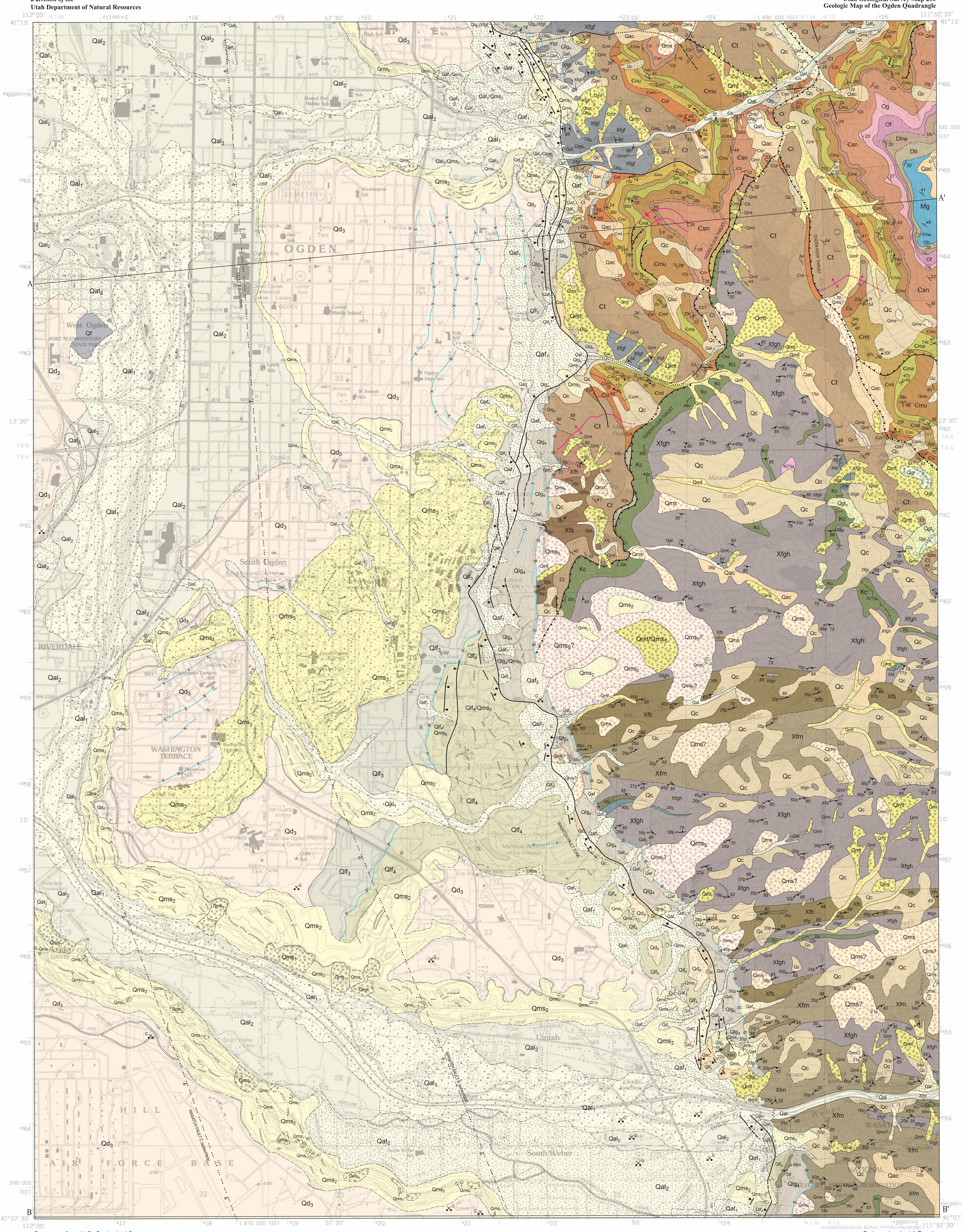


Base map from U.S. Geological Survey
Ogden 7.5' quadrangle, 1998

Cartographer, Lori J. Douglas

SCALE 1 : 24,000

1 1/2 0 1 MILE

1000 0 1000 2000 3000 4000 5000 6000 7000 FEET

1 .5 0 1 KILOMETER

CONTOUR INTERVAL 40 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

13°
237 mils

2004 MAGNETIC DECLINATION
AT CENTER OF SHEET

UTAH

QUADRANGLE LOCATION

1	2	3
4		5
6	7	8

1 Plain City
2 North Ogden
3 Huntsville
4 Roy
5 Snow Basin
6 Clearfield
7 Kaysville
8 Peterson

ADJOINING 7.5' QUADRANGLE NAMES

ISBN 1-55791-706-X

GEOLOGIC MAP OF THE OGDEN 7.5′ QUADRANGLE, WEBER AND DAVIS COUNTIES, UTAH

by

Adolph Yonkee
and
Mike Lowe

2004

DESCRIPTION OF MAP UNITS

Quaternary Surficial Deposits

Units are subdivided based on dominant process (l- lacustrine, d- deltaic, a- alluvial, m- mass wasting, g- glacial), and on relative age (1- Holocene (younger), 2- Holocene (older), 3- Lake Bonneville regressive, 4- Lake Bonneville transgressive, and 5- pre-Lake Bonneville).
Units with form X/Y indicates thin (generally less than 3 meters [10 ft] thick) deposits of X overlying deposits of Y.

Qlg_3 Lacustrine gravel-bearing deposits, Bonneville regressive– *Clast-supported, moderately to well-sorted, pebble to cobble gravel and gravelly sand, interlayered with some silt and sand; deposited and reworked in higher energy environments along the Provo and regressive shorelines near the mountain front; mapped at elevations below Provo shoreline; thickness less than 6 meters (20 ft).*

Qlf_3 Lacustrine fine-grained deposits, Bonneville regressive– *Medium sand to silt deposited and reworked in moderate-energy environments near and below Provo shoreline away from mountain front in southern part of quadrangle; also includes calcareous clay, silt, and fine sand deposited in deeper water environments in the subsurface within western part of quadrangle; thickness of deposits near shoreline generally less than 6 meters (20 ft).*

Qlg_4 Lacustrine gravel-bearing deposits, Bonneville transgressive– *Clast-supported, moderately to well-sorted, pebble to cobble gravel, with some silt to sand in interfluve areas and away from mountain front; gravels contain rounded to subrounded clasts, and some subangular clasts derived from reworking of mass-wasting and alluvial-fan deposits; deposited in higher energy environments along shorelines and small fan deltas as Lake Bonneville was transgressing; grades westward away from shorelines into fine-grained lacustrine deposits (Qlf_4); total thickness locally as much as 60 meters (200 ft).*

Qlf_4 Lacustrine fine-grained deposits, Bonneville transgressive– *Intervals of calcareous clay to silt, and intervals of rhythmically interbedded fine to medium sand and silt near mouth of Weber Canyon; deposited in deeper water environments, and as delta bottomset beds during transgression of Lake Bonneville; total thickness, including subsurface deposits, locally as much as 150 meters (500 ft).*

Qd_3 Deltaic deposits, Bonneville regressive– *Main part of unit includes foreset beds of rhythmically interlayered, gently inclined, fine to medium sand and silt, and topset beds of clast-supported, moderately to well-sorted, pebble and cobble gravel and gravelly sand; gravels contain rounded to subrounded clasts; deposited when Lake Bonneville was at and regressing from Provo shoreline; forms large, gently westward-inclined surface that was locally reworked along regressive shorelines; total thickness locally as much as 30 meters (100 ft). Unit also includes moderately to well-sorted, pebble and cobble gravel in smaller terraces more than 30 meters (100 ft) above modern stream level that are graded to delta deposits and shorelines above the Gilbert level; exposed thickness of terrace gravels up to 6 meters (20 ft).*

Qd_4 Deltaic deposits, Bonneville transgressive– *Topset beds of clast-supported, moderately to well-sorted, pebble gravel and gravelly sand; contains abundant subrounded to rounded basement clasts; deposited as Lake Bonneville was near a transgressive shoreline at an elevation of about 1,520 meters (5,000 ft); thickness of topset beds 2 to 4 meters (7 - 13 ft).*

Qal Stream alluvium, undivided– *Mostly clast-supported, moderate- to well-sorted, pebble and cobble gravel, gravelly sand, and silty sand; deposited along modern channels and inactive benches; mapped where active channels and benches are too narrow to map separately; exposed thickness less than 12 meters (40 ft).*

Qal_1 Younger stream alluvium, Holocene– *Clast-supported, moderate- to well-sorted, pebble and cobble gravel, gravelly sand, and silty sand; deposited along modern channels and flood plains; mapped where fluvial processes are currently or episodically active; exposed thickness less than 6 meters (20 ft).*

Qal_2 Older stream alluvium, Holocene– *Clast-supported, moderately to well-sorted, pebble and cobble gravel, gravelly sand, and silty sand; deposited along inactive flood plains and terraces 3 to 9 meters (10-30 ft) above modern stream level; mapped where fluvial processes are generally no longer active; exposed thickness less than 6 meters (20 ft).*

Qat_2 Older alluvial terrace deposits, Holocene– *Clast-supported, moderately to well-sorted, pebble and cobble gravel and gravelly sand; contains subangular to rounded clasts; forms terraces 9 to 15 meters (30-50 ft) above modern stream level that appear graded to base levels below the Gilbert shoreline; exposed thickness less than 6 meters (20 ft).*

Qag_4 Alluvial gravel of Ogden Canyon–*Clast-supported, moderately sorted, pebble to boulder alluvial gravel, with some lacustrine sand layers at top of unit; gravel contains angular to subrounded clasts and is weakly to strongly cemented by calcite; present in small erosional remnants along Ogden Canyon; original thickness as much as 60 meters (200 ft).*

Qaf Alluvial-fan deposits, undivided– *Mixture of clast-supported, moderately sorted, pebble to cobble gravel and sand deposited by streams, and matrix-supported, poorly sorted, pebble to boulder gravel to diamicton deposited by debris flows; mapped where deposits lack cross-cutting relations and relative age is uncertain; exposed thickness less than 9 meters (30 ft).*

Qaf_1 Younger alluvial-fan deposits, Holocene– *Mixture of gravel and sand deposited by streams, and diamicton deposited by debris flows; forms fans having distinct levees and channels at mouths of mountain-front canyons; exposed thickness less than 6 meters (20 ft).*

