qal_1) is poorly constrained along Center Creek due to subtle geomorphology and modification by agriculture.

Alluvial deposits are Holocene in age and are gradational with mixed alluvial and colluvial deposits. They are typically 0 to about 30 feet (0–9 m) thick.

Stream-terrace deposits (Qat_2,Qat_3): We mapped stream-terrace deposits only along Daniels Creek east of Big Hollow, and in an isolated deposit along the west side of Deer Creek Reservoir. These terraces form level to gently sloping alluvial surfaces above the modern flood plain, and consist of moderately to well-sorted sand, silt, clay, and pebble to boulder gravel deposited principally in river channels and flood plains. The deposits locally include small alluvial-fan and colluvial deposits adjacent to nearby steep slopes. The subscript denotes the relative age and height above the modern drainages: level 2 deposits are about 10 to 20 feet (3–6 m) and level 3 deposits are typically about 30 feet (9 m) above modern drainages, but the level-3 deposit near Deer Creek Reservoir is about 45 feet (12 m) above the level of the flooded Provo River. Stream and terrace profiles constructed for Daniels Creek show that level 3 deposits may be correlative with, and in part older than, level 2 and 3 valley-fill deposits (Qa_2 and Qa_3) of Heber Valley (Biek and others, 2003). Level-3 stream-terrace deposits are thus likely late Pleistocene in age; level-2 deposits are assumed to be late Pleistocene to early Holocene in age. Stream-terrace deposits range from 0 to about 30 feet (0–9 m) thick.

Valley-fill deposits (Qa_2): Valley-fill deposits in the southwest part of Heber Valley form a gently west-sloping surface partly dissected by the Provo River and Daniels Creek (figure 2). These deposits consist of moderately sorted sand, silt, and pebble to boulder gravel probably deposited by braided streams choked with Pinedale-age (30 to 12 ka) glacial outwash. The deposits are locally blanketed by loess veneer. Excavations in valley-fill deposits for a Central Utah Project water facility just southeast of Heber City revealed moderately well-developed calcic paleosols in the upper part of the deposit (Stage II to II+ carbonate of Birkeland and others, 1991) (Biek and others, 2003).

Soil profiles reported by Sullivan and others (1988) suggested a latest Pleistocene age for much of the alluvial surface in Heber Valley, but a veneer of Holocene alluvial deposits is locally present. Valley-fill deposits are probably less than 100 feet (30 m) thick. They form the upper part of basin-fill deposits of southern Heber Valley that locally exceed 450 feet (140 m) thick based on driller's logs of water wells (see plate 1). Based on a gravity survey, Peterson (1970) estimated slightly more than 800 feet (245 m) of basin fill in the southwest part of Heber Valley.

Figure 2. *View northeast to sand and gravel pit on the southwest side of Heber Valley, in the SE1/4 section 14, T. 4 S., R. 4 E.; Highway 189 cuts diagonally across the photo. The flat valley floor is underlain by sand and gravel probably deposited by braided streams choked with Pinedale-age (30 to 12 ka) glacial outwash. They form the upper part of basin-fill deposits (Qa_2) of southern Heber Valley that are as much as 800 feet (245 m) thick.*

Level-1 alluvial-fan deposits (Qaf_1): Active alluvial fans are present throughout the quadrangle and are best developed where they spill out onto the floors of Round Valley and Heber Valley. They consist of poorly to moderately sorted, weakly to non-stratified, clay- to boulder-size sediment deposited principally by debris flows and debris floods at the mouths of active drainages. These fans are active depositional surfaces, as attested by locally well developed debris-flow levees that radiate away from the fan apex. Most level-1 alluvial-fan deposits are probably less than 40 feet (12 m) thick and are Holocene in age.

Level-2 alluvial-fan deposits (Qaf_2): Level-2 alluvial-fan deposits are present along the margins of Heber Valley, but are most widespread in Round Valley. These alluvial-fan deposits form moderately incised, gently sloping surfaces that are a few tens of feet above modern drainages; the fan surfaces are thus typically inactive. Level-2 alluvial-fan deposits consist of poorly to moderately sorted, weakly to non-stratified, clay- to boulder-size sediment derived from upgradient drainage basins. They are characterized by moderately well-developed calcic paleosols in the upper part of the deposits (Stage II to III carbonate development of Birkeland and others, 1991). The deposits are probably as much as about 50 feet (15 m) thick.

Level-2 alluvial-fan deposits may be cut by a previously unrecognized, down-to-the-west fault that trends parallel to the Boren ditch in the southeastern part of the quadrangle; soils differ across the inferred fault (Woodward and others, 1976), further suggesting a possible fault. Sullivan and Nelson (1983) and Sullivan and others (1988) assigned a latest Pleistocene age to level-2 alluvial-fan deposits at the mouth of Big Hollow based on soil profile development. Along the southeast margin of Heber Valley, these deposits appear to be truncated by valley-fill deposits (Qa_2 and Qa_3) of Heber Valley (Biek and others, 2003). Level-2 alluvial-fan deposits thus predate the valley-fill deposits, the latter of which are believed to represent Pinedale-age glacial outwash deposited between about 30 and 12 ka. Level-2 alluvial-fan deposits are thus probably late Pleistocene in age.

Level-3 alluvial-fan deposits (Qaf_3): Level-3 alluvial-fan deposits are similar to level-2 alluvial-fan deposits, but are mapped near the northwest end of Round Valley where they stand at an elevation intermediate between adjacent level-2 (Qaf_2) and late Tertiary alluvial-fan (Taf) deposits. Level-3 deposits are characterized by well-developed calcic paleosols in the upper part of the deposits (Stage III carbonate development of Birkeland and others, 1991). Queried deposits at the north end of Round Valley lie at a similar level as older alluvial-fan deposits (Taf), complicating differentiation of these two units. Level-3 alluvial-fan deposits appear to be cut by a previously unrecognized, down-to-the-northeast fault that trends northwest through section 36, T. 4 S., R. 4 E. The deposits are considered late Pleistocene in age and are 0 to about 50 feet (0–15 m) thick.

Older alluvial-fan deposits (Qafo): Older alluvial-fan deposits form the deeply incised eastern margin of Round Valley, and they are also present in the northwest corner of the quadrangle. They consist of poorly to moderately sorted, weakly to non-stratified, clay- to boulder-size sediment with well-developed calcic paleosols (Stage III+ to IV carbonate development of Birkeland and others, 1991).

Older alluvial-fan deposits are cut by the east Round Valley fault in the SE1/4 section 9, T. 5 S., R. 5 E. and are likely in fault contact with Wallsburg Ridge strata elsewhere along the trace of the fault in this quadrangle. The deposits are also cut by the Round Valley fault in the adjacent Center Creek quadrangle (Biek and others, 2003).

Older alluvial-fan deposits form the upper part of basin-fill deposits of Round Valley, but their thickness there is uncertain; limited water well data show that basin fill there at least locally exceeds 370 feet (110 m) thick (see plate 1 and Sullivan and others, 1988). Older alluvial-fan deposits are probably middle to early-late Pleistocene in age.

Artificial deposits (Qf)

As mapped, artificial deposits consist of fill, principally local borrow material, used to create road and railroad beds. Although only larger fill deposits are mapped, fill of variable composition may be present in any developed or disturbed area, including as flood-control levees along the Provo River. The maximum thickness of mapped fill in this quadrangle is as much as about 30 feet (9 m).

Colluvial Deposits (Qc)

Colluvial deposits consist of poorly to moderately sorted, clay- to boulder-size, locally derived sediment deposited principally by slopewash and soil creep on moderate slopes. Colluvium is common on most slopes in the quadrangle, but is only mapped where deposits are thick and extensive enough to conceal large areas of bedrock. These deposits locally include talus and mixed alluvial and colluvial deposits that are too small to be mapped separately. Colluvial deposits range up to about 30 feet (9 m) thick and are Holocene to possibly late Pleistocene in age.

Mass-Movement Deposits

Landslide deposits (Qms,Qms?): Landslide deposits consist of very poorly sorted, clay- to boulder- and very large block-size, locally derived sediment deposited principally by rotational and translational movement; the query indicates uncertain designation due to poorly developed geomorphic features. The landslides are characterized by hummocky topography, numerous internal scarps, and chaotic bedding, but landslide features such as scarps and slide blocks are morphologically subdued.

Landslides in the Charleston quadrangle involve the Twin Creek Limestone, Oquirrh Formation, and Big Cottonwood Formation, but the location of most slides—on steep, colluvial-covered slopes—suggests that slip surfaces may be principally in overlying colluvial and regolithic debris derived from these formations. The thickness of landslide deposits is highly variable, but most deposits are likely at least several tens of feet thick.

The large landslide at the head of Big Hollow, which involves both Wallsburg Ridge bedrock and overlying colluvial and regolithic debris, may exceed 300 feet (100 m) in thickness. Widely scattered pieces of weathered volcanic tuff are present near the upper part of this landslide, but we found no outcrops in this heavily vegetated and colluvial-covered area.

It is important to note that while landslides may be characterized by subdued morphology, leading many to interpret them as older features, these landslides may have historical movement. New research shows that even landslides with subdued morphology (suggesting that they are older, weathered, and may have not experienced large movement recently) may continue to exhibit slow creep or are capable of renewed movement if stability thresholds are exceeded (Ashland, 2003). Age and stability determinations of landslides require detailed geotechnical investigations. Many of our mapped landslides are newly recognized, but occur on slopes previously mapped as having a moderate landslide-hazard potential (Hylland and Lowe, 1995; Hylland and others, 1995).

Talus deposits (Qmt): Talus consists of locally derived material deposited principally by rock fall on and at the base of steep slopes. These deposits consist of very poorly sorted, angular boulders and lesser fine-grained interstitial sediments. Talus is widespread over bedrock units in the Charleston quadrangle, especially the Oquirrh Formation, but we mapped only the larger, more prominent deposits, typically where they partly fill the uppermost reaches of small drainages. These deposits are characterized by angular boulder fields that lack vegetation and are up to about 30 feet (9 m) thick. They are considered Holocene to possibly late Pleistocene in age.

Mixed-environment deposits

Alluvial and colluvial deposits (Qac,Qaco): We mapped mixed alluvial and colluvial deposits in swales, small drainages, and the upper reaches of larger ephemeral streams. These deposits consist of poorly to moderately sorted, generally poorly stratified, clay- to boulder-size, locally derived sediment deposited by both alluvial and colluvial processes. Mixed alluvial and colluvial deposits (Qac) are generally less than 30 feet (9 m) thick, and are considered Holocene in age. Older, inactive and deeply incised deposits (Qaco) are mapped in Owens Canyon in the southwest part of the quadrangle and west of Deer Creek Reservoir; they are 0 to about 50 feet (0–15 m) thick and are considered to be Holocene to latest Pleistocene in age.

Alluvial-fan and colluvial deposits (Qafc): Mixed alluvial-fan and colluvial deposits consist of poorly to moderately sorted, weakly to non-stratified, clay- to boulder-size sediment deposited principally by debris flows and debris floods at the mouths of active drainages, but include significant colluvial sediment shed from adjacent slopes, thus forming a coalescing apron of alluvial-fan and colluvial deposits impractical to map separately at this scale. The upper parts of the deposits are typically characterized by abundant boulders and debris-flow levies that radiate away from fan apices. Mixed alluvial-fan and colluvial deposits are equivalent to level-1 and level-2 alluvial-fan deposits and are considered Holocene to late Pleistocene in age. Most deposits are probably less than 50 feet (15 m) thick, but the deposits at Soldier Hollow form a thinner mantle over Nugget Sandstone.