Qaf_2 Older alluvial-fan deposits, Holocene– *Mixture of gravel and sand deposited by streams, and diamicton deposited by debris flows; forms fans with poorly preserved levees that are slightly incised by modern stream channels; exposed thickness less than 6 meters (20 ft).*

Qaf_3 Alluvial-fan deposits, Bonneville regressive– *Mixture of gravel and sand deposited by streams, and diamicton deposited by debris flows; contains mostly angular to subrounded clasts plus some recycled, well-rounded lacustrine clasts; forms fans having subdued morphology that are graded to the Provo or other regressive shorelines and are incised by modern stream channels; exposed thickness less than 9 meters (30 ft).*

Qaf_4 Alluvial-fan deposits, Bonneville transgressive– *Mixture of gravel deposited by streams and diamicton deposited by debris flows; gravel contains mostly angular to subrounded clasts; locally weakly cemented with calcite; fans have subdued morphology, display top surfaces graded to the Bonneville shoreline, and are deeply incised by modern stream channels; total thickness of some composite fans as much as 60 meters (200 ft).*

Qms Landslide deposits, undivided– *Unsorted, unstratified deposits of angular boulders, sand, silt, clay, and bedrock blocks; deposits generally found on steeper slopes that are covered by thick vegetation and display hummocky topography; deposits formed by single to multiple slides, slumps, and flows; mapped where lack of cross-cutting relations prevents relative age determination; querried where hummocky topography is more subdued; thickness uncertain.*

Qms_1 Younger landslide deposits, Holocene– *Unsorted, unstratified mixtures of gravel, sand, silt, and clay redeposited by slides, slumps, and flows; deposits display distinctly hummocky topography and fresh scarps, and are currently or have been recently active; many of these deposits are within older slide complexes.*

Qms_2 Older landslide deposits, Holocene– *Unsorted, unstratified mixtures of mostly sand, silt, and clay redeposited by single to multiple slides, slumps, and flows; deposits display hummocky topography but lack fresh scarps and are mostly inactive; deposits found mostly along moderate slopes where rivers and streams have incised into finer grained lacustrine and deltaic deposits; unit also includes slides of boulder-rich diamicton that reactivated parts of older slide complexes in the Wasatch Range.*

Qms_3 Landslide deposits, Bonneville regressive– *Mixture of silt, fine sand, and minor gravel redeposited in a flow slide and lateral spread as a result of liquefaction, probably during large earthquake(s); deposits display disrupted bedding, landslide-related lineaments and scarps, and hummocky topography; one large deposit is present in the quadrangle and formed after regression from the Provo level but before major downcutting by streams.*

Qms_5 Landslide deposits, pre-Bonneville to Bonneville transgressive– *Unsorted, unstratified deposits of angular boulders, sand, silt, clay, and bedrock blocks; deposited by multiple slides, slumps, and flows; parts of these slides are covered by Lake Bonneville deposits and reworked along the Bonneville shoreline, and parts of some slides are interlayered with Bonneville-transgressive lacustrine deposits.*

Qmf Debris-flow deposits, undivided– *Matrix- to clast-supported cobble and boulder gravel, with variable amounts of sand, silt, and clay matrix; surfaces variably rubbly and commonly have levees and channels; includes multiple events graded to various levels above modern channels; unit grades into alluvial fans at mouths of canyons, and into colluvium, talus, and slide deposits at higher elevations in source areas; thickness probably less than 9 meters (30 ft).*

Qmt Talus– *Deposits of angular pebble to boulder fragments with little or no matrix and little to no vegetation cover, which have accumulated at bases of some steep bedrock slopes and cliffs; thickness uncertain in most areas, but probably less than 15 meters (50 ft).*

Qma Avalanche deposits– *Diamicton and vegetative debris that have accumulated from repeated avalanches along moderately steep, northerly facing chutes at higher elevations; only one relatively large deposit mapped.*

Qc Colluvium– *Weakly to non-layered, variably sorted, matrix- to clast-supported, pebble to boulder gravel and diamicton of local origin; contains angular to subangular clasts in variable amounts of clay, silt, and sand matrix; deposits formed mostly by creep and slope wash, also includes small landslides, talus, debris cones, minor alluvium, and small bedrock exposures; found mostly along vegetated slopes in Wasatch Range, and locally covering scarps along the Wasatch fault zone; thickness probably less than 15 meters (50 ft) in most areas.*

Qac Colluvium and alluvium, undivided– *Pebble to boulder gravel and clay- to boulder-rich diamicton; includes hillslope colluvium, small fans, stream alluvium, and small landslide deposits; mapped along some vegetated canyon areas in Wasatch Range; thickness probably less than 15 meters (50 ft) in most areas.*

Qgr Rock-glacier deposits– *Bouldery debris with little or no matrix; displays hummocky forms with cross-slope ridges and little or no vegetation; present near bases of some cirque headwalls at higher elevations near Mount Ogden.*

Qgt_y Glacial till, younger– *Boulders to pebbles in sparse sandy to silty matrix; displays distinct moraine crests and limited soil development; present in upper part of cirque basin northeast of Mount Ogden.*

Qgt_o Glacial till, older– *Boulders to pebbles in variable amounts of sandy to silty matrix; displays more subdued moraine crests and greater soil development compared to younger till; present within cirque basins near Mount Ogden; probably late Pinedale age (about 25 to 10 ka).*

Qf Artificial fill– *Excavated and reworked debris; only larger areas mapped along rail and roadways in Weber Canyon, and near an abandoned landfill.*

Basin Fill

Qb Quaternary basin fill– *Weakly to non-consolidated mixture of alluvial and lacustrine clay, silt, sand, gravel, marl, and thin tuffaceous layers; includes two thicker, gravel-bearing zones corresponding to the Sunset and Delta aquifers; shown only on cross sections; up to 400 meters (1,300 ft) thick.*

Tb Late Tertiary basin fill– *Weakly to strongly consolidated mixture of conglomerate, sandstone, mudstone, tuffaceous sandstone, tuff, and lacustrine limestone; only shown on cross sections; up to 2,400 meters (8,000 ft) thick.*

Tertiary Igneous Rocks

Td Tertiary igneous dikes– *Dark colored, non-foliated dikes composed of altered hornblende, biotite, and feldspar phenocrysts in a fine-grained, highly altered matrix; interpreted to be Tertiary age.*

Cretaceous Altered and Deformed Rocks

Kc Chloritic gneiss, cataclasite, and mylonite– *Dark- to gray-green, variably fractured and altered gneiss, intensely fractured cataclasite, and mylonite to phyllonite with micaceous cleavage; derived by greenschist-facies alteration and varying degrees of cataclastic and plastic deformation that overprinted protoliths from the Farmington Canyon Complex; contains variable amounts of fine-grained, recrystallized chlorite, muscovite, and epidote; found within shear zones and along the Ogden floor thrust.*

Kfx Imbricated fault rocks– *Intensely deformed, complexly imbricated fault-zone rocks derived from a mixture of Farmington Canyon Complex and Cambrian sedimentary rock protoliths; contains fault-bounded slices of limestone and shale with intense cleavage and tight folds, and mixed cataclasite to mylonite; mapped along parts of the Ogden floor thrust.*

K(?)q Quartz veins and pods– *Veins and pods of quartz with minor chlorite, epidote, muscovite, and hematite; veins and pods cross cut gneissic foliation and are locally associated with chlorite alteration within rocks of the Farmington Canyon Complex; only larger bodies mapped; interpreted to be mostly related to Cretaceous alteration.*

Paleozoic Sedimentary Rocks

Mg Gardison Limestone– *Ledge- to cliff-forming, medium- to dark-gray, thin- to thick-bedded, fossiliferous limestone to dolomitic limestone; contains local chert lenses and widespread fragments of fossil corals, crinoids, and brachiopods; top not exposed in quadrangle but about 200 meters (660 ft) thick in nearby areas.*

Db Beirdneau Formation– *Overall slope-forming, yellow- to red- to light-gray, interlayered, sandy to silty dolomite and limestone, fine- to medium-grained sandstone, shale, flat-pebble conglomerate, and sedimentary breccia; uppermost part consists of argillaceous limestone and shale; about 50 to 100 meters (170-330 ft) thick, but thickness varies due to widespread minor faulting and folding.*

Dhw Hyrum Dolomite and Water Canyon Formation, undivided– *Hyrum consists of ledge-forming, medium- to dark-gray, medium- to thick-bedded, dolomite and minor silty limestone; Water Canyon consists of slope-forming, light- to yellow-gray, sandy to silty dolomite; unit is about 50 to 100 meters (170-330 ft) thick.*

Of Fish Haven Dolomite– *Cliff-forming, medium- to dark-gray, medium- to thick-bedded, slightly fossiliferous dolomite; about 40 to 80 meters (130-260 ft) thick.*

Og Garden City Formation– *Ledge- and slope-forming, tan to light-gray, thin- to thick-bedded, silty dolomite, dolomite, silty limestone, and siltstone; has well-layered appearance; some layers are slightly fossiliferous and some layers contain siltstone-filled cracks; about 60 to 120 meters (200-400 ft) thick, but thickness varies due to widespread minor faulting.*

Ꞓsn St. Charles and Nounan Formations, undivided– *St. Charles consists mostly of cliff-forming, light- to dark-gray, massive-weathering dolomite, with a thin interval of sandy dolomite and sandstone corresponding to the Worm Creek Quartzite Member at its base; Nounan consists of cliff-forming, light- to dark-gray, massive-weathering, dolomite and minor silty dolomite with local twiggy structures; unit is about 300 to 450 meters (1,000-1,500 ft) thick.*

Ꞓb Bloomington Formation– *Slope-forming, orange-gray to brown, thin-bedded, interlayered, shaley limestone, shale, fine-grained limestone with abundant orange-weathering silty ribbons, flat-pebble conglomerate, oncolitic limestone, and oolitic limestone; about 30 to 60 meters (100-200 ft) thick, but thickness varies due to widespread minor faulting.*

Ꞓm Maxfield Formation, undivided– *Total thickness about 180 to 300 meters (600-1000 ft), but total thickness and thicknesses of individual members vary due to widespread deformation.*