Colluvial and alluvial deposits (Qca): We mapped mixed alluvial and colluvial deposits just southeast of Deer Creek Reservoir, in an abandoned meander of the Provo River in the NW1/4 section 3, T. 5. S., R. 4 E., where they partly conceal Bear Canyon strata and late Tertiary to Quaternary ancestral Provo River gravels. The deposits consist of poorly to moderately sorted, clay- to boulder-size, locally derived sediment that is similar to mixed alluvial and colluvial deposits (Qac), but with a more abundant component of colluvium. The deposits are generally less than 20 feet (6 m) thick and are considered to be Holocene to possibly late Pleistocene in age.

Residual and colluvial deposits (Qrc): Mixed residual and colluvial deposits obscure bedrock throughout much of the quadrangle, but are mapped only where they are extensive enough to conceal large areas of bedrock and bedrock contacts. Such areas commonly correspond to north-facing, densely vegetated slopes. These deposits consist of poorly to moderately sorted, clay- to boulder-size, locally derived sediment derived from in-situ weathering of underlying bedrock and also modified by colluvial processes. Similar deposits are also mapped near Highway 189 just north of Main Creek where they may contain reworked finer grained alluvial and loess deposits. Mixed residual and colluvial deposits range up to about 20 feet (6 m) thick and are considered Holocene to late Pleistocene in age.

Talus and colluvial deposits (Qmtc): Mixed talus and colluvial deposits are present in steep washes throughout the quadrangle. They consist of very poorly sorted, angular to subangular, clay- to boulder-size sediment deposited principally by rock fall and slope wash; locally, they include minor alluvial sediment at the bottom of the washes. The deposits are generally less than 40 feet (12 m) thick and are considered Holocene to late Pleistocene in age.

Stacked-unit deposits

Valley-fill deposits over calcareous spring tufa deposits (Qa_2/Qst): These deposits form a gently south-sloping surface incised by Snake Creek in the northwest corner of the quadrangle. The valley-fill deposits are derived principally from the Wasatch Range west of Heber Valley and form a veneer over and interfinger with calcareous spring tufa deposits. The tufa is pale grayish yellow, weathers light brown, and is highly porous and vuggy; it is exposed at and near mapped springs and likely underlies much of the surrounding surface where it is concealed beneath tilled and cultivated valley-fill deposits. Tufa, interbedded with basin-fill deposits, is reported to depths of nearly 170 feet (52 m) in monitoring wells (Wallace, 2005) and to 392 feet (120 m) in a water well near the Midway fish hatchery (Mayo and others, 2005). The deposits are considered to be Holocene to late Pleistocene in age.

STRUCTURE

Regional Setting

The Charleston quadrangle lies on the south side of a structural and topographic saddle between the Uinta Mountains and Wasatch Range. The Uinta Mountains are a 160-mile-long (250 km) west-trending anticline cored by Proterozoic rocks and flanked by Paleozoic and Mesozoic strata. Uplift of the Uinta Mountains began in the late Campanian to early Maastrichtian (about 75 million years ago)—as demonstrated by growth strata of the Currant Creek Formation—and continued through the end of the middle Eocene (about 40 million years ago) (Constenius and others, 2003). Major uplift occurred in late Paleocene to middle Eocene time (Bryant and Nichols, 1988). The Uinta uplift projects westward into the Cottonwood arch, in the central Wasatch Range, which exposes Late Proterozoic, Paleozoic, and Mesozoic rocks that were uplifted principally in the Miocene and Pliocene. These uplifts divide the Sevier orogenic belt into two segments marked by abrupt changes in stratigraphy within allochthons and by differences in the age and amount of thrust displacement (see, for example, Bradley and Bruhn, 1988; Paulsen and Marshak, 1999).

The Charleston quadrangle also straddles the Charleston thrust fault, which bounds the north edge of the Charleston-Nebo salient of the Sevier orogenic belt. The northern part of this salient (the Charleston allochthon) was emplaced during the late Early Cretaceous and early Late Cretaceous at the height of the Sevier orogeny in central Utah (Bryant and Nichols, 1988). Constenius and others (2003) interpreted the Charleston-Nebo salient as the upper horse of a crustal-scale antiformal duplex they called the Santaquin culmination. The salient is bounded on the west by a large duplex in Paleozoic rocks of the Wasatch Range, truncated at its western margin by the Wasatch fault zone, whereas the east part of the salient consists of an imbricate thrust system in Permian through Cretaceous rocks. Much of the east part of the salient is covered by Late Cretaceous to late middle Eocene synorogenic strata shed off the thrust belt and subsequently deformed by thrusting (Constenius and others, 2006).

The Charleston-Nebo salient was thrust eastward about 30 to 60 miles (50–100 km) during the middle Cretaceous (Crittenden, 1961; Constenius and others, 2003). Thrusting resulted in juxtaposition of a 9- to 10-mile-thick (15-16.5 km) section of Proterozoic to Lower Cretaceous miogeoclinal strata against a cratonic shelf section of the same age that is only about one-third as thick (Baker, 1959; Riess, 1985; Constenius and others, 2003).

Constenius (1996) and Constenius and others (2003) described the extensional collapse of the Sevier orogenic belt during a late Eocene to early Miocene episode of crustal extension. West and south slip on low-angle normal faults, including the Deer Creek detachment fault, and half grabens superimposed on the Charleston-Nebo salient, show that 3 to 4 miles (5–7 km) of extension occurred on the Charleston-Nebo sole thrust during the late Eocene to early Miocene (Royse, 1983; Riess, 1985; Houghton, 1986; Constenius, 1995, 1996; Constenius and others, 2003). Subsequently, late Tertiary normal faulting, associated with Miocene to recent Basin-Range extension, created Heber Valley and Round Valley.

Charleston Thrust Fault

The Charleston thrust fault bounds the north flank of the Charleston-Nebo salient (Baker, 1959, 1976; Bryant, 1992). The fault is concealed at the south margin of Heber Valley, but is exposed west of Deer Creek Reservoir, where it places Upper Proterozoic Big Cottonwood Canyon Formation on the upper part of the Middle Jurassic Twin Creek Limestone. To the east in the adjacent Center Creek quadrangle, the Charleston thrust places Upper Pennsylvanian Wallsburg Ridge strata over Upper Jurassic to lower Upper Cretaceous strata (Biek and others, 2003). In the Placid Oil Company West Daniels Land #1 well (section 11, T. 5 S., R. 5 E.), also in the adjacent Center Creek quadrangle, the Charleston thrust separates Mississippian strata from a nearly complete section of the Jurassic Twin Creek Limestone (Sprinkel, 1994; Biek and others, 2003). Thus, the Charleston thrust ramps up-section from west to east and from south to north, suggesting that the thrust is a sidewall decollement ramp in this area.

Emplacement of the Charleston allochthon can only be dated as post-early Turonian (early Late Cretaceous) in the adjacent Center Creek quadrangle (Biek and others, 2003), but exposures farther east along the salient show an emplacement age of Turonian to Campanian (middle Late Cretaceous) (Bryant and Nichols, 1988); in the Co-op Creek quadrangle, Constenius and others (2006) mapped allochthonous strata thrust over the Upper Cretaceous Mesaverde Formation. Compressional deformation continued into the late middle Eocene (see, for example, Constenius and others, 2003), thus development of the salient represents a protracted period of compressional deformation between about 100 and 40 million years ago (early Late Cretaceous to late Eocene).

Deer Creek Detachment Fault

The Deer Creek detachment fault is a major low-angle normal fault that accommodated 3 to 4 miles (5–7 km) of west and southwest displacement during the late Eocene to early Miocene, during extensional collapse of the Sevier orogenic belt (Royse, 1983; Riess, 1985; Houghton, 1986; Constenius, 1995, 1996; Constenius and others, 2003). In the Charleston quadrangle, two splays of the Deer Creek detachment fault are exposed in the vicinity of Deer Creek Reservoir. Along the east shore of the reservoir, the upper splay places the Bridal Veil Limestone Member of the Oquirrh Formation on the Great Blue Limestone; the intervening Manning Canyon Shale—a sequence of interbedded shale, limestone, and quartzitic sandstone that served as one of several regional detachment horizons for Cretaceous and early Tertiary contractional and extensional deformation (Paulsen and Marshak, 1998, 1999; Constenius and others, 2003)—is missing. During this mapping project, the upper splay was exposed in a new U.S. Highway 189 road cut about 500 feet (150 m) west of State Highway 113. There, the Deer Creek detachment fault is marked by a thin sliver of dense, black, graphitic clay fault gouge, sharply overlain by very pale orange to grayish orange clay fault gouge (figure 3a, b). This graphitic fault gouge is all that remains of the Manning Canyon Shale along this part of the upper Deer Creek detachment.

Immediately to the west of this road-cut exposure, a second, structurally lower splay of the Deer Creek detachment fault places Mississippian Great Blue strata on the Upper Proterozoic Big Cottonwood Formation. This same relationship is exposed along the west shore of the reservoir. The relationship of younger-over-older strata, with some intervening strata cut out, is typical of detachment faults.

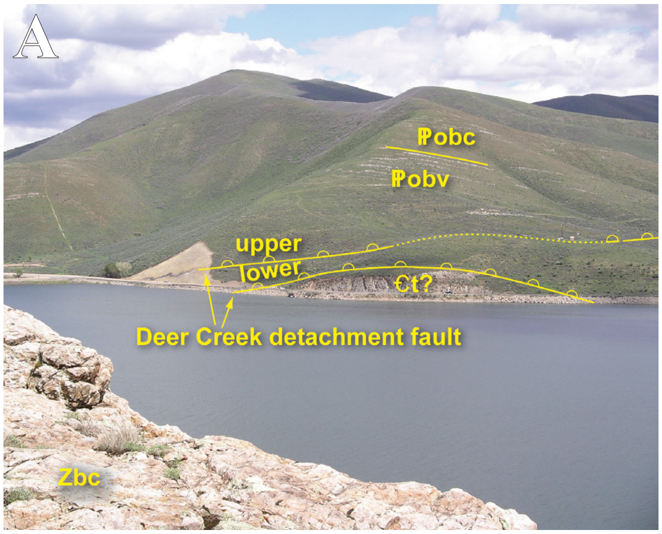


Figure 3A. *View east-southeast to a new Highway 189 road cut along the east side of Deer Creek Reservoir. Note black line in road cut, shown in more detail below, which marks the upper Deer Creek detachment fault (shown as dotted line where concealed behind low hill of the Great Blue Limestsone). Also shown are ledges of the Bridal Veil Limestone Member (*ℙobv*) of the Oquirrh Formation, newly identified in this mapping project.* ℙobc *= Bear Canyon Member of the Oquirrh Formation, Mgb = Great Blue Formation,* Ꞓt? *= Tintic Quartzite,* Zbc *= Big Cottonwood Formation.* ***B****. Closer view of the upper splay of the Deer Creek detachment fault that here places the Bridal Veil Limestone on top of the Great Blue Formation. The 1650-foot-thick (500 m) Manning Canyon Shale is cut out by the fault—all that remains is a thin sliver of dense, black, graphitic clay fault gouge, sharply overlain by very pale orange to grayish orange clay fault gouge of similar thickness.*

A small low-angle normal fault, east of Big Hollow, places the Wallsburg Ridge Member on the Bear Canyon Member, cutting out the intervening Shingle Mill Limestone. Displacement dies out to the southeast and the fault appears to accommodate late Eocene to early Miocene southwest extension along the north edge of the Charleston thrust plate. The fault is well exposed in the quarry at the mouth of Big Hollow; there, quartzitic sandstone of the Bear Canyon Member is shattered by this fault and by its proximity to the much larger Deer Creek detachment fault (figure 4). Pervasively shattered rock in the structurally lower part of the hanging wall is a common feature of detachment faults.