Ꞓmu Upper limestone and dolomite member– *Upper part consists mostly of cliff-forming, light- to dark-gray, medium- to thick-bedded, dolomite, oolitic dolomite, and minor limestone, with widespread twiggy structures; lower part consists mostly of ledge-forming, light- to medium-gray, thin- to thick-bedded, oolitic limestone, fine-grained limestone with yellow-weathering silty ribbons, and minor dolomite; distinctive interval of interlayered dark-gray cherty dolomite and light-gray boundstone found near top of the member; about 100 to 150 meters (330-500 ft) thick.*

Ꞓma Middle argillaceous limestone member– *Overall slope-forming, overall brown to orange-gray, thin- to medium-bedded, interlayered, argillaceous limestone with black, clay-filled cracks, shale with limestone nodules, fine-grained limestone with orange-weathering silty ribbons, oolitic limestone, oncolitic limestone, and flat-pebble conglomerate; about 40 to 80 meters (130-260 ft) thick.*

Ꞓml Lower limestone member– *Ledge-forming, light- to medium-gray, thin- to medium-bedded limestone with abundant orange-weathering silty ribbons and minor oolitic limestone; thin interval of shaley limestone near middle of member separates upper and lower ledges; about 40 to 80 meters (130-260 ft) thick.*

Ꞓo Ophir Shale, undivided– *Total thickness of about 90 to 200 meters (300-700 ft), but total thickness and thicknesses of individual members vary widely due to intense deformation.*

Ꞓou Upper shale member– *Slope-forming, gray-brown to olive-drab, variably calcareous, silty to micaceous shale (or argillite), with some thin, silty limestone beds; generally poorly exposed and strongly deformed; probably about 40 to 80 meters (130-260 ft) thick.*

Ꞓom Middle limestone member– *Ledge-forming, light- to medium-gray, thin- to medium-bedded limestone with abundant orange-weathering silty ribbons and minor oolitic limestone; probably about 6 to 20 meters (20-70 ft) thick.*

Ꞓol Lower shale member– *Slope-forming, brown- to olive-drab, silty to micaceous shale (or argillite), with some fine-grained sandstone layers at base; generally poorly exposed and strongly deformed; probably about 40 to 100 meters (130-330 ft) thick.*

Ꞓt Tintic Quartzite– *Main part of formation consists of cliff-forming, white to tan, thin- to thick-bedded, quartz-rich, well-cemented sandstone (orthoquartzite) with some lenses of quartz-pebble conglomerate and thin layers of argillite; argillite intervals increase in abundance and quartz pebbles decrease in abundance toward the top of the formation; basal part of the formation consists of heterogeneous mixture of green to purple to tan, arkosic sandstone, quartz-pebble conglomerate, and micaceous siltstone; about 400 to 450 meters (1,300-1,500 ft) thick.*

Early Proterozoic Metamorphic and Igneous Rocks

Xf Farmington Canyon Complex, undivided– *Shown only on cross sections.*

Units exposed in footwall of Ogden floor thrust

Xfgf Granitic gneiss of Ogden footwall– *Light- to pink-gray, moderately to strongly foliated, hornblende-bearing granitic gneiss; unit also contains widespread, variably deformed pegmatitic dikes and some pods of amphibolite.*

Xfh Hornblende-plagioclase gneiss– *Dark-gray to black, moderately to strongly foliated, hornblende-plagioclase gneiss, with minor garnet, quartz, and biotite in some layers; garnet grains up to 2.5 centimeters (1 inch) in size.*

Xfs Muscovite-bearing schist– *Gray-brown, strongly foliated, schist to gneiss containing variable amounts of muscovite, biotite, quartz, and feldspar, with minor garnet in some layers; muscovite grains are up to 2.5 centimeters (1 inch) in size; unit also contains some thin layers of hornblende-plagioclase gneiss.*

Units exposed in hanging wall of Ogden floor thrust

Xfa Meta-gabbro and amphibolite– *Black to green-black, non- to strongly foliated, pyroxene-bearing meta-gabbro to amphibolite with varying amounts of plagioclase; forms pods in granitic gneiss but only larger bodies mapped.*

Xfgh Granitic gneiss of Ogden hanging wall– *Light- to pink-gray, moderately to strongly foliated, fine- to medium-grained, hornblende-bearing granitic gneiss with rare orthopyroxene; gneiss is locally fractured and displays red hematite alteration; gneiss cut by variably deformed, light-colored pegmatitic dikes; unit also contains small pods of meta-gabbro and amphibolite; gradational contacts with migmatitic gneiss.*

Xfm Migmatitic gneiss– *Medium- to light-pink-gray, strongly foliated and layered, migmatitic, quartzo-feldspathic gneiss with widespread garnet and biotite; gneiss cut by widespread, variably deformed, pegmatitic dikes; unit also contains widespread amphibolite layers, granitic gneiss bands, and some thin layers of biotite-rich schist; gradational contacts with granitic gneiss.*

Xfb Biotite-rich schist– *Medium-gray to dark-brown, strongly foliated, biotite-rich schist with widespread garnet and sillimanite; displays alternating biotite-rich and quartz-feldspar-rich bands that are rotated into complex fold patterns; schist cut by variably deformed, garnet-bearing pegmatite dikes; unit also contains some thin layers of amphibolite, quartz-rich gneiss, and granitic gneiss; gradational contacts with migmatitic gneiss.*

Xfq Quartz-rich gneiss– *Milky- to green-white, quartz gneiss with lesser amounts of plagioclase and chrome-green mica; locally contains thin layers of biotite-rich schist and amphibolite.*

Xfu Meta-ultramafic and mafic rocks– *Dark-green to black, variably foliated, pyroxene-, amphibole-, and olivine-bearing ultramafic rock, hornblendite, and amphibolite.*

MAP AND CROSS-SECTION SYMBOLS

Contact--*Dashed where location approximate; dotted where concealed.*

Scratch Contact--*Used between subunits and combined unit.*

Normal Fault--*Dashed where location approximate; dotted where concealed; solid bar and ball on downthrown side; arrows show relative movement on cross section.*

Normal Fault--*Concealed; inferred and delineated from geophysical data; open ball and bar on downthrown side; arrows show relative movement on cross section.*

Steeply Dipping Fault--*High-angle fault with normal apparent stratigraphic throw; actual offset may be reverse; dashed where location approximate; dotted where concealed; U and D show up and down on throw.*

Thrust Fault--*Dotted where concealed; teeth on upper plate; arrows show relative movement on cross section.*

Lineament--*Related to liquefaction and possible ground cracks in* Qms_3

Quartz veins related to K(?)q.

Moraine Crests

Landslide Scarp

Erosional Scarp--*Related to river terraces incised into Lake Bonneville delta along Weber River.*

Fold Axial Traces--*Location approximate; dotted where concealed.*

anticline

syncline

Strike and Dip of bedding

inclined

overturned

Trend and Plunge of minor fold

Strike and Dip of cleavage

Strike and Dip of high-grade metamorphic foliation

Trend and Plunge of mineral lineation

Prospect Pit

Gravel Pit

Shorelines

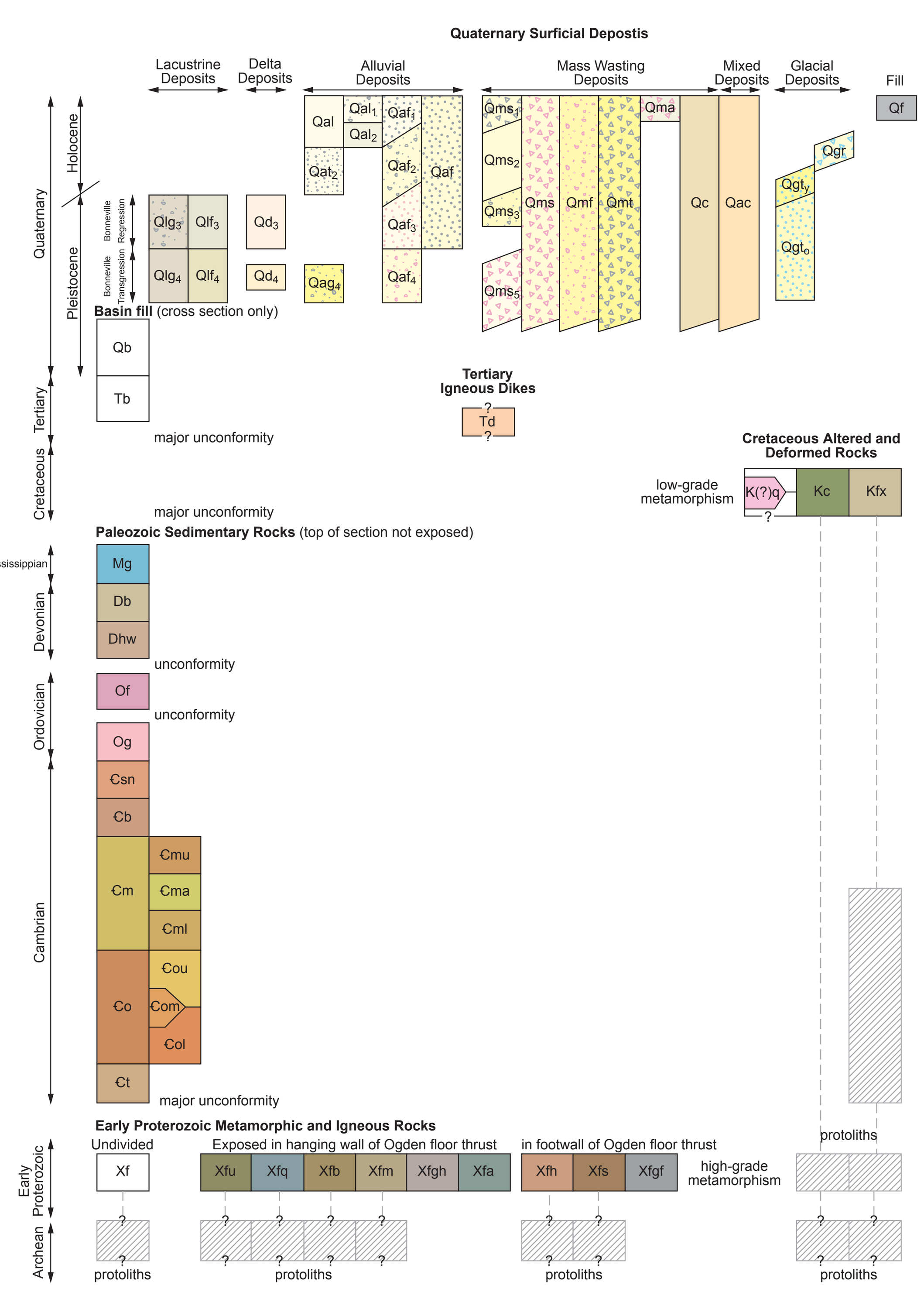
Regressive shoreline of Lake Bonneville

Provo shoreline of Lake Bonneville

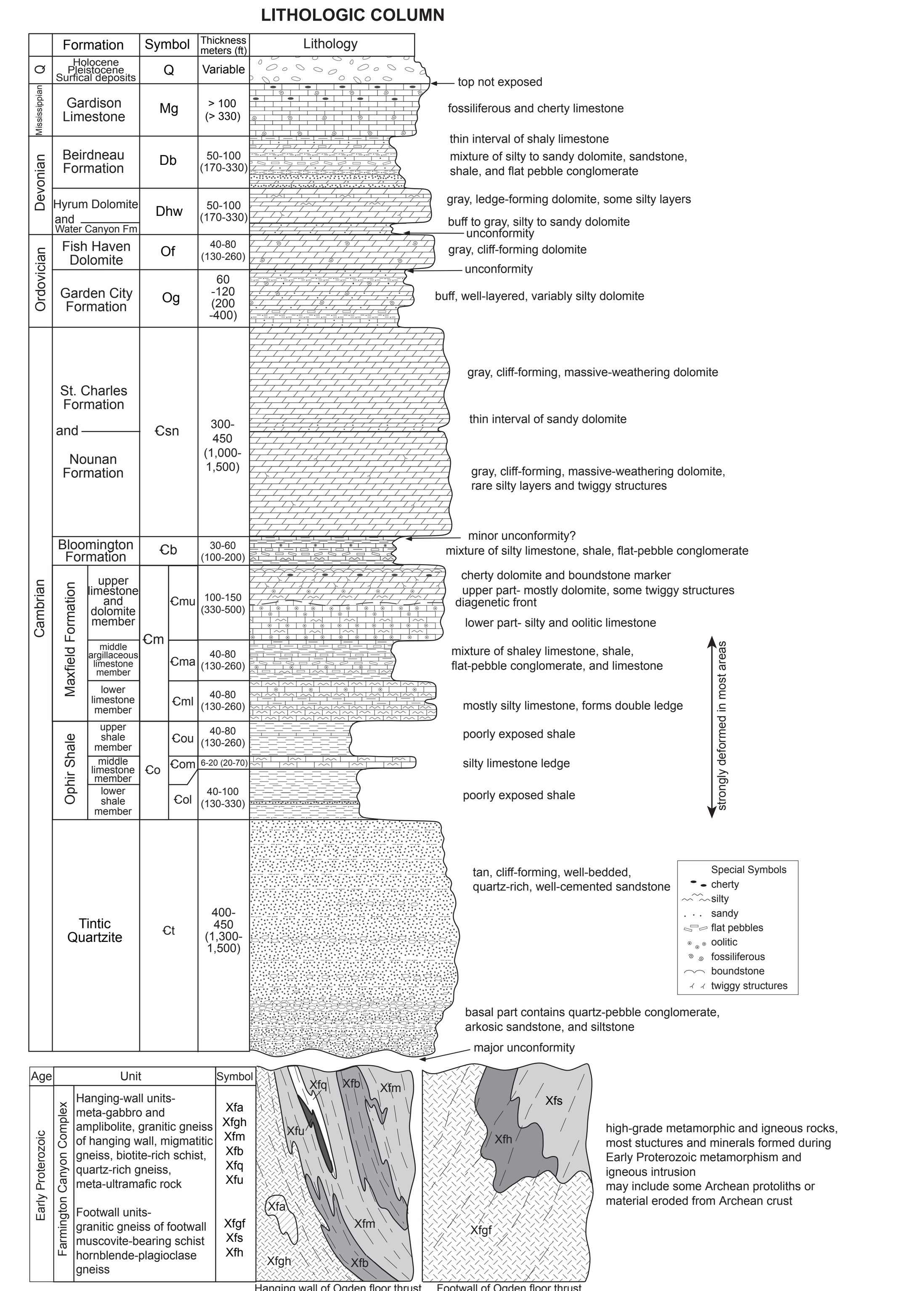
Bonneville shoreline of Lake Bonneville

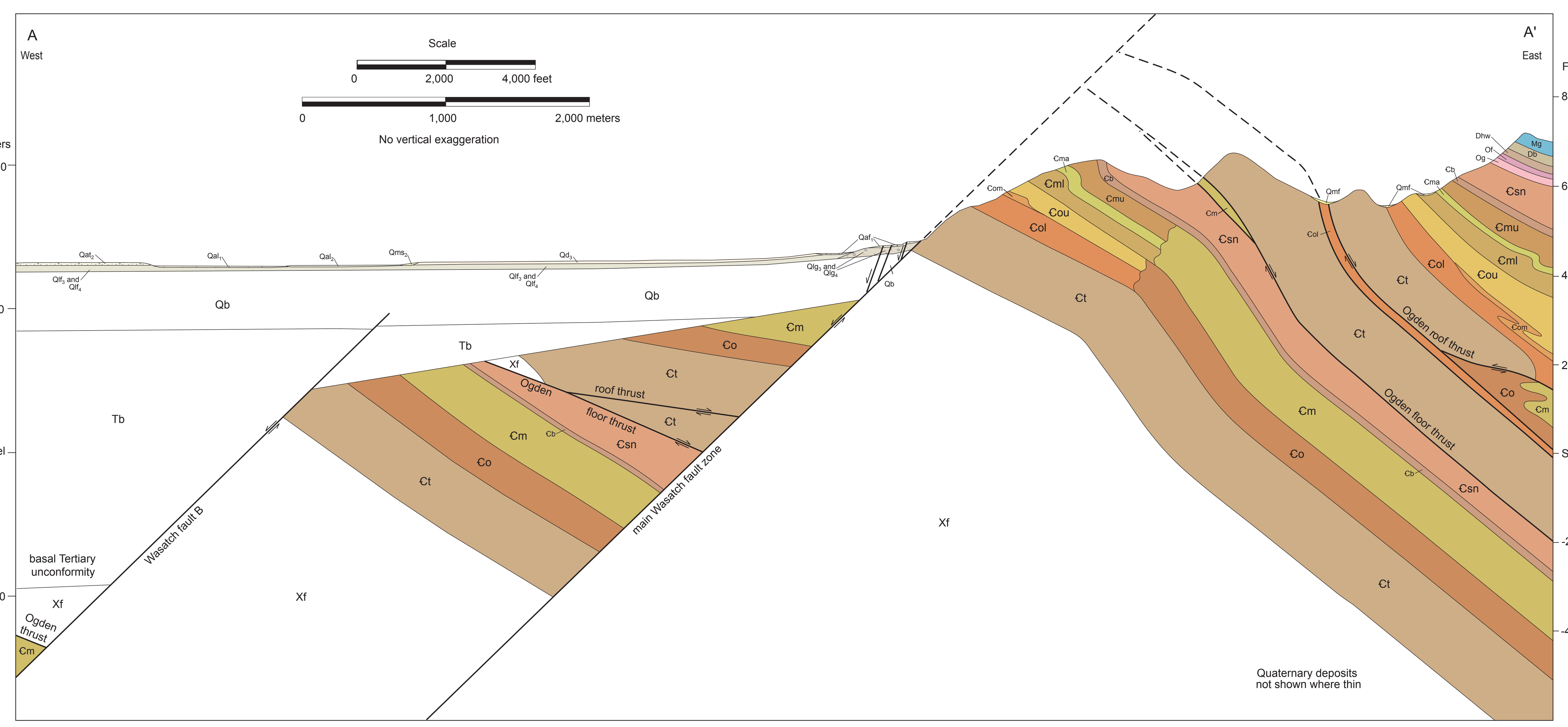
Transgressive shoreline of Lake Bonneville

CORRELATION OF MAP UNITS

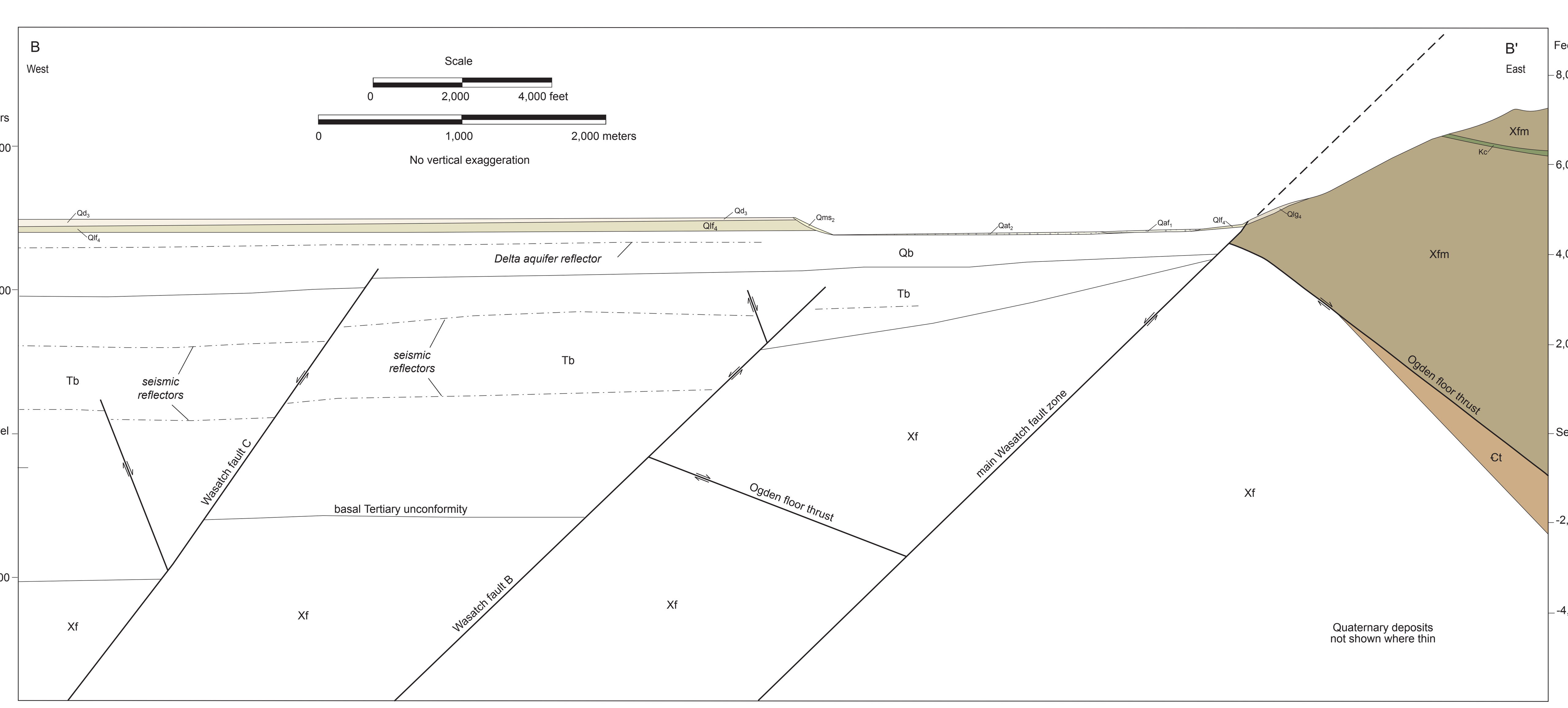


LITHOLOGIC COLUMN





Geophysical data source for subsurface structure of Wasatch Front basin from Cook and others (1967). Structure of pre-Tertiary rocks beneath Wasatch Front basin uncertain and only shown schematically.