Figure 4. *View east to a small low-angle normal fault, exposed in an aggregate quarry at the mouth of Big Hollow, that here places Bear Canyon orthoquartzite on top of itself. Displacement dies out to the southeast and the fault appears to accommodate tearing apart of the north edge of the Charleston thrust plate, likely during an episode of late Eocene to early Miocene extension. The orthoquartzite here is shattered due to its proximity to the concealed Charleston thrust and Deer Creek detachment faults, which are buried under the south edge of Heber Valley. The horizontal line halfway up the quarry wall above the vehicle is an artifact of stockpiled aggregate, not a fault.*

Allochthonous Rocks

A nearly complete section of the Oquirrh Formation comprises allochthonous rocks of the Charleston thrust plate, in the southern part of the quadrangle where they are folded into the northwest-trending Big Hollow syncline and, in the adjacent Center Creek quadrangle, into the Daniels Canyon anticline. The Big Hollow syncline, named by Welsh (unpublished notes, 1980–81) for exposures at Big Hollow in the Charleston quadrangle, is best defined by outcrops of the Shingle Mill

Limestone of the Oquirrh Formation. The syncline plunges gently southeast, roughly parallel to the Daniels Canyon anticline. The west limb of the syncline is truncated by the East Round Valley fault and an unnamed en echelon fault that trends west-northwest to Deer Creek Reservoir.

The Daniels Canyon anticline, first mapped in a general way by Baker (1976), is also best defined by outcrops of the Shingle Mill Limestone. The anticline plunges southeast, and at the mouth of Daniels Canyon, the axis of the fold lies just north of State Highway 40 (Biek and others, 2003). The crest of the anticline is broken by two steeply dipping normal faults that trend parallel to the axis of the fold and create a horst along the anticlinal axis. The concealed, down-to-the-northeast normal fault at the entrance to Daniels Canyon may link up with the down-to-the-northeast fault that bounds the north side of this horst.

A small, poorly defined syncline, truncated by the West Round Valley fault, is present in Bear Canyon strata along the east side of Deer Creek Reservoir. We find no evidence of an anticline separating this small syncline from the much larger Big Hollow syncline. If such an anticline were present, it is now dismembered and rendered unidentifiable by faulting associated with the Round Valley graben.

Para-Autochthonous Rocks

In the Charleston quadrangle, exposed para-autochthonous rocks include the Thaynes Limestone, Ankareh Formation, Nugget Sandstone, and Twin Creek Limestone. These strata dip about 20° to 30° east-southeast at the west margin of Heber Valley. Their homoclinal dip and para-autochthonous nature reflect the quadrangle's location at the southeastern margin of the Cottonwood arch (Constenius and Stern, 1998).

Heber Valley and Round Valley

Heber and Round Valleys are two back valleys (fault-bounded valleys east of the Wasatch fault zone) first described by Gilbert (1928). In plan view, Heber Valley resembles an irregular triangle that is 8 to 10 miles (13–16 km) long on a side; only the southwest part of the valley lies within the Charleston quadrangle. The valley is somewhat anomalous in that its margins are sinuous and lack evidence of late Quaternary basin-bounding faults (Bromfield and others, 1970; Sullivan and others, 1988; Bryant, 1992; Biek and others, 2003). Sullivan and Nelson (1983) trenched across a 2000-foot-long (600 m), 3- to 40-foot-high (1–12 m) linear scarp in level-2 alluvial-fan deposits (Qaf_2) at the entrance to Big Hollow on the south side of the valley in the Charleston quadrangle and concluded that it formed as an erosional feature. Similar escarpments are cut in level-2 alluvial-fan deposits both west and east of the mouth of the Center Creek drainage (in the central parts of sections 11 and 15, T. 4 S., R. 5 E.), and, although they have not been trenched, they too are interpreted as erosional in nature (Biek and others, 2003). Sullivan and Nelson (1983) also suggested that bedrock facets between embayments along the south margin of Heber Valley may have formed by lateral stream migration and erosion of brecciated Oquirrh bedrock by the Provo River and its tributaries. Finally, reprocessing and reinterpretation of Amoco seismic line GFR-31, which extends from the west side of Heber City, south to U.S. Highway 189 and then south along U.S. Highway 189 to the junction with Utah Highway 222 to Wallsburg, does not suggest an east-west-trending normal fault bounding the south side of Heber Valley (Kurt Constenius, written communication, January 11, 2007). This southern valley margin appears to be the result of differential erosion of relatively non-resistant Middle Jurassic Twin Creek Limestone in the lower plate of the Charleston thrust sheet versus resistant sandstone and limestone of the Oquirrh Formation that makes up the thrust sheet itself.

We did, however, map the inferred trace of what we call the West Heber Valley fault, which is on strike with and which appears to be the northward continuation of the West Round Valley fault. Both faults are down-to-the-east normal faults, and together they may form a relay zone in the vicinity of Deer Creek Reservoir. Tectonic displacement on the faults is uncertain due to lack of stratigraphic marker beds, but likely exceeds several hundred feet. The West Heber Valley fault helps to explain: (1) the depth of Heber Valley, which may have as much as 800 feet (245 m) of basin fill (Peterson, 1970), and (2) the capture of the Keetley drainage by the Provo River in Heber Valley (Sullivan and others, 1988). Baker (1964, 1976) showed that the structural floor of Heber Valley lies at a lower elevation than its outlet, requiring that the valley be down-dropped relative to its outlet along one or more faults. Sullivan and others (1988) summarized evidence that suggests Heber Valley may have been near its present relative level for the last several hundred thousand years even though the lower and probably the upper Provo Canyons have deepened considerably over the same time period. They suggested that a combination of mid-Tertiary extension and episodes of erosion and aggradation by the Provo River and its tributaries best explains the present topography of Heber Valley.

In contrast, Quaternary basin-bounding faults are easily recognized at Round Valley (figure 5) (Sullivan and others, 1988; Bryant, 1992). Round Valley is a graben bounded on the east by the East Round Valley fault and on the west by the West Round Valley fault. The valley is entirely within the Charleston allochthon, and the lack of mid-Cenozoic deposits there suggests that the valley developed after mid-Cenozoic extensional reactivation of the Charleston thrust (Sullivan and others, 1988). The East Round Valley fault cuts older alluvial-fan deposits (Qafo) in the southeast part of the quadrangle, and Biek and others (2003) mapped a 50- to 80-foot (15–24 m) high scarp in these deposits in the extreme southwest corner of the adjacent Center Creek quadrangle. The East Round Valley fault ends abruptly in section 32, T. 4 S., R. 5 E., at what may be a relay ramp with an en echelon fault that trends west-northwest through section 31. While the age of the most recent displacement on the East Round Valley fault is not constrained, Hecker (1993) suggested that it is middle to late Pleistocene, based in part on comparison with the better studied Morgan fault (40 miles [65 km] to the north). The west margin of Round Valley is bounded by what we call the West Round Valley fault; it reveals significant offset of the Shingle Mill Limestone in section 10, T. 5 S., R. 4 E., but no scarps in unconsolidated deposits were observed in this quadrangle. The West Round Valley fault is on strike with the West Heber Valley fault and we interpret the two faults to be linked in the vicinity of Deer Creek Reservoir.

Figure 5. *View southeast to the East Round Valley fault, which here places older alluvial-fan deposits (Qafo) down on the west against the Wallsburg Ridge Member of the Oquirrh Formation (ℙowr). The East Round Valley fault dies out abruptly near the west edge of the photo, where the fault steps left, forming a relay ramp between the two fault sections.*

Normal faults also offset Quaternary deposits within Round Valley. We mapped a down-to-the-northeast fault scarp in level-3 alluvial-fan deposits (Qaf_3) at the north end of Round Valley. We also mapped a northwest-trending, down-to-the-west scarp, which we interpret to be a fault scarp, that offsets younger, level-2 alluvial-fan deposits (Qaf_2) south and east of Wallsburg. Constenius and others (2006) showed that this scarp continues to the south end of Round valley.

ECONOMIC GEOLOGY

Aggregate

Aggregate has been extracted from alluvial and alluvial-fan deposits at several locations in the Charleston quadrangle. The Materials Inventory of Wasatch County (Utah State Department of Highways, 1966) contains basic analytical information on these workings, which are shown on the map. Alluvial deposits in Heber Valley in the northern part of the quadrangle contain large amounts of moderately sorted sand and gravel. Crushed stone is intermittently quarried from highly fractured orthoquartzite in the Bear Canyon Member of the Oquirrh Formation near the mouth of Big Hollow, and from a similar quarry southeast of Charleston. Similar aggregate is quarried from Wallsburg Ridge strata near the north end of Round Valley. These quarries tap a nearly unlimited supply of highly fractured and brecciated Oquirrh sandstones. Because these sandstones are siliceous and generally only slightly feldspathic, they are classified as orthoquartzite. When crushed and screened, they provide a source of high-quality aggregate.

Oil and Natural Gas

Exploration for oil and gas in the Charleston quadrangle resulted in the drilling in 1950 of the Bullock #1 well near the mouth of Daniels Canyon, in the SW1/4NE1/4NE1/4 section 21, T. 4 S., R. 5 E., that was reported to have reached a depth of 515 feet (157 m) (Hansen and Scoville, 1955). No other information is available for this well. In the Center Creek quadrangle to the east, Placid Oil Company West Daniels Land #1 wildcat well (API # 43-051-30014) was spudded in 1982 and plugged and abandoned in 1983 in the NE1/4NW1/4NW1/4 section 11, T. 5 S., R. 5 E. The well is one of many drilled during the overthrust exploration boom of the late 1970s and early 1980s. The well was abandoned at 17,322 feet (5281 m) in the Weber Quartzite before reaching the intended target, a structure in Mississippian carbonates below the Charleston thrust, due to repeated problems believed to result from shales flowing into and bridging the hole at about 10,800 feet (3290 m) (Doug Sprinkel, Utah Geological Survey, verbal communication, November 4, 1999). Oil shows were reported but not tested in Park City and Weber strata.

Prospects

South of Charleston, on the east side of Deer Creek Reservoir, several small prospects and pits are present in the Great Blue Formation. The limestone is filled with calcite-healed fractures, and the calcite, possibly for use as poultry grit, is probably what prospectors were after. Up the hill, two small but similar prospects are in Bridal Veil Limestone. To the south, two small prospects, each with minor iron mineralization, are present just east of Highway 189, east of Deer Creek Reservoir in the NW1/4 section 34, T. 4 S., R. 4 E., and in the NE1/4 section 3 , T. 5 S., R. 4 E.