Geophysical data source for subsurface structure of Wasatch Front basin from Glen and others (1980).

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ISBN 1-55791-706-X

MAP 200
Utah Geological Survey
a division of
Utah Department of Natural Resources

2004

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by

Adolph Yonkee[1] and Mike Lowe[2]

ABSTRACT

The Ogden 7.5-minute quadrangle includes parts of Utah's Wasatch Range and Wasatch Front basin, which preserve a rich geologic history. Bedrock exposed in the Wasatch Range consists of Early Proterozoic high-grade metamorphic and igneous (basement) rocks of the Farmington Canyon Complex, Paleozoic sedimentary rocks, rocks altered and deformed during the Cretaceous, and small Tertiary igneous dikes. The Farmington Canyon Complex includes abundant migmatitic gneiss, quartz-rich gneiss, and biotite-rich schist derived mostly from metamorphism of sediments, and granitic gneiss derived from large plutons, which all underwent high-grade metamorphism associated with major mountain building. Paleozoic strata include a basal quartzite and overlying carbonate-rich sequence, which record shifting patterns of mostly shallow-marine deposition following rifting of the western margin of North America. During the Cretaceous Sevier orogeny, these rocks were thrust faulted, folded, and underwent local low-grade metamorphism and alteration. During late Cenozoic basin-and-range extension, basin fill consisting of clastic sediments and minor tuff accumulated in the Wasatch Front basin as the Wasatch Range was uplifted and eroded.

Quaternary surficial deposits, which cover the western part of the quadrangle and locally overlie bedrock in the Wasatch Range, record a complex history of lacustrine, fluvial, mass-wasting, and glacial processes that varied over time in response to changing climatic and tectonic controls. During the late Pleistocene, Lake Bonneville covered much of the western part of the quadrangle, with deposition of extensive delta sediments where the Ogden and Weber Rivers entered the lake, coarse-grained sediments in higher energy environments along shorelines, and fine-grained sediments in deeper waters. Glacial deposits accumulated locally at higher elevations within the Wasatch Range. During the Holocene, lower base levels of Great Salt Lake induced downcutting by the Ogden and Weber Rivers, with accumulation of alluvium along recently and currently active flood plains. Many landslides, including large complexes, formed in the Wasatch Range during the Quaternary. A liquefaction-induced flow slide formed in lacustrine and deltaic deposits, probably in response to large early Holocene earthquake(s). Widespread landslides developed during the Holocene where the Weber and Ogden Rivers incised into fine-grained sediments. Alluvial-fan deposits accumulated throughout the Quaternary near the mouths of mountain drainages.

Principal geologic structures in the quadrangle include high-grade metamorphic foliation, gneissic layering, and complex folds in basement rocks related to Early Proterozoic mountain building; the Ogden thrust fault system, shear zones in basement rocks, and folds, cleavage, and minor faults in sedimentary rocks related to Cretaceous shortening; and the Weber segment of the Wasatch normal fault zone and associated faults related to late Cenozoic extension. The Ogden thrust system has an estimated 16 to 20 kilometers (10-12 mi) of top-to-east slip, and includes a roof thrust that repeats Cambrian strata and a floor thrust that imbricates basement rocks and Cambrian strata. Complex folds, cleavage, and minor faults produced significant variations in tectonic thickness of formations in the sedimentary cover. The Wasatch fault zone and associated normal faults dip moderately west, and have an aggregate slip greater than 10 kilometers (6 mi) that produced uplift of the Wasatch Range. The Weber segment has experienced 6 to 10 surface rupturing events in the past 15 ka. East-striking cross faults in the Wasatch Range show decreasing displacement away from the Wasatch fault zone and appear to be associated with differential tilting of the range.

Mineral resources include widespread gravel and sand in the western part of the quadrangle, limited metallic mineralization in basement rocks, and limestone, dolomite, and quartzite. Significant amounts of gravel and sand have been mined from pits excavated into deltaic and alluvial deposits, along and near the Weber River.

The Weber and Ogden Rivers contribute most of the surface water flowing into and across the quadrangle. Small springs and gaining parts of rivers and streams in the Wasatch Range record limited fluid flow through fractured-bedrock aquifers. Gravel-bearing intervals within Quaternary basin fill, including the Delta and Sunset aquifers, are important ground-water sources. Recharge to this system includes infiltration of surface waters and precipitation in a primary recharge area along the mountain front, plus ground-water flow from bedrock across the Wasatch fault zone.

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Declining water levels in the Delta aquifer indicate that ground-water mining is a concern.

Active geologic processes in the Ogden quadrangle result in various seismic, mass-movement, and flooding hazards. The Weber segment of the Wasatch fault zone is capable of generating magnitude 7 to 7.5 earthquakes that would likely lead to surface rupture along the fault trace; widespread, strong ground shaking; local liquefaction; and seismically induced ground failure. Multiple mass movements in the quadrangle have been active in historical time, including slides, slumps, and flows along slopes above the Ogden and Weber Rivers and in the Wasatch Range. Flooding and debris flows, related to intense precipitation or rapid melting of thick snowpack, have also occurred in historical time along and at the mouths of some mountain drainages and along floodplains of the Weber and Ogden Rivers.

INTRODUCTION

The Ogden 7.5-minute quadrangle is located within Weber and Davis Counties, northern Utah, and includes parts of the communities of Ogden, Riverdale, and South Weber. The eastern part of the quadrangle lies within the Wasatch Range section of the Rocky Mountains physiographic province, and the western part lies within the Wasatch Front Valleys section of the Great Basin physiographic province as defined by Stokes (1986) (figures 1 and 2). Elevation ranges from 2,918 meters (9,572 ft) at the top of Mount Ogden along the east side of the quadrangle to about 1,300 meters (4,270 ft) at the Weber River along the west side of the quadrangle. The Ogden River flows through the northern part of the quadrangle and the Weber River flows along the southern and western margins of the quadrangle.

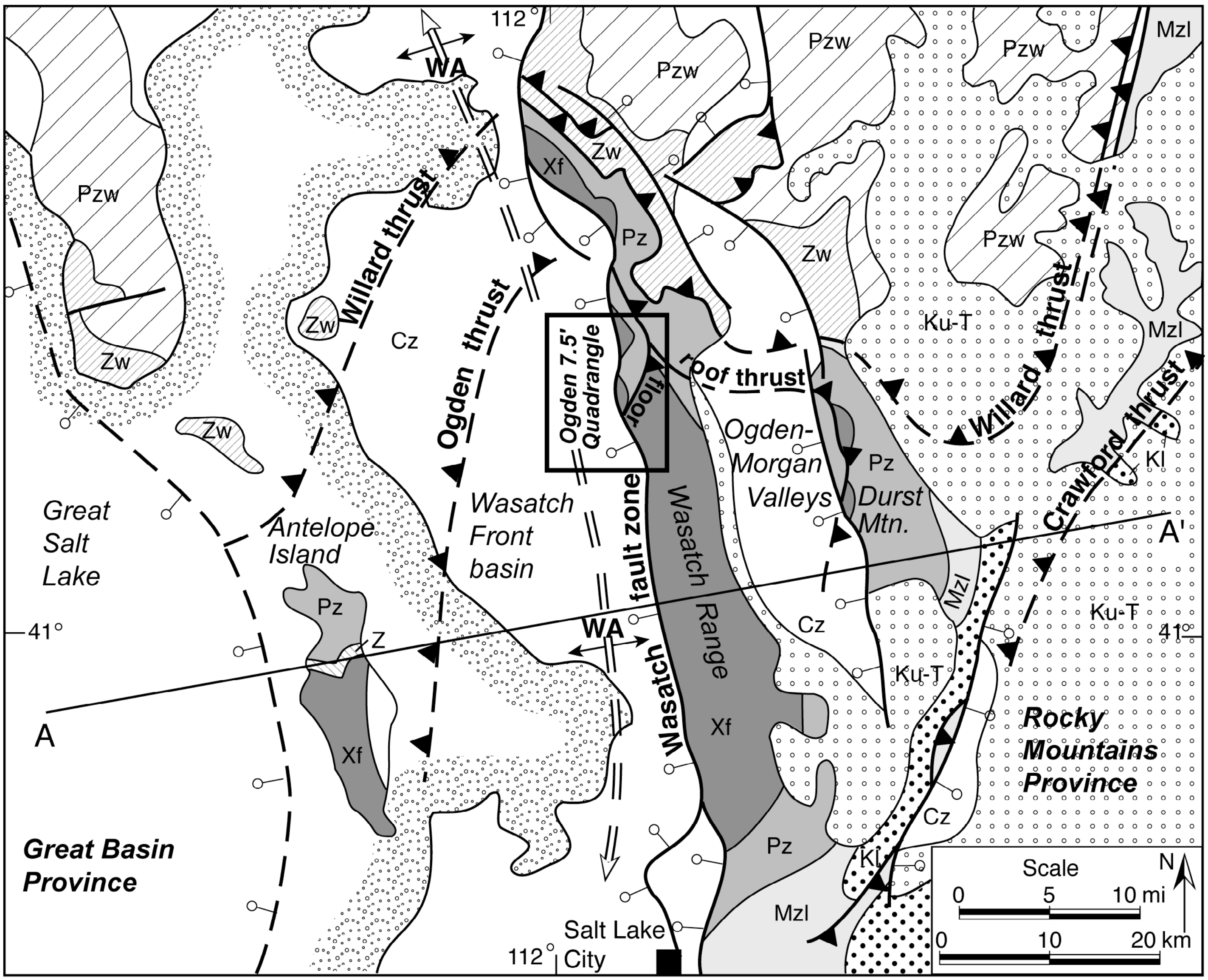

Figure 1. Location of Ogden quadrangle relative to major structural and topographic features in northern Utah. The Willard thrust carries a thick shelf sequence of Late Proterozoic (Zw) and Paleozoic strata (Pzw). The Ogden thrust system and Crawford thrust imbricate basement rocks of the Farmington Canyon Complex (Xf) and overlying thin platform sequence of Paleozoic (Pz) and lower Mesozoic (Mzl) strata. Synorogenic deposits include Lower Cretaceous strata (Kl) derived from erosion of the Willard thrust sheet, and Upper Cretaceous to earliest Tertiary strata (Ku-T) derived from erosion of frontal thrust sheets. Tertiary to Quaternary basin fill (Cz) is associated with Cenozoic extension. Cross section A-A' shown on figure 9. WA= Wasatch anticlinorium.