Geothermal Resources

Geothermal springs are present near Midway, on the west side of Heber Valley mostly north of the Charleston quadrangle, and have long been enjoyed by local residents (Willis and Willis, 2003, 2004), and springs at the Mountain Spa and Homestead Resorts are still used to heat swimming pools and for therapeutic baths. The Midway springs issue from several widespread, coalescing travertine and tufa mounds with water temperatures ranging from 90 to 115 degrees Fahrenheit (31–46°C) (Baker, 1968; Kohler, 1979; Blackett, 1994; Mayo and Loucks, 1995). Travertine deposits are also present around mapped springs north of Charleston in this quadrangle, and are known to be interbedded with valley fill deposits to a depth of nearly 400 feet (120 m) (Roark and others, 1991).

Baker (1968) reasoned that the spring water is meteoric, originating in the mountains to the northwest and emerging through fractures at Midway. Mayo and Loucks (1995) proposed a model in which ground water is heated by the natural geothermal gradient as it circulates to a depth of 1.2 to 1.5 miles (2–2.5 km) before it encounters the West Heber Valley fault zone. The fault zone acts as a conduit for warm ground water to rise to the surface, mix with cooler shallow ground water, and emerge as springs (Mayo and Loucks, 1995; Diazconti and others, 2003).

Building and Ornamental Stone

The Nugget Sandstone has long been quarried in northern Utah as a source of building and ornamental stone, but no quarries are in the Charleston quadrangle. Quarries near the mouth of Lake Creek, at the east end of Heber Valley east of the Charleston quadrangle, provide a reddish-orange, or "salmon" colored, fine- to medium-grained sandstone widely used in Utah for building and decorative work. The sandstone naturally splits into thin sheets and blocks along cross-bedding surfaces and closely spaced joints. This sandstone was used for a number of historic buildings in Heber City.

Travertine, mostly from the Midway area just north of the quadrangle, was widely used for foundations and homes in that community, and is still locally used for fences and decorative stone. Travertine is present near mapped springs in this quadrangle, and locally underlies valley fill deposits north of Deer Creek Reservoir.

WATER RESOURCES

Average annual precipitation in the Charleston quadrangle is between about 16 and 25 inches (41–64 cm) (Ashcroft and others, 1992). Most of this precipitation is associated with low-pressure storms between October and May, although significant precipitation also occurs in August during cloudburst storms. More than half of the annual precipitation falls as snow, mostly in the higher elevations (Richardson, 1976). Runoff and spring flow are concentrated in several perennial and numerous ephemeral stream channels within the quadrangle.

The surface- and ground-water resources in the Charleston quadrangle were evaluated as part of regional hydrogeologic studies in the area (Hyatt and others, 1969; Baker, 1970; Roark and others, 1991), for classification of the Heber Valley valley-fill aquifer (Jensen, 1995; Lowe, 1995), and as part of a pesticide vulnerability assessment (Lowe and Butler, 2003). The following information is largely compiled from these sources.

Surface Water

Lake Creek, Center Creek, and Daniels Creek flow across the quadrangle from east to west in Heber Valley, Snake Creek flows into Heber Valley from the north, and Main Creek flows across Round Valley from southeast to northwest. These streams are relatively major tributaries to the Provo River, which enters the quadrangle from the north and flows into Deer Creek Reservoir before exiting Heber Valley via Provo Canyon to the west of the quadrangle. Within Heber and Round Valleys, the Provo River, Snake Creek, and Main Creek (downstream from Wallsburg) are perennial with discharges of 307, 57, and 18 cubic feet per second (8.7, 1.6, and 0.5 m^3/s), respectively; Daniels, Lake, and Center Creeks are diverted at the valley margins for irrigation and flow within Heber Valley only during winter and early spring (Roark and others, 1991). Daniels Creek is the largest of the three streams, having an estimated discharge of 15.6 cubic feet per second (0.44 m^3/s) (Roark and others, 1991). Estimated average discharges of Lake and Center Creeks are 10.9 cubic feet per second (0.31 m^3/s) and 6.5 cubic feet per second (0.18 m^3/s), respectively (Roark and others, 1991). Deer Creek Reservoir, at the west edge of the quadrangle, has a storage capacity of about 153,000 acre-feet (189 hm^3). Surface water in streams in the eastern Heber Valley area is calcium-bicarbonate type and is generally low in dissolved solids (Hyatt and others, 1969).

Ground Water

Ground water occurs in both fractured bedrock and in unconsolidated sediments in the Charleston quadrangle. Consolidated rocks crop out in the hills and mountains surrounding valley lowlands, and also underlie unconsolidated valley-fill sediments in the valleys, commonly at relatively shallow depths.

Fractured Bedrock Aquifers

Water users in the mountains and hills surrounding valley lowlands obtain most of their supply from springs and wells discharging from bedrock aquifers (Baker, 1970). Springs discharging from consolidated rocks are the primary source of public-water supplies for the communities of Charleston, Daniel, Heber City, and Wallsburg (Roark and others, 1991). Bedrock aquifers are also an important source of recharge to unconsolidated valley-fill aquifers.

Aquifer characteristics: Bedrock units in the Charleston quadrangle are locally extensively fractured by faulting and folding. In soluble rocks, such as limestone, the fractures may have been enlarged by dissolution as water moved through the rocks. Water moves along fractures which cut across rock unit boundaries, and any rock unit, at least locally, may be water bearing (Baker, 1970). On a large scale, fractures are found in all consolidated rocks in the area and, for the purpose of evaluating regional ground-water flow, the rocks can be viewed as large homogenous aquifers (Baker, 1970). At a smaller scale, however, the aquifers are very heterogeneous and wells designed to intercept water moving through fractures have varying degrees of success. Aquifer characteristics such as transmissivity, storativity, and hydraulic conductivity are variable in fractured-rock aquifers. Unconfined (water-table) conditions are predominant in the bedrock aquifers, but Roark and others (1991) reported confined (artesian) conditions for one well completed in consolidated rock below tufa and unconsolidated deposits in the Midway area.

Recharge and discharge: Recharge to bedrock aquifers in western Wasatch County is by infiltration of precipitation and stream flow, and leakage from local unconsolidated aquifers (Roark and others, 1991). Most recharge takes place in the mountains and hills surrounding valley lowlands; estimates of the amount of recharge to bedrock are not available.

Movement of water in bedrock aquifers is generally from the mountains and hills toward streams and springs at valley margins. Fractures may control the direction of ground-water flow in localized areas (Roark and others, 1991), so the direction of ground-water flow is not always directly downslope. Fractures may also allow ground-water flow across surface-drainage divides.

Discharge of water from bedrock aquifers is primarily by flow from springs, subsurface flow to unconsolidated valley-fill aquifers, and pumping from wells (Roark and others, 1991). The larger springs generally discharge from limestone (Roark and others, 1991).

Water quality: Most water from bedrock is of high quality and is suitable for drinking. However, some water from volcanic rocks, which are exposed along the north and east sides of Heber Valley, is high in iron, and one sample contained 34 mg/L iron (Baker, 1970). Three types of water can be distinguished from three general bedrock types in the Wasatch County area. Water from sandstone and limestone of Jurassic age and older is of calcium-magnesium-bicarbonate type with total-dissolved-solids concentrations ranging from 104 to 488 mg/L (Baker, 1970). Water from Triassic-age shale is of calcium-sulfate type with total-dissolved-solids concentrations ranging from 218 to 691 mg/L (Baker, 1970). Water from volcanic rocks is of calcium-bicarbonate type with total-dissolved-solids concentrations ranging from 249 to 1020 mg/L (Baker, 1970).

Fractured-rock aquifers are highly susceptible to pollution because soil cover is thin or nonexistent, and little remediation of contaminants takes place once contaminated water is in fractures because of the high permeability and low filtering capacity associated with the fractures. Fractured-rock terrain is generally not suitable for the siting of waste-disposal facilities such as landfills and septic-tank soil-absorption systems.

Valley-Fill Aquifers

The principal source of water to wells in western Wasatch County is the unconsolidated sediments in the major valleys (Baker, 1970). Unconsolidated deposits in the mountains and hills are generally not significant sources of ground water.

The valley-fill deposits consist of poorly sorted clay- to boulder-sized particles (Roark and others, 1991). Tufa deposits in the Midway area interfinger with the unconsolidated sediments and are considered to be part of the valley-fill (Roark and others, 1991). The valley-fill deposits locally exceed 450 feet (140 m) thick and thin towards the valley margins based on driller's logs of water wells (see plate 1). Based on a gravity survey, Peterson (1970) estimated slightly more than 800 feet (245 m) of basin fill in the southwest part of Heber Valley. Driller's reports from scattered water wells in Round Valley suggest that basin fill there locally exceeds 200 feet (60 m) or more (plate 1). Ground water is as shallow as 5 to 20 feet (1.5–6 m) below the ground surface at the eastern end of Heber Valley, becomes deeper to the west in the central Heber Valley, and is doubtless fairly shallow near Charleston, in the vicinity of Deer Creek Reservoir.

Aquifer characteristics: Aquifer characteristics such as transmissivity, storativity, and hydraulic conductivity are variable in the valley-fill aquifers. Hydraulic conductivity in the Heber Valley and Round Valley area ranges from 1 to about 200 feet per day (0.3 to 60 m/d), the highest values being in the Daniel and Charleston areas (Roark and others, 1991). One transmissivity value in the area exceeded 2500 feet squared per day (232 m^2/d), but, with the exception of the Daniel and Charleston areas, transmissivity in most of the valley-fill deposits in Heber Valley and Round Valleys is less than 500 feet squared per day (46 m^2/day) (Roark and others, 1991).

In general, the valley-fill deposits form a "single, essentially homogeneous, water-table aquifer" (Baker, 1970). However, artesian conditions occur at depths greater than 50 feet (15 m) in the lower areas of Heber Valley near Deer Creek Reservoir and Midway where numerous layers of clay and silt form confining layers (Roark and others, 1991). Also, tufa deposits in the Midway area are a confining layer (Roark and others, 1991). Artesian conditions have also been identified in Round Valley in the SE1/4NW1/4NE1/4 section 12, T. 5 S., R. 4 E.; the extent of the confining beds is unknown, but is probably "localized in a small area" (Roark and others, 1991).

Recharge and discharge: Recharge to the valley-fill aquifers is from precipitation on the valley floor, infiltration of stream flow and unconsumed irrigation water, and subsurface flow from bedrock (Roark and others, 1991). Recharge to the valley-fill deposits in Heber Valley is estimated to be about 154 cubic feet per second (111,600 acre-ft/yr, 4.4 m^3/s); recharge to the valley-fill deposits in Round Valley is estimated to be about 11 cubic feet per second (8000 acre-ft/yr, 0.3 m^3/s) (Roark and others, 1991). The primary recharge area for Heber and Round Valleys consists of the valley floor and hill slopes surrounding the valleys below the surface-drainage divides. Keetley Valley, north of Heber Valley, and the east side of the hills east of Heber Valley are considered a secondary recharge area to Heber Valley because streams in these areas flow into the Provo River, which recharges Heber Valley. The potential for flow of ground water through the hills north and east of Heber Valley is unknown.