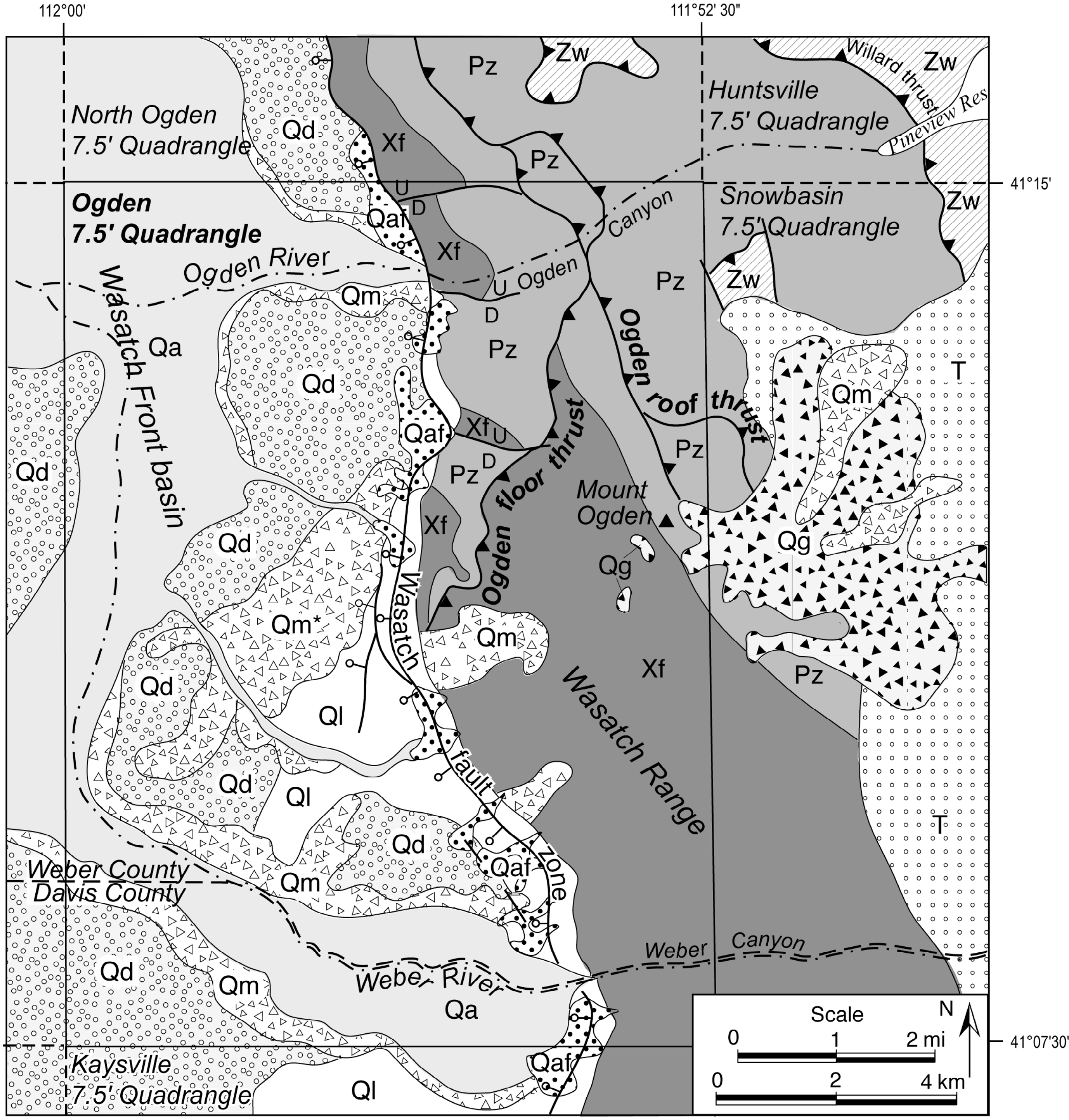

Figure 2. *Simplified geologic map of the Ogden quadrangle and adjacent areas. Unit symbols: Xf- Early Proterozoic basement rocks of the Farmington Canyon Complex, Zw- Late Proterozoic rocks in the Willard thrust sheet, Pz- Paleozoic sedimentary rocks, T- Tertiary Wasatch Formation and Norwood Tuff, Qa- Quaternary stream and river alluvium, Qaf- Quaternary alluvial fan deposits, Qd- mostly deltaic deposits, Qg- glacial deposits, Ql- mostly lacustrine deposits, and Qm- mass-wasting deposits (* refers to liquefaction-induced flow slide). Smaller areas of Quaternary deposits in Wasatch Range not shown.*

The Ogden quadrangle contains a variety of rock types, surficial deposits, and structural features (figure 2). Early Proterozoic high-grade metamorphic and igneous rocks and an unconformably overlying sequence of Paleozoic sedimentary rocks are exposed in the Wasatch Range in the eastern part of the quadrangle. These rocks are partly covered by Quaternary mass-wasting, alluvial, and glacial deposits. Quaternary lacustrine, deltaic, and alluvial deposits, locally modified by mass movements, cover the western part of the quadrangle, and overlie a thick sequence of Tertiary basin-fill deposits. Principal structural features include the Ogden thrust fault system, which formed during Cretaceous shortening deformation, and the Wasatch normal fault zone, which formed during late Cenozoic extensional deformation.

Previous geologic maps covering the Ogden area include a regional map of the Farmington Canyon Complex by Bryant (1984, scale 1:100,000), a regional map of the northern Wasatch Front compiled by Davis (1985, scale 1:100,000), and a map of surficial deposits along the Wasatch fault zone by Nelson and Personius (1993, scale 1:50,000).

Previous 1:24,000-scale geologic mapping in adjacent areas includes the North Ogden quadrangle (Crittenden and Sorensen, 1985), the Huntsville quadrangle (Sorensen and Crittenden, 1979), the Clearfield quadrangle (Sack, 2003a), and the Roy quadrangle (Sack, 2003b). This previous mapping, combined with prior stratigraphic and petrographic studies (Rigo, 1968; Bryant, 1988a), formed the basis for our map units. Erickson and others (1968) mapped soils for the Davis-Weber area (scale 1:15,840).

Fieldwork for this study was done mostly between 1992 and 1996, with additional refinements and sampling completed between 1997 and 1999. Geologic contacts were mapped in the field using aerial photographs and topographic maps. Several differences exist between our unit divisions in the Ogden quadrangle (plate 1) and previous division of Precambrian units mapped by Bryant (1984), and division of Quaternary units mapped by Nelson and Personius (1993). Some of our contacts of Cambrian units differ from those mapped by Crittenden and Sorensen (1985). Differences in Precambrian and Quaternary units are discussed under the specific unit descriptions. Discrepancies in Cambrian contacts are related to different interpretations of Cambrian stratigraphy in areas of complex deformation, where we interpreted a limestone layer to be the middle limestone member of the Ophir Shale, whereas Crittenden and Sorensen (1985) locally mapped this layer as the lower limestone member of the Maxfield Formation.

STRATIGRAPHY

Rocks and surficial deposits in the Ogden quadrangle can be divided into six groups: (1) Early Proterozoic metamorphic and igneous rocks of the Farmington Canyon Complex, (2) Paleozoic sedimentary rocks, (3) Cretaceous altered and deformed rocks, (4) Tertiary igneous rocks, (5) Tertiary to Quaternary basin fill, and (6) Quaternary surficial deposits (figure 2). The Farmington Canyon Complex, which is well exposed from near Mount Ogden to Weber Canyon, provides an important window into the Precambrian history of northern Utah (Bryant, 1988a, 1988b; Nelson and others, 2002). Total structural thickness of the complex is greater than 6.5 kilometers (4 mi). Paleozoic sedimentary rocks, which include Cambrian to Lower Mississippian strata exposed along Ogden Canyon, record shifting patterns of shallow-marine deposition and erosion (Rigo, 1968). Total thickness of the Paleozoic section exposed within the quadrangle is about 1,500 meters (5,000 ft), but original thicknesses of individual units were locally modified by minor faulting and folding during mostly Cretaceous deformation. Cretaceous deformation and hydrothermal alteration formed regions of chloritic gneiss, cataclasite and mylonite, zones of imbricated fault rock, and quartz veins. Tertiary and Quaternary basin fill, up to 3,000 meters (10,000 ft) thick, underlies the western part of the quadrangle, and was deposited during late Cenozoic extension as the Wasatch Front basin was downdropped and the Wasatch Range was uplifted and eroded (Zoback, 1983). Quaternary surficial deposits, which cover basin fill in the western part of the quadrangle and locally overlie bedrock in the eastern part of the quadrangle, record a complex history of transgression and regression of Lake Bonneville, deposition and downcutting by streams, glaciation, and multiple periods of slope failure.