Movement of ground water in the valley-fill aquifer in Heber Valley is generally toward the Provo River and down valley toward Deer Creek Reservoir (Roark and others, 1991). Movement of ground water in unconsolidated deposits in Round Valley is toward Main Creek and down valley toward Deer Creek Reservoir (Baker, 1970).

Discharge of ground water from the unconsolidated valley-fill deposits in Heber and Round Valleys is from evapotranspiration, and seepage to rivers, springs, and wells (Baker, 1970; Roark and others, 1991). Discharge from the valley-fill aquifer in Heber Valley also includes leakage to Deer Creek Reservoir, which is a ground-water discharge area (Roark and others, 1991). Discharge from valley-fill deposits in Heber Valley is estimated at 154 cubic feet per second (111,600 acre-ft/yr, 4.4 cubic m^3/s); discharge from unconsolidated deposits in Round Valley is estimated at 11 cubic feet per second (8000 acre-ft/yr, 0.3 cubic m^3/s) (Roark and others, 1991).

Ground-water quality: Ground water in most unconsolidated deposits in Heber Valley and Round Valley is high-quality calcium-bicarbonate-type water with total-dissolved-solids concentrations generally less than 500 mg/L (Roark and others, 1991). Water samples analyzed as part of Wasatch County's petition to the Utah Water Quality Board for aquifer classification (Jensen, 1995) indicate that, with the exception of the Midway area, average total-dissolved-solids concentrations and nitrate levels in the valley-fill aquifers in Heber and Round Valleys are 284 and 1.87 mg/L, respectively (Jensen, 1995). Ground water in unconsolidated deposits near Midway, however, is calcium-sulfate-type and calcium-bicarbonate-sulfate-type water, which may exceed total-dissolved-solids concentrations of 500 mg/L and may contain sulfate concentrations greater than 250 mg/L (Roark and others, 1991). Water samples analyzed as part of Wasatch County's aquifer classification petition (Jensen, 1995) indicate that average total-dissolved-solids concentrations and nitrate levels in the Midway area are 1233 and 0.83 mg/L, respectively (Jensen, 1995).

GEOLOGIC HAZARDS

Geologic hazards are naturally occurring geologic processes that present potential dangers to life and/or property, and therefore should be considered in land-use planning. Potential geologic hazards in the Charleston quadrangle include landsliding, stream flooding, alluvial-fan flooding, debris flows, shallow ground water, problem soil and rock, earthquakes, and radon. Hylland and others (1995) mapped geologic-hazards in western Wasatch County, including much of the Charleston quadrangle.

Landslides and Rock Falls

Over two dozen landslides, many of them newly recognized, are mapped in the Charleston quadrangle. The landslide deposits include combinations of translational slides, rotational slides, and earth flows, and typically involve the Pennsylvanian Oquirrh Formation and Jurassic Twin Creek Limestone, and colluvial and residual deposits derived from these units. These landslides are typically characterized by slightly to moderately subdued landslide features, but they may have historical movement. New research shows that even landslides with subdued morphology (suggesting that they are older, weathered, and may have not experienced large movement recently) may continue to exhibit slow creep or are capable of renewed movement if stability thresholds are exceeded (Ashland, 2003). Age and stability determinations of landslides require detailed geotechnical investigations.

Although prehistoric landslides may be dormant or inactive, they pose a hazard in that they may become reactivated as a result of changes in ground-water conditions, seismic activity, or slope modifications resulting from development or erosion. Hylland and Lowe (1997) calculated critical slope inclinations, which represent slope inclinations above which landsliding has typically taken place under climatic conditions similar to the present, to be 35% (about 32 degrees) for landslides in the Oquirrh Formation; the Twin Creek Limestone was not considered in the Hylland and Lowe (1997) evaluation.

Rock fall is another type of mass movement that may also be a hazard in the Charleston quadrangle. Although rock fall is likely not a significant hazard in much of the quadrangle because of a lack of source areas near existing residential areas, they may occur locally below steep exposures such as road cuts, cliffs, or stream banks. The likelihood of rock fall increases significantly during strong ground shaking accompanying earthquakes of magnitude 4.0 or greater (Keefer, 1984). Because of steep slopes adjacent to many areas along U.S. Highway 189 and Heber Railroad, the rock-fall hazard is probably greatest near the head of Provo Canyon.

Stream Flooding

Stream flooding may be caused by direct precipitation, typically during summer cloudburst rainstorms, melting snow, typically during the spring, or a combination of both. Hylland and others (1995) mapped flood hazards in western Wasatch County, including the Charleston quadrangle, by compiling 100-year flood plains delineated by the Federal Insurance Administration (FIA) (1980a,b, 1987) and the Federal Emergency Management Agency (FEMA) (1983) for major drainages, and by mapping Holocene alluvium (Qal_1) for minor drainages not delineated by the FIA or FEMA.

Flooding may also result from dam failure. Dam failures generally occur with little warning, and the severity of flooding depends on the extent of failure and the size of the reservoir impounded behind the dam. The U.S. Bureau of Reclamation (1993) has prepared a dam-failure inundation study for Jordanelle Reservoir, upstream on the Provo River, that indicates failure could cause flooding in parts of the Charleston quadrangle. Additionally, nine small dams in the Lake Creek and Center Creek drainages are considered high-hazard dams (Matthew Lindon, Utah Division of Water Rights, Dam Safety Section, written communication, 1996) and could cause flooding in parts of the Charleston quadrangle; the high hazard rating is based on dam size, reservoir volume, and the potential for loss of life in the event of a dam failure (Lindon, 1992).

Alluvial-Fan Flooding, Debris Floods, and Debris Flows

Alluvial-fan flooding, debris floods, and debris flows occur when mixtures of water, rock, soil, and organic material flow downslope. Associated hazards are found on Holocene alluvial fans (Qaf_1, Qafc), and may locally be a hazard on some alluvial and colluvial deposits (Qac, Qc, Qal_1). The type of hazard is classified based on the percent of solids by weight; debris flows have 90 to 70% solids, debris floods (also called mud floods and hyperconcentrated streamflows) have 70 to 40% percent solids, and floods and normal streamflow have less than 40% solids (Costa, 1984). Hazard events commonly form a continuum of sediment/water mixtures that grade into each other with changes in the relative proportion of sediment to water and with changes in stream gradient (Pierson and Costa, 1987). During alluvial-fan flooding, debris floods, and debris flows, the mixtures of water and solids generally remain confined to stream channels in mountainous areas, but may flood and deposit debris over large areas at and beyond canyon mouths. Like normal stream flooding, alluvial-fan hazards can result from intense precipitation during cloudburst rainstorms and rapid spring snowmelt, with sediment derived from scouring of the ground surface or stream channels. The potential for flooding and increased sediment yield is commonly increased if vegetation in drainage basins is removed by wildfire, over grazing, or development. Sediment can also come from landslides.

Alluvial-fan flooding, debris floods, and debris flows have not been a significant hazard in the Charleston quadrangle in historical time, but new development is expanding onto valley margin alluvial fans, thus increasing the risk. Hylland and others (1995) mapped the general extent of alluvial-fan flood hazards in western Wasatch County, including the Charleston quadrangle.

Shallow Ground Water

Ground water is considered shallow where the water table is within 30 feet (9 m) of the ground surface (Hecker and others, 1988). Problems from shallow ground water typically arise when the saturated zone is within about 10 feet (3 m) of the ground surface, because that is the depth to which many building foundations are excavated. Shallow ground water is also a significant hazard that should be considered when siting waste-disposal facilities and septic-tank soil absorption systems. Shallow ground water is present in the Charleston quadrangle in the vicinity of the Provo River, near the shore of Deer Creek Reservoir in southwest Heber Valley, in the central valley floor area of Round Valley, and locally along minor drainages in the quadrangle (Hylland and others, 1995).

Problem Soil and Rock

Problem soils are surficial geologic materials susceptible to volumetric change due to expansion or swelling, collapse, subsidence, or dissolution. Problem soils that may exist in the Charleston quadrangle include expansive and collapsible soils. U.S. Soil Conservation Service maps indicate that soils in the Charleston quadrangle generally have a low to moderate shrink-swell potential (Woodward and others, 1976). The Ankareh Formation and parts of the Twin Creek Limestone, especially the Boundary Ridge Member, may contain beds that exhibit a moderate shrink-swell potential. Collapsible soils are most likely to be found in areas underlain by Holocene alluvial fans containing clayey deposits; Hylland and others (1995) mapped collapsible soil hazards in western Wasatch County, including the Charleston quadrangle. Problems with soils can also occur due to differential compaction when construction occurs on sediments having different characteristics.

Earthquakes and Seismic Hazards

The Charleston quadrangle is in the Intermountain seismic belt, an active earthquake zone that extends from northwestern Montana to southern Nevada (Smith and Sbar, 1974; Smith and Arabasz, 1991). Many faults within the Intermountain seismic belt are active and capable of producing earthquakes of magnitude 6.5 or larger, including the Wasatch fault zone about 15 miles (24 km) west of the quadrangle.

In addition, non-surface-faulting earthquakes that are not necessarily attributable to a mapped fault could also occur within the region and cause damage (Smith and Arabasz, 1991). For example, on October 1, 1972, a magnitude 4.7 earthquake having an epicenter about 3 miles (5 km) east of Heber City caused minor damage associated with ground shaking in Heber City and the nearby communities of Midway and Wallsburg (Langer and others, 1979). Also, on February 13, 1958, ground shaking from an earthquake caused minor damage in Wallsburg in the southern part of the Charleston quadrangle (Brazee and Cloud, 1960); based on a maximum Modified Mercalli intensity of VI, this is estimated to have been a magnitude 5.0 earthquake (Arabasz and McKee, 1979; Hopper, 1988). Seismic hazards in the Charleston quadrangle include surface-fault rupture, ground shaking, liquefaction, and seismically induced slope failures.

Surface-fault rupture: Surface-faulting hazards in the Charleston quadrangle are likely greatest in Round Valley where normal faults cut older alluvial-fan deposits (Qaf_2, Qaf_3, and Qafo). Ages and recurrence intervals for movement on the East and West Round Valley faults are unknown, but Sullivan and others (1988) believed the Round Valley faults may have been active in late Quaternary time. The down-to-the-west fault near the Boren ditch, southeast of Wallsburg, offsets Qaf_2 deposits that we interpret to be latest Pleistocene in age. Black and others (2003) summarized information available for the Round Valley faults. Hylland and others (1995) delineated surface-fault-rupture special-study zones for the Round Valley faults and provided recommendations for hazard studies prior to development within these zones. Faults bounding Heber Valley in the Midway area are poorly understood but may also present a surface-fault-rupture hazard.

Ground shaking: Ground shaking is the most widespread and frequently occurring seismic hazard and has been responsible for the majority of earthquake-caused damage throughout the world. Significant ground shaking may occur at distances greater than 60 miles (100 km) from the epicenter of a large-magnitude earthquake, and shaking may be locally amplified, depending on sediment and soil conditions. The extent of damage due to ground shaking is determined by several factors: (1) strength of seismic waves reaching the surface, including amplitude, frequency, and duration of shaking; (2) types of foundation materials; and (3) building design (Costa and Baker, 1981; Hays and King, 1982). The strength of seismic waves depends on earthquake magnitude, distance to the epicenter, efficiency of seismic wave propagation, and local site conditions.

The strength of earthquake ground-motions is typically reported as a fraction of the force of gravity (g, a unit of acceleration). Based on probabilities of large earthquakes from paleoseismic data and expected characteristics of seismic wave propagation in the Charleston quadrangle, there is a 2% probability over a 50-year time period of horizontal ground acceleration exceeding 40 percent of the force of gravity (0.4g) (Frankel and others, 1996, in Utah Seismic Safety Committee, 2003). New buildings in the Charleston quadrangle should be designed and constructed to meet the seismic provisions in the current *International Building Code*, including use of appropriate ground-motion values.

Liquefaction: Ground shaking can cause increased pore-water pressure, which decreases shear strengths of some sediments, causing liquefaction. When sediments undergo liquefaction, they behave like liquids—foundations may crack, buildings may tip, buoyant buried structures may rise, and gentle slopes may fail. The potential for liquefaction depends on sediment and ground-water conditions, and on the severity and duration of ground shaking, with liquefaction most common in areas of shallow ground water (less than 30 feet [9 m] deep) and loose sandy sediments. An earthquake of magnitude 5 or greater is generally needed to induce liquefaction (Kuribayashi and Tatsuoka, 1975), and liquefaction becomes more likely over larger areas for larger magnitude earthquakes. Earthquakes of magnitude 7.0 to 7.5 that may occur along the Wasatch fault zone could induce liquefaction up to 120 miles (200 km) from the earthquake epicenter, based on analogy to other earthquakes (Youd and Perkins, 1987). Anderson and others (1994) produced liquefaction-potential maps for the Heber Valley area, which shows that alluvium, containing cohesionless soils susceptible to liquefaction, along the Provo River has a moderate liquefaction potential while most other parts of the valley have a very low liquefaction potential. For moderate-potential areas, a 10 to 50% probability exists for ground shaking to induce liquefaction in susceptible sediments in the next 100 years (Anderson and others, 1994).

Slope failure: Local slope failure commonly accompanies earthquakes with magnitudes greater than 4.5 (Keefer, 1984), and some form of slope failure (predominantly rock fall) has been noted in the descriptions of 12 earthquakes having magnitudes 4.3 to 6.6 that occurred in or immediately adjacent to Utah from 1850 to 1986 (Keaton and others, 1987). Slope failure may occur as far as 185 miles (300 km) from the epicenters of large magnitude (greater than 6.5) earthquakes (Keaton and others, 1987). Liquefaction may also induce slope failure of various types that can be very damaging.

Indoor Radon

Radon (^{222}Rn) is an odorless, tasteless, and colorless radioactive gas of geologic origin that is of concern because of its link to lung cancer. Derived from the decay of uranium that is found in small quantities in many geologic materials, radon can pose a health hazard when it accumulates in enclosed spaces such as buildings. Although indoor radon concentrations can vary significantly over short distances due to both non-geologic (construction type and quality and other issues) and geologic factors (including rock and soil type in foundation materials and ground-water levels), the geologic factors (presence of uranium-bearing soil or rock, permeability, water saturation) can be quantified to assess the radon-hazard potential. Although indoor radon generally is not a major geologic hazard in the Charleston quadrangle, combinations of geologic factors contributing to a potential hazard exist locally. As part of a statewide evaluation of geologic conditions related to radon hazard, Black (1993) identified a moderate radon-hazard potential in much of the Charleston quadrangle area, except for Heber Valley, where the hazard potential is low due to shallow ground water, and the Wallsburg area, where the radon potential is mapped as being high. Indoor testing is the recommended method to determine if a radon hazard exists for a specific building (U.S. Environmental Protection Agency [EPA], 1992). Techniques are available for reducing indoor-radon levels in existing buildings and preventing elevated levels in new construction (EPA, 1992, 1994).

ACKNOWLEDGMENTS

Thanks to Scott Ritter (Brigham Young University) for his advice in the field concerning the Bridal Veil and Shingle Mill Limestones, and for collecting and analyzing conodont samples from those members. Thanks also to Kurt Constenius (Tucson, Arizona) for discussions in the field and in the office, for sharing his knowledge of the Charleston-Nebo thrust sheet and Deer Creek detachment fault, and for arranging for and interpreting the reprocessed Amoco seismic line. Co-author Biek gratefully acknowledges the unpublished mapping and measured sections of the late John E. Welsh, which guided our mapping in this quadrangle. Dan Aubrey (Utah Division of Water Rights) made available an unpublished consultant's report on water resources at the Midway Fish Hatchery. We also thank Mike Hylland, Robert Ressetar, Jon King, Barry Solomon, and Grant Willis, each with the Utah Geological Survey (UGS), who provided reviews of this report, and Kent Brown (UGS), who set up photogrammetry for this project.

REFERENCES

Ashland, F.X., 2003, Characteristics, causes, and implications of the 1998 Wasatch Front landslides, Utah: Utah Geological Survey Special Study 105, 49 p.

Anderson, L. R., Keaton, J.R., and Rice, J.D., 1994, Liquefaction potential map for central Utah—complete technical report: Utah Geological Survey Contract Report 94-10, 134 p., scale 1:48,000.

Arabasz, W.J., and McKee, M.E., 1979, Utah earthquake catalog 1850–June 1962, *in* Arabasz, W.J., Smith, R.B., and Richins, W.D., editors, Earthquake studies in Utah 1850 to 1978: University of Utah Seismograph Stations Special Publication, p. 119-143.

Ashcroft, G.L., Jensen, D.T., and Brown, J.L., 1992, Utah climate: Logan, Utah Climate Center, Utah State University, 125 p.

Baker, A.A., 1947, Stratigraphy of the Wasatch Mountains in the vicinity of Provo, Utah: U.S. Geological Survey Oil and Gas Preliminary Chart OC-30, scale 1:6000.

Baker, A.A., 1959, Faults in the Wasatch Range near Provo, Utah, *in* Williams, N.C., editor, Guidebook to the geology of the Wasatch and Uinta Mountains transition area: Intermountain Association of Petroleum Geologists, 10th Annual Field Conference, p. 153-158.

Baker, A.A., 1964, Geology of the Aspen Grove quadrangle, Utah: U.S. Geological Survey Geologic Quadrangle Map GQ-239, 9 p., scale 1:24,000.

Baker, A.A., 1972, Geology of the Bridal Veil Falls quadrangle, Utah: U.S. Geological Survey Geologic Quadrangle Map GQ-998, 1 plate, scale 1:24,000.

Baker, A.A., 1976, Geologic map of the west half of the Strawberry Valley quadrangle, Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I-931, 11 p., scale 1:63,360.

Baker, A.A., and Crittenden, M.D., Jr., 1961, Geology of the Timpanogos Cave quadrangle, Utah: U.S. Geological Survey Geologic Quadrangle Map GQ-132, 1 plate, scale 1:24,000.

Baker, A.A., Calkins, F.C., Crittenden, M.D., Jr., and Bromfield, C.S., 1966, Geologic map of the Brighton quadrangle, Utah: U.S. Geological Survey Geologic Quadrangle Map GQ-534, 1 plate, scale 1:24,000.

Baker, C.H., Jr., 1968, Thermal springs near Midway, Utah: U.S. Geological Survey Professional Paper 600-D, p. D63-D70.

Baker, C.H., Jr., 1970, Water resources of the Heber-Kamas-Park City area, north-central Utah: Utah Department of Natural Resources Technical Publication 27, 79 p., scale 1:250,000.

Biek, R.F., 2004, Geologic map of the Saratoga Springs 7.5' quadrangle, Utah County, Utah: Utah Geological Survey Map 201, 2 plates, scale 1:24,000.

Biek, R.F., Hylland, M.D., Welsh, J.E., and Lowe, M., 2003, Geologic map of the Center Creek quadrangle, Wasatch County, Utah: Utah Geological Survey Map 192, 26 p., scale 1:24,000.

Birkeland, P.W., Machette, M.N., and Haller, K.M., 1991, Soils as a tool for applied Quaternary geology: Utah Geological and Mineral Survey Miscellaneous Publication 91-3, 63 p.

Black, B.D., 1993, The radon-hazard-potential map of Utah: Utah Geological Survey Map 149, 12 p., scale 1:1,000,000.

Black, B.D., Hecker, S., Hylland, M.D., Christenson, G.E., and McDonald, G.N., 2003, Quaternary fault and fold database and map of Utah: Utah Geological Survey Map 193 DM.

Blackett, R.E., 1994, Low-temperature geothermal water in Utah—a compilation of data for thermal wells and springs through 1993: Utah Geological Survey Open-File Report 311, 74 p., scale 1:750,000.

Blakey, R.C., 1994, Paleogeographic and tectonic controls on some Lower and Middle Jurassic erg deposits, Colorado Plateau, *in* Caputo, M.V., Peterson, J.A., and Franczyk, K.J., editors, Mesozoic systems of the Rocky Mountain region, USA: Denver, Colorado, Rocky Mountain Section of the Society for Sedimentary Geology, p. 273-298.

Blakey, R.C., and Gubitosa, R., 1983, Late Triassic paleogeography and depositional history of the Chinle Formation, southern Utah and northern Arizona, *in* Reynolds, M.W., and Dolly, E.D., editors, Mesozoic paleogeography of the west-central United States: Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, Rocky Mountain Paleogeography Symposium 2, p. 57-76.

Bradley, M.D., and Bruhn, R.L., 1988, Structural interactions between the Uinta arch and the overthrust belt, north-central Utah—implications of strain trajectories and displacement modeling, *in* Schmidt, C.J., and Perry, W.J., Jr., editors, Interaction of the Rocky Mountain foreland and the Cordilleran thrust belt: Geological Society of America Memoir 171, p. 431-445.

Brazee, R.J., and Cloud, W.K., 1960, United States earthquakes, 1958: U.S. Coast and Geodetic Survey, 76 p.

Bromfield, C.S., Baker, A.A., and Crittenden, M.D., Jr., 1970, Geologic map of the Heber quadrangle, Wasatch and Summit Counties, Utah: U.S. Geological Survey Geologic Quadrangle Map GQ-864, 1 plate, scale 1:24,000.

Bryant, Bruce, 1992, Geologic and structure maps of the Salt Lake City 1° x 2° quadrangle, Utah and Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I-1997, scale 1:125,000.

Bryant, B.C., and Nichols, D.J., 1988, Late Mesozoic and early Tertiary reactivation of an ancient crustal boundary along the Uinta trend and its interaction with the Sevier orogenic belt, *in* Schmidt, C.J., and Perry, W.J., Jr., editors, Interaction of the Rocky Mountain foreland and the Cordilleran thrust belt: Geological Society of America Memoir 171, p. 411-430.

Calkins, F.C., Butler, B.S., and Heikes, V.C., 1943, Geology and ore deposits of the Cottonwood-American Fork area: U.S. Geological Survey Professional Paper 201, 152 p.

Chan, M.A., Kvale, E. P., Archer, A.W., and Sonett, C.P., 1994, Oldest direct evidence of lunar-solar tidal forcing encoded in sedimentary rhythmites, Proterozoic Big Cottonwood Formation, central Utah: Geology, v. 22, p. 791-794.