Early Proterozoic Metamorphic and Igneous Rocks

A complex mixture of high-grade metamorphic and igneous rocks comprise the Farmington Canyon Complex, which is exposed along the Wasatch Front, on Antelope Island, and at Durst Mountain (figure 1) (Eardley, 1944; Bryant, 1984; Yonkee and others, 2000). Bryant (1984) divided the complex into four main units: quartz-monzonite gneiss; migmatite; schist and gneiss; and mixed quartzite and gneiss; with smaller exposures of amphibolite, pegmatite, and mica-rich schist. As a result of more detailed mapping of the Ogden quadrangle, we subdivided the Farmington Canyon Complex into nine map units. Units exposed within the hanging wall of the Ogden floor thrust fault consist of the following: (1) meta-ultramafic and mafic rocks (Xfu), which correspond to part of the amphibolite of Bryant (1984); (2) quartz-rich gneiss (Xfq), (3) biotite-rich schist (Xfb), and (4) migmatitic gneiss (Xfm), which together correspond to the migmatite of Byrant (1984); (5) granitic gneiss of Ogden hanging wall (Xfgh), which corresponds to part of the quartz-monzonite gneiss of Bryant (1984); and (6) meta-gabbro and amphibolite (Xfa), which correspond to part of the amphibolite of Bryant (1984). Rock units exposed within the footwall of the Ogden floor thrust fault consist of the following: (7) muscovite-bearing schist (Xfs), which corresponds to the mica-rich schist of Byrant (1984); (8) hornblende-plagioclase gneiss (Xfh), which corresponds to part of the amphibolite of Bryant (1984); and (9) granitic gneiss of Ogden footwall (Xfgf), which corresponds to part of the quartz-monzonite gneiss of Bryant (1984). Descriptions of the map units are given below, and are then combined with geochronologic and petrologic data to develop a simple model for the Precambrian history of the area (see Precambrian Geologic History). Map units are assigned to the Early Proterozoic, based on the age of high-grade metamorphism responsible for most observed textures and minerals. Some units, however, have isotopic evidence for incorporating Archean material (Hedge and others, 1983), and all units display local, younger retrograde alteration. A related unit - chloritic gneiss, cataclasite, and mylonite (Kc) - which consists of Precambrian protoliths overprinted by more pervasive Cretaceous alteration and deformation, is discussed later.

Meta-Ultramafic and Mafic Rocks (Xfu)

This unit consists of pods of dark green to black ultramafic rock, amphibolite, and minor hornblendite. Ultramafic rock is variably foliated and consists of abundant pyroxene, amphibole, and minor olivine that are partly altered to serpentine and talc, plus accessory oxides. Amphibolite is well foliated, and consists of abundant hornblende and plagioclase, accessory oxides, and rare pyroxene. Hornblendite occurs locally along contacts between ultramafic and amphibolite bands. This unit is similar to rare pods of meta-ultramafic and mafic rocks found on Antelope Island, and may represent highly deformed dikes, parts of layered mafic intrusions, or thin tectonic slices of oceanic crust (Yonkee and others, 2000).

Quartz-Rich Gneiss (Xfq)

This unit consists mostly of distinctive layers of quartz-rich gneiss, locally more than 10 meters (30 ft) thick, composed dominantly of quartz, with lesser amounts of plagioclase, biotite, and chrome-green mica that may be fuchsite. Plagioclase is partly altered to sericite and biotite is partly altered to chlorite. Geochemically, quartz-rich gneiss is characterized by very high SiO_2 contents (table 1). Foliation, partly defined by preferred orientation of minor mica, is subparallel to overall layering. The gneiss forms vitreous, milky- to green-white, fractured, resistant outcrops. This unit also includes some thin layers of biotite-rich schist and amphibolite. This unit is similar to quartz-rich gneiss found on Antelope Island, and probably formed by metamorphism of quartz-rich sedimentary rocks (Yonkee and others, 2000).

Biotite-Rich Schist (Xfb)

This unit consists mostly of distinctive layers of biotite-rich schist containing widespread sillimanite and garnet. Schist layers contain greater than 20 volume percent (vol%) biotite, with variable amounts of sillimanite, garnet, quartz, plagioclase, K-feldspar, and accessory oxides. Biotite and garnet are partly altered to chlorite, and plagioclase is partly altered to sericite and epidote. Whole-rock chemical compositions of biotite-rich schist are relatively rich in Al_2O_3 and poor in SiO_2 (table 1). Well-developed foliation is partly defined by preferred orientation of biotite, and local compositional layering is defined by alternating darker, biotite-sillimanite-rich bands and lighter, quartz-feldspar-rich bands, which probably formed by partial melting. Foliation and layering are locally rotated into complex minor folds that record protracted or multiple phases of intense deformation. The schist is cut by widespread pegmatite pods, which consist of abundant quartz and feldspar, minor biotite, and garnet grains to 5 centimeters (2 in) in size, and probably incorporated local partial melts. This unit also contains some thin layers of amphibolite, quartz-rich gneiss, and granitic gneiss, and grades into migmatitic gneiss with decreasing biotite content. Overall, biotite-rich schist forms less resistant, medium-gray to dark-brown slopes and ledges, with pegmatite pods forming more resistant, white to gray knobs. This unit is similar to biotite-rich schist found on Antelope Island, and probably formed by high-grade metamorphism and partial melting of mostly clay-rich sediments (Yonkee and others, 2000).

Migmatitic Gneiss (Xfm)

This unit consists mostly of migmatitic, fine- to medium-grained, mostly garnet- and biotite-bearing, quartzofeldspathic gneiss (figure 3a). Migmatitic gneiss contains about 20 to 40 vol% quartz, 20 to 40 vol% K-feldspar, 20 to 40 vol% plagioclase, 0 to 20 vol% garnet, 0 to 20 vol% biotite, and accessory oxides based on point counts of thin sections; some samples also contain up to 5 vol% hornblende and rare orthopyroxene. Plagioclase is partly altered to sericite and epidote, K-feldspar is slightly altered to sericite, and biotite and garnet are partly altered to chlorite. Whole-rock chemical compositions of migmatitic gneiss are similar to compositions of granitic gneiss, but are more variable and generally have slightly higher Al_2O_3 and SiO_2 contents and slightly lower K_2O (table 1). Well-developed foliation is defined by preferred orientation of biotite and quartz aggregates. Small-scale layering is defined by alternating, sharp to diffuse, dark bands containing more biotite and garnet, and light-colored, quartz-feldspar-rich bands that may have formed by partial melting and small-scale igneous intrusion. Foliation and layering are locally rotated into tight folds, with two foliations preserved in fold hinges, recording pro-

Table 1. *Average whole-rock chemistry of rock types in the Ogden quadrangle and nearby areas.*

	quartz-rich gneiss[(a)]	**biotite-rich schist**[(b)]	**amphibolite**[(c)]	**migmatitic gneiss**[(d)]	**granitic gneiss**[(e)]	**phyllonite, mylonite**[(f)]	**cataclasite**[(g)]
wt%							
SiO_2	92.4	54.4	48.5	71.1	69.6	70.7	68.9
$Al2O_3$	3.8	20.1	14.4	12.5	12.0	12.3	11.9
FeO	0.4	9.4	11.1	6.1	6.5	5.8	6.2
MgO	0.1	3.8	7.6	0.5	0.4	3.8	2.3
CaO	0.1	1.4	10.2	1.7	2.0	0.4	0.5
Na_2O	0.5	1.6	2.4	2.8	2.8	0.6	2.5
K_2O	1.3	3.4	1.2	3.9	4.3	2.6	4.0
TiO_2	0.1	1.1	1.0	0.5	0.6	0.5	0.5
P_2O_5	0.0	0.2	0.1	0.1	0.2	0.1	0.1
LOI	0.5	3.5	1.0	0.7	0.6	3.4	2.8

(a) average of two samples reported by Bryant (1988a, table 2) and one sample from this study
(b) average of two samples reported by Bryant (1988a, table 2)
(c) average of four samples reported by Bryant (1988a, table 3), includes amphibolite dikes within migmatitic gneiss and meta-gabbro in granitic gneiss
(d) average of 10 samples from along Weber Canyon (this study)
(e) average of four samples reported by Bryant (1988a, table 1) and six samples from this study
(f) average of 11 samples from shear zone in Weber Canyon (this study)
(g) average of 10 samples along trace of Ogden floor thrust (this study)

Note: only samples from Ogden and adjacent quadrangles reported in tables of Bryant (1988a) used for averages, samples from other quadrangles not included tracted or multiple periods of deformation. The gneiss is cut by widespread, variably deformed, concordant to discordant, granitic to pegmatitic dikes mostly from 0.01 to 1 meter (0.03-3 ft) thick. The dikes consist mostly of coarse-grained feldspar and quartz; some dikes contain rare orthopyroxene grains to 5 centimeters (2 in) in size, and others contain minor garnet. This unit also contains widespread thin layers of amphibolite, bands of hornblende-bearing granitic gneiss, and local layers of biotite-rich schist. Overall, this unit forms moderately resistant, medium- to light-pink-gray, well-layered exposures, which are well displayed along Weber Canyon. The contact with the granitic gneiss unit is gradational and placed at a change from mostly garnet-bearing layers in the migmatitic gneiss to mostly hornblende-bearing layers in the granitic gneiss unit. The contact with the biotite-rich schist unit is also gradational and placed where biotite-sillimanite-rich layers become dominant. The migmatitic gneiss unit is similar to the layered gneiss unit of Yonkee and others (2000) on Antelope Island, and probably represents highly metamorphosed greywacke to feldspathic sandstone, and possibly some intermediate to silicic volcanic rocks, which experienced widespread partial melting and intrusion of pegmatitic to granitic dikes.

Unmapped, mostly 0.3- to 6-meter-thick (1-20 ft) concordant to discordant layers of amphibolite are widespread within the unit, and similar layers also occur within the quartz-rich gneiss and biotite-rich schist units. These amphibolite layers consist mostly of hornblende and plagioclase with accessory oxides, although some layers also contain minor biotite and quartz. Amphibolite forms small, moderately resistant, black exposures. Amphibolite layers contain about 50 wt% SiO_2, and have geochemical characteristics consistent with basaltic protoliths (table 1). The layers are similar to amphibolite layers exposed on Antelope Island, and probably represent highly deformed and metamorphosed mafic igneous dikes, although a few larger layers that are up to 20 meters (70 ft) thick may represent mafic lava flows (Yonkee and others, 2000).