Christie-Blick, N., 1983, Glacial-marine and subglacial sedimentation, Upper Proterozoic Mineral Fork Formation, Utah, *in* Molina, B.F., editor, Glacial-marine sedimentation: New York, Plenium Press, p. 703-776.

Constenius, K., 1995, Extensional structures superimposed on the Charleston-Nebo allochthon, central Utah: Geological Society of America Abstracts with Programs, v. 27, p. 6.

Constenius, K., 1996, Late Paleogene extensional collapse of the Cordilleran foreland fold and thrust belt: Geological Society of America Bulletin, v. 108, no. 1, p. 20-39.

Constenius, K.N., Esser, R.P., and Layer, P.W., 2003, Extensional collapse of the Charleston-Nebo salient and its relationship to space-time variations in Cordilleran orogenic belt tectonism and continental stratigraphy, *in* Reynolds, R.G., and Flores, R.M., editors, Cenozoic Systems of the Rocky Mountain Region: Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, p. 303-353.

Constenius, K., and Stern, N., 1998, The Charleston-Nebo allochthon—missing link of the Sevier belt: American Association of Petroleum Geologists-Utah Geological Association field trip guidebook, 37 p.

Constenius, K.N., Coogan, J.C., and Biek, R.F., 2006, Progress report geologic map of the east part of the Provo 30' x 60' quadrangle, Utah: Utah Geological Survey Open-File Report 490, 32 p., scale 1:50,000.

Costa, J.E., 1984, Physical geomorphology of debris flows, *in* Costa, J.E., and Fleisher, P.J., editors, Developments and applications of geomorphology: New York, Springer-Verlag, p. 268-317.

Costa, J.E., and Baker, V.R., 1981, Surficial geology, building with the earth: New York, John Wiley and Sons, 498 p.

Crittenden, M.D., Jr., 1961, Magnitude of thrust faulting in northern Utah: U.S. Geological Survey Professional Paper 424-D, p. D128-D131.

Crittenden, M.D., Jr., Sharp, B.J., and Calkins, F.C., 1952, Geology of the Wasatch Mountains east of Salt Lake City: Utah Geological Society, Guidebook to the geology of Utah, no. 8, p. 1-37.

Crittenden, M.D., Jr., Christie-Blick, N., and Link, P.K., 1983, Evidence for two pulses of glaciation during the late Proterozoic in northern Utah and southeastern Idaho: Geological Society of America Bulletin, v. 94, no. 4, p. 437-450.

Davis, L.E., Webster, G.D., and Dyman, T.S., 1994, Correlation of the West Canyon, Lake Point, and Bannock Peak Limestones (Upper Mississippian to Middle Pennsylvanian), basal formations of the Oquirrh Group, northern Utah and southeastern Idaho: U.S. Geological Survey Bulletin 2088, 30 p.

Diazconti, C.C., Nelson, S.T., Mayo, A.L., Tingey, D.G., and Smith, M., 2003, A mixed groundwater system at Midway, Utah—discriminating superimposed local and regional discharge: Journal of Hydrology, v. 273, p. 119-138.

Ehlers, T.A., Chan, M.A., and Link, P.K., 1997, Proterozoic tidal, glacial, and fluvial sedimentation in Big Cottonwood Canyon, Utah, *in* Link, P.K., and Kowallis, B.J., editors, Proterozoic to recent stratigraphy, tectonics, and volcanology, Utah, Nevada, southern Idaho and central Mexico: Brigham Young University Geology Studies, v. 42, part 1, p. 31-58.

Federal Emergency Management Agency, 1983, Flood hazard boundary map, Wasatch County, Utah (unincorporated areas): Federal Emergency Management Agency Map H-01 – 74, Scale 1:240,000.

Federal Insurance Administration, 1980a, Flood insurance rate map, town of Charleston, Utah, Wasatch County: U.S. Department of Housing and Urban Development, Community Panel No. 490165 0001 A, scale 1:7,200.

Federal Insurance Administration, 1980b, Flood insurance rate map, city of Midway, Utah, Wasatch County: U.S. Department of Housing and Urban Development, Community Panel No. 490167 0005 B, scale 1:9,600.

Federal Insurance Administration, 1987, Flood insurance rate map, city of Heber City, Utah, Wasatch County: U.S. Department of Housing and Urban Development, Community Panel No. 490166 0001 B, scale 1:6,000.

Frankel, A., Mueller, C., Barnhard, T., Perkins, D., Leyendecker, E.V., Dickman, N., Hanson, S., and Hopper, M., 1996, National seismic-hazard maps—documentation, June 1996: U.S. Geological Survey, Open-File Report 96-532, 110 p.

Gilbert, G.K., 1928, Studies of Basin-Range structure: U.S. Geological Survey Professional Paper 153, 92 p.

Gordon, M., Jr., Tooker, E.W., and Dutro, J.T., Jr., 2000, Type locality for the Great Blue Limestone in the Bingham nappe, Oquirrh Mountains, Utah: U.S. Geological Survey Open-File Report 00-012, 61 p.

Hansen, G.H., and Scoville, H.C., 1955, Drilling records for oil and gas in Utah: Utah Geological and Mineral Survey Bulletin 50, 116 p.

Hays, W.W., and King, K.W., 1982, Zoning of the earthquake ground-shaking hazard along the Wasatch fault zone, Utah: Third International Microzonation Conference Proceedings, v. 3, p. 1307-1317.

Hecker, S., 1993, Quaternary tectonics of Utah with emphasis on earthquake-hazard characterization: Utah Geological Survey Bulletin 127, 157 p., scale 1:500,000.

Hecker, S., Harty, K.M., and Christenson, G.E., 1988, Shallow ground water and related hazards in Utah: Utah Geological and Mineral Survey Map 110, 17 p., scale 1:750,000.

Hopper, M.G., 1988, Isoseismals of some historical earthquakes affecting the Wasatch Front area, Utah, *in* Gori, P.L., and Hays, W.W., editors, Assessment of regional earthquake hazards and risk along the Wasatch Front, Utah, Volume III: U.S. Geological Survey Open-File Report 88-680, p. Y-1 to Y-28.

Houghton, W.P., 1986, Structural analysis of the Salt Lake–Provo segment boundary of the Wasatch fault zone: Salt Lake City, University of Utah, M.S. thesis, 64 p.

Hyatt, L.M., Skogerboe, G.V., Haws, F.W., and Austin, L.H., 1969, Hydrologic inventory of the Utah Lake discharge area: Logan, Utah Water Research Laboratory, 138 p.

Hylland, M.D., and Lowe, M., 1995, Landslide hazards of western Wasatch County, Utah, *in* Lund, W.R., editor, Environmental and engineering geology of the Wasatch Front region: Utah Geological Association Publication 24, p. 121-136.

Hylland, M.D., and Lowe, M., 1997, Regional landslide-hazard evaluation using landslide slopes, western Wasatch County, Utah: Environmental & Engineering Geoscience, v. III, no. 1, p. 31-43.

Hylland, M.D., Lowe, M., and Bishop, C.E., 1995, Engineering geologic map folio, western Wasatch County, Utah: Utah Geological Survey Open-File Report 319, 12 plates, scale 1:24,000.

Imlay, R.W., 1967, Twin Creek Limestone (Jurassic) in the Western Interior of the United States: U.S. Geological Survey Professional Paper 540, 105 p.

Imlay, R.W., 1980, Jurassic paleobiogeography of the conterminous United States: U.S. Geological Survey Professional Paper 1062, 134 p.

James, L.P., 1979, Geology, ore deposits, and history of the Big Cottonwood mining district, Salt Lake County, Utah: Utah Geological and Mineral Survey Bulletin 114, 98 p.

Jensen, D.B., 1995, Petition for aquifer classification, Wasatch County, Utah: Heber City, Utah, unpublished Wasatch County petition to the Utah Water Quality Board, 15 p.

Keaton, J.R., Anderson, L.R., Topham, D.E., and Rathbun, D.J., 1987, Earthquake-induced landslide potential in and development of a seismic slope stability map of the urban corridor of Davis and Salt Lake Counties, Utah: Salt Lake City, Dames & Moore Consulting Engineers, and Department of Civil and Environmental Engineering, Utah State University, 47 p.

Keefer, D.K., 1984, Landslides caused by earthquakes: Geological Society of America Bulletin, v. 95, p. 406-421.

Kingsbury, E.M., Link, P.K., and Fanning, Mark, 2008, Detrital zircon populations in the Neoproterozoic (Cryogenian) Uinta Mountain Group – the Laurentian barcode: Geological Society of America Abstracts with Programs, v. 40, no. 1, p.

Kocurek, G., and Dott, R.H., Jr., 1983, Jurassic paleogeography and paleoclimate of the central and southern Rocky Mountains region, *in* Reynolds, M.W., and Dolly, E.D., editors, Mesozoic paleogeography of the west-central United States: Denver, Rocky Mountain Section Society of Economic Paleontologists and Mineralogists, p. 101-116.

Kohler, J.F., 1979, Geology, characteristics, and resource potential of the low-temperature geothermal system near Midway, Wasatch County, Utah: Utah Geological and Mineral Survey Report of Investigation 142, 45 p.

Konopka, E.H., 1999, Stratigraphy and sedimentology of the Butterfield Peaks Formation (Middle Pennsylvanian), in central Utah: University of Wisconsin-Madison, Ph.D. dissertation, 316 p.

Kuribayashi, E., and Tatsuoka, F., 1975, Brief review of liquefaction during earthquakes in Japan: Soils and Foundations, v. 15, no. 4, p. 81-92.

Langer, C.J., Keller, G.R., and Smith, R.B., 1979, A study of the aftershocks of the October 1, 1972 $m_b = 4.7$, Heber City, Utah, earthquake, *in* Arabasz, W.J., Smith, R.B., and Richins, W.D., editors, Earthquake studies in Utah, 1850 to 1978: Salt Lake City, University of Utah Seismograph Stations Special Publication, p. 383-394.

Lindon, M.C., 1992, Dam safety and risk, *in* Eldredge, S.N., editor, Utah natural hazards handbook: Utah Division of Comprehensive Emergency Management, p. 46-49.

Link, P.K., Christie-Blick, N., Devlin, W.J., Elston, D.P., Horodyski, R.J., Levy, M., Miller, J.M.G., Pearson, R.C., Prave, A., Stewart, J.H., Winston, D., Wright, L.A., and Wrucke, C.T., 1993, Middle and Late Proterozoic stratified rocks of the western U.S. Cordillera, Colorado Plateau and Basin and Range Province, *in* Reed, J.C., Jr., Bickford, M.E., Houston, R.S., Link, P.K., Rankin, D.W., Sims, P.K., and Van Schmus, W.R., editors, Precambrian – Conterminous U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America, v. C-2, p. 463-595.

Lowe, M., 1995, Hydrogeology of western Wasatch County, Utah, with emphasis on recharge-area mapping for the principal valley-fill aquifers in Heber and Round Valleys, *in* Lund, W.R., editor, Environmental and engineering geology of the Wasatch Front region: Utah Geological Association Publication 24, p. 269-277.

Lowe, M., and Butler, M., 2003, Ground-water sensitivity and vulnerability to pesticides, Heber and Round Valleys, Wasatch County, Utah: Utah Geological Survey Miscellaneous Publication MP-03-5, 23 p., 2 pl., scale 1:50,000, CD-ROM.

Marzolf, J.E., 1994, Reconstruction of the early Mesozoic cordilleran cratonal margin adjacent to the Colorado Plateau, *in* Caputo, M.V., Peterson, J.A., and Franczyk, K.J., editors, Mesozoic systems of the Rocky Mountain region, USA: Denver, Colorado, Rocky Mountain Section of the Society for Sedimentary Geology, p. 181-216.

Mayo, A.L., and Loucks, M., 1995, Solute and isotopic geochemistry and ground water of the central Wasatch Range, Utah: Journal of Hydrology, v. 172, p. 3-59.

Mayo, A.L., Nelson, S.T., and Durrant, C., 2005, Analysis of aquifers and production wells, Midway Fish Hatchery, Completion report for Utah Division of Fish and Game, May 10, 2005: Provo, Utah, Brigham Young University unpublished report, 47 p.

Morris, H.T., and Lovering, T.S., 1961, Stratigraphy of the East Tintic Mountains, Utah: U.S. Geological Survey Professional Paper 361, 145 p.

Paulsen, T., and Marshak, S., 1998, Charleston transverse zone, Wasatch Mountains, Utah—structure of the Provo salient's northern margin, Sevier fold-thrust belt: Geological Society of America Bulletin, v. 110, no. 4, p. 512-522.

Paulsen, T., and Marshak, S., 1999, Origin of the Uinta recess, Sevier fold-thrust belt, Utah—influence of basin architecture on fold-thrust belt geometry: Tectonophysics, v. 312, p. 203-216.

Peterson, D.L., 1970, A gravity and aeromagnetic survey of Heber and Rhodes Valleys, *in* Baker, C.H., Jr., Water resources of the Heber-Kamas-Park City area, north-central Utah: Utah Department of Natural Resources Technical Publication 27, p. 54-60.

Peterson, F., 1994, Sand dunes, sabkhas, streams, and shallow seas—Jurassic paleogeography in the southern part of the Western Interior basin, *in* Caputo, M.V., Peterson, J.A., and Franczyk, K.J., editors, Mesozoic systems of the Rocky Mountain region, USA: Denver, Colorado, Rocky Mountain Section of the Society for Sedimentary Geology, p. 233-272.

Pierson, T.C., and Costa, J.E., 1987, A rheologic classification of subaerial sediment-water flows, *in* Costa, J.E., and Wieczorek, G.F., editors, Debris flows/avalanches—Process, recognition, and mitigation: Geological Society of America Reviews in Engineering Geology, v. VII, p. 1-12.

Pipiringos, G.N., and O'Sullivan, R.B., 1978, Principal unconformities in Triassic and Jurassic rocks, Western Interior United States—a preliminary survey: U.S. Geological Survey Professional Paper 1035-A, 29 p.

Richardson, E.A., 1976, Climate, *in* Woodward, L., Jensen, E.H., and Harvey, J.L., editors, Soil survey of Heber Valley area, Utah—parts of Wasatch and Utah Counties: U.S. Department of Agriculture, Soil Conservation Service and Forest Service in cooperation with Utah Agricultural Research Station, p. 119.

Riess, S.K., 1985, Structural geology of the Charleston thrust fault, central Utah: Salt Lake City, University of Utah, M.S. thesis, 73 p., scale 1:12,000.

Roark, D.M., Holmes, W.F., and Shlosar, H.K., 1991, Hydrology of Heber and Round Valleys, Wasatch County, Utah, with emphasis on simulation of ground-water flow in Heber Valley: Utah Department of Natural Resources Technical Publication 101, 93 p.

Royse, F., Jr., 1983, Extensional faults and folds in the foreland thrust belt, Utah, Wyoming, Idaho: Geological Society of America Abstracts with Program, v. 15, p. 295.

Shoore, D.J., 2005, Sequence stratigraphy of the Bridal Veil Falls Limestone, Carboniferous, lower Oquirrh Group, on Cascade Mountain, Utah—a standard Morrowan cyclostratigraphy for the Oquirrh Basin: Provo, Utah, Brigham Young University, M.S. thesis, 203 p.

Shoore, D.J., and Ritter, S.M., 2007, Sequence stratigraphy of the Bridal Veil Limestone Member of the Oquirrh Formation (Lower Pennsylvanian) in the central Wasatch Range, Utah—towards a Bashkirian cyclostratigraphy for the Oquirrh Basin, *in* Willis, G.C., Hylland, M.D., Clark, D.L., and Chidsey, T.C., Jr., editors, Central Utah—diverse geology of a dynamic landscape: Utah Geological Association Publication 36, p. 55-74.

Silberling, N.J., Nichols, K.M., Trexler, J.H., Jr., Jewell, P.W., and Crosbie, R.A., 1997, Overview of Mississippian depositional and paleotectonic history of the Antler foreland, eastern Nevada and western Utah, *in* Link, P.K., and Kowallis, B.J., editors, Proterozoic to recent stratigraphy, tectonics, and volcanology, Utah, Nevada, southern Idaho and central Mexico: Brigham Young University Geology Studies, v. 42, part 1, p. 161-196.

Smith, H.P., 1969, The Thaynes Formation of the Moenkopi Group, north-central Utah: Salt Lake City, University of Utah, Ph.D. dissertation, 378 p. 13 plates.

Smith, R.B., and Arabasz, W.J., 1991, Seismicity of the Intermountain seismic belt, *in* Slemmons, D.B., Engdahl, E.R., Zoback, M.D., and Blackwell, D.D., editors, Neotectonics of North America: Geological Society of America, Decade of North American Geology, vol. 1, p. 185-228.

Smith, R.B., and Sbar, M.L., 1974, Contemporary tectonics and seismicity of the western United States with emphasis on the Intermountain seismic belt: Geological Society of America Bulletin, v. 85, no. 8, p. 1,205-1,218.

Sprinkel, D.A., 1982, Twin Creek Limestone-Arapien Shale relations in central Utah, *in* Nelson, D.L., editor, Overthrust belt of Utah: Utah Geological Association Publication 10, p. 169-179.

Sprinkel, D.A., 1994, Stratigraphic and time-stratigraphic cross sections—a north-south transect from near the Uinta Mountains axis across the Basin and Range transition zone to the western margin of the San Rafael Swell, Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I-2184D, 31 p., 2 plates.

Stewart, J.H., Poole, F.G., and Wilson, R.F., 1972, Stratigraphy and origin of the Chinle Formation and related Upper Triassic strata in the Colorado Plateau region, with a section on sedimentary petrology by R.A. Cadigan and on conglomerate studies by William Thordarson, H.F. Albee, and J.H. Stewart: U.S. Geological Survey Professional Paper 690, 336 p.

Stokes, W.L., 1986, Geology of Utah: Utah Museum of Natural History and Utah Geological and Mineral Survey, 307 p.

Sullivan, J.T., and Nelson, A.R., 1983, Late Cenozoic faulting in Heber and Keetley Valleys, northeastern Utah, *in* Gurgel, K.D., editor, Geologic excursions in neotectonics and engineering geology in Utah—Guidebook part IV: Utah Geological and Mineral Survey Special Studies 62, p. 55-62.

Sullivan, J.T., Nelson, A.R., LaForge, R.C., Wood, C.K., and Hansen, R.A., 1988, Central Utah regional seismotectonic study for USBR dams in the Wasatch Mountains: Denver, U.S. Bureau of Reclamation Seismotectonic Report 88-5, 337 p.

Tooker, E.W., and Roberts, R.J., 1970, Upper Paleozoic rocks in the Oquirrh Mountains and Bingham mining district, Utah, with a section on biostratigraphy and correlation by MacKenzie, Gordon, Jr., and Duncan, H.M.: U.S. Geological Survey Professional Paper 629-A, 76 p.

U.S. Bureau of Reclamation, 1993, Jordanelle Dam, Bonneville Unit, Central Utah Project, Utah, Upper Colorado Region: U.S. Department of Interior, Emergency Preparedness Brief (with inundation map) from Standard Operating Procedures, 13 p.

U.S. Environmental Protection Agency, 1992, Consumer's guide to radon reduction: U.S. Environmental Protection Agency, 402-K92-003, 12 p.

U.S. Environmental Protection Agency, 1994, Model standards and techniques for control of radon in new residential buildings: U.S. Environmental Protection Agency, Office of Air and Radiation, EPA 402-R-94-009, 15 p.

Utah Seismic Safety Commission, 2003, Utah earthquake ground-shaking maps: Utah Seismic Safety Commission Geoscience Committee, not paginated.

Utah State Department of Highways, 1966, Materials inventory, Utah and Wasatch Counties: Utah State Department of Highways, 25 p., 4 maps, scale approximately 1:200,000.

Veevers, J.J., and Powell, C.M., 1987, Late Paleozoic glacial episodes in Gondwanaland reflected in transgressive-regressive depositional sequences in Euramerica: Geological Society of America Bulletin, v. 98, no. 4, p. 475-487.

Wallace, Janae, 2005, Geologic logs of water wells, Utah: Online, Utah Division of Water Rights and Utah Geological Survey, http://www.waterrights.utah.gov/wellinfo/default.htm#, accessed June 8, 2005.

Webster, G.D., 1984, Conodont zonations near the Mississippian-Pennsylvanian boundary in the eastern Great Basin, *in* Lintz, J., Jr., editor, Western geological excursions: Geological Society of America, 1984 annual meeting guidebook, p. 78-82.

Webster, G.D., Gordon, M., Jr., Langenheim, R.L., and Henry, T.W., 1984, Road logs for the Mississippian-Pennsylvanian boundary in the eastern Great Basin – Salt Lake City, Utah to Las Vegas, Nevada, *in* Lintz, J., Jr., editor, Western geological excursions: Geological Society of America, 1984 annual meeting guidebook, v. 1, p. 1-86.

Welsh, J.E., and Bissell, H.J., 1979, The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States: U.S. Geological Survey Professional Paper 1110-Y, 35 p.

Willis, J.B., and Willis, G.C., 2003, Geology of Wasatch Mountain State Park, Utah, *in* Sprinkel, D.A., Chidsey, T.C., Jr., and Anderson, P.B., editors, Geology of Utah's Parks and Monuments, revised second edition: Utah Geological Association and Bryce Canyon Natural History Association, Utah Geological Association Publication 28, second edition, p. 495-516.

Willis, J.B., and Willis, G.C., 2004, Geology of Wasatch Mountain State Park road logs, Utah, *in* Anderson, P.B., and Sprinkel, D.A., editors, Geologic road, trail, and lake guides to Utah's parks and monuments: Utah Geological Association Publication 29, second edition, compact disc, p. 1-59.

Woodward, L., Jensen, E.H., and Harvey, J.L., 1976, Soil survey of Heber Valley area, Utah—parts of Wasatch and Utah Counties: U.S. Department of Agriculture, Soil Conservation Service and Forest Service in cooperation with Utah Agricultural Research Station, 124 p.

Youd, T.L., and Perkins, D.M., 1987, Mapping of liquefaction severity index: Journal of Geotechnical Engineering, v. 113, p. 1374-392