Granitic Gneiss of Ogden Hanging Wall (Xfgh)

Medium- to fine-grained, hornblende-bearing, granitic gneiss comprises most of this unit (figure 3b). This unit is exposed over a large area west of Mount Ogden, and in several east-trending belts north and south of Weber Canyon within the hanging wall of the Ogden floor thrust. These belts become narrower and have more gradational contacts with migmatitic gneiss to the south. Granitic gneiss consists of about 20 to 35 vol% quartz, 20 to 35 vol% plagioclase, 25 to 35 vol% K-feldspar, 3 to 15 vol% hornblende, 0 to 5 vol% biotite, and accessory oxides based on point counts; minor orthopyroxene is present locally as grains up to 1 centimeter (0.4 in) in size. Locally, the gneiss has a spotty distribution of hornblende aggregates that may have formed by recrystallization of original igneous orthopyroxene grains. Plagioclase is partly altered to sericite and epidote, K-feldspar is slightly altered to sericite, and hornblende is partly altered to chlorite and a light-blue, fine-grained amphibole in some areas. Granitic gneiss contains about 70 wt% SiO_2 and has relatively high FeO and K_2O contents (table 1). The gneiss displays moderate to strong foliation defined by preferred orientation of hornblende grains and aggregates. Much of the gneiss also displays weakly to moderately developed migmatitic layering defined by numerous, quartz-feldspar-rich bands that are 1 to 10 centimeters (0.4-4 in) thick. The bands are deformed, overall subparallel to foliation, have diffuse to sharp contacts, and many have hornblende-rich selvages along their margins. Foliation and layering are overall east-striking, and continu-

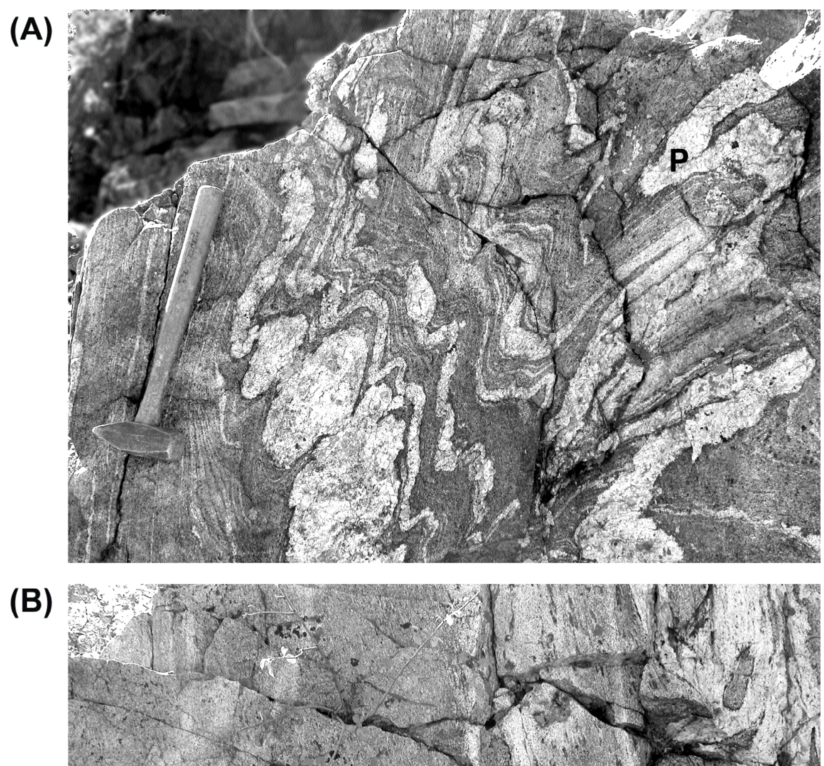

Figure 3. (A) Outcrop of migmatitic gneiss near Burch Canyon. The gneiss displays well-developed compositional layering, which is folded with local development of a second foliation. Hammer for scale is about 40 centimeters (16 in) long. (B) Outcrop of granitic gneiss in hanging wall of Ogden floor thrust west of Mount Ogden. Granitic gneiss displays a single foliation defined by preferred orientation of hornblende. Pegmatite dikes (P) locally cross cut steeply dipping foliation. Hammer for scale.

ous with foliation in adjoining migmatitic gneiss. Granitic gneiss is cut by light-colored, coarse-grained, less deformed granite and pegmatitic dikes that have sharp contacts and thicknesses mostly from 0.01 to 3 meters (0.03-10 ft). The dikes consist mostly of feldspar and quartz, but some dikes also contain minor hornblende and orthopyroxene grains to 8 centimeters (3 in) in size. In most areas, granitic gneiss weathers to form overall resistant, light- to pink-gray, massive-appearing exposures. However, in some northern areas, the gneiss displays widespread fracturing and hematite alteration, and in some areas the gneiss is less foliated and lacks migmatitic layering. Granitic gneiss probably formed by metamorphism and deformation of a large intrusion(s) (Bryant, 1988a). Pyroxene-bearing dikes and locally preserved pyroxene-bearing granitic gneiss indicate that parts of the intrusion may have been charnockitic, with relatively high temperature and low water content. Hematite-altered gneiss may represent locally concentrated hydrothermal alteration, and less foliated gneiss may record another phase(s) of intrusion. This unit is locally interlayered with migmatitic gneiss, and includes small pods of meta-gabbro and amphibolite.

Meta-Gabbro and Amphibolite (Xfa)

This unit consists of fine- to coarse-grained, pyroxene-hornblende- to plagioclase-rich rock, which forms large to small pods within the granitic gneiss, mainly near Mount Ogden; only larger bodies are mapped. Rocks in these pods consist of about 30 to 70 vol% plagioclase, 30 to 70 vol% pyroxene and hornblende, and accessory oxides based on point counts of thin sections, with pyroxene being the main mafic phase in meta-gabbro and hornblende being more abundant in foliated amphibolite. Foliation varies from strong along the margins of smaller amphibolite pods to absent in the cores of larger meta-gabbro bodies that retain ophitic textures. This unit is locally cut by undeformed, late-stage pegmatitic dikes. Pods may represent metamorphosed gabbro that was intruded into the granitic gneiss during later stages of metamorphism, or xenoliths of older amphibolite dikes.

Muscovite-Bearing Schist (Xfs)

This unit consists mostly of schist to gneiss layers having distinctive muscovite grains up to 2.5 centimeters (1 in) in size, and is exposed in the footwall of the Ogden floor thrust fault, along and south of Waterfall Canyon (plate 1). The schist consists of variable amounts of quartz and plagioclase, up to 20 vol% muscovite, biotite, and accessory oxides, with minor garnet in some layers. Plagioclase is partly altered to sericite and epidote, and biotite is partly altered to chlorite. Well-developed foliation is defined by preferred orientation of mica and quartz aggregates. Schist layers are cut by variably deformed, light-colored pegmatitic dikes, and the unit also contains some thin layers of hornblende-plagioclase gneiss. Overall, the unit is less resistant and forms slopes with brown-gray ledges. The schist is interpreted to have formed by metamorphism of some combination of feldspathic to semipelitic sedimentary rocks, and intermediate- to felsic-composition volcanic rocks.

Hornblende-Plagioclase Gneiss (Xfh)

This unit consists of hornblende-plagioclase gneiss exposed in the footwall of the Ogden floor thrust fault near Waterfall Canyon (plate 1). The gneiss contains about 20 to 50 vol% hornblende, 20 to 60 vol% plagioclase, 0 to 10 vol% garnet (with grains up to 2.5 centimeters [1 in] in size), 0 to 10 vol% quartz, and accessory oxides, with minor biotite in some layers. Locally, plagioclase is partly altered to sericite and epidote, and hornblende and garnet are partly altered to chlorite. Moderate to strong foliation is defined by preferred orientation of hornblende, and is parallel to crude layering defined by variations in plagioclase and hornblende abundances. The gneiss weathers to form moderately resistant, dark-gray to black exposures. We interpret this unit to have formed by metamorphism of mafic volcanic rocks, sills, and dikes.

Granitic Gneiss of Ogden Footwall (Xfgf)

This unit consists mostly of medium- to fine-grained, light- to pink-gray, hornblende-bearing granitic gneiss, and is exposed along the western parts of Ogden Canyon and Taylor Canyon within the footwall of the Ogden floor thrust. This granitic gneiss consists of about 25 to 40 vol% quartz, 20 to 30 vol% plagioclase, 25 to 40 vol% K-feldspar, 2 to 10 vol% hornblende, minor biotite, and accessory oxides, based on point counts. Moderate- to well-developed, variably oriented and refolded foliation is defined by preferred orientation of hornblende aggregates. This unit also contains widespread pegmatite dikes and some amphibolite pods. Pegmatite dikes have diffuse to sharp contacts, are foliated to undeformed, have thicknesses from 0.05 to 3 meters (0.02-10 ft), and consist mostly of feldspar and quartz, with some hornblende grains up to 8 centimeters (3 in) in size. Amphibolite pods, mostly 0.1 to 1 meter (0.3-3 ft) thick, are variably foliated and composed of varying amounts of hornblende and plagioclase. This gneiss is similar to the granitic gneiss of the Ogden hanging wall, but generally lacks pyroxene, and probably represents a different granitic pluton.

Precambrian Geologic History

Limited geochronologic and geothermobarometric data constrain the geologic history of the Farmington Canyon Complex in the Ogden area (figure 4). Rb-Sr whole-rock data for garnet-bearing migmatitic gneiss (as mapped in this study) define a crudely linear array (Hedge and others, 1983), which may record a Late Archean metamorphic event (Bryant, 1988b) or deposition of sedimentary protoliths for migmatitic gneiss that incorporated material eroded from nearby Archean crust (Barnett and others, 1993; Nelson and others, 2002). Three Nd-Sm model ages for migmatitic gneiss and amphibolite dikes may record Archean crustal growth (Hedge and others, 1983; Bryant, 1988b), or inclusion of material eroded from Archean crust.

U-Pb data for zircon from granitic gneiss (as mapped in this study) define a chord with an upper intercept corresponding to an age of about 1,800 Ma, and Rb-Sr whole-rock data define an isochron that also yields an age of about 1,800 Ma, with a very high initial $^{87}Sr/^{86}Sr$ ratio of 0.769 (Hedge and others, 1983). However, these isotopic data come from samples of both the granitic gneiss of Ogden hanging wall and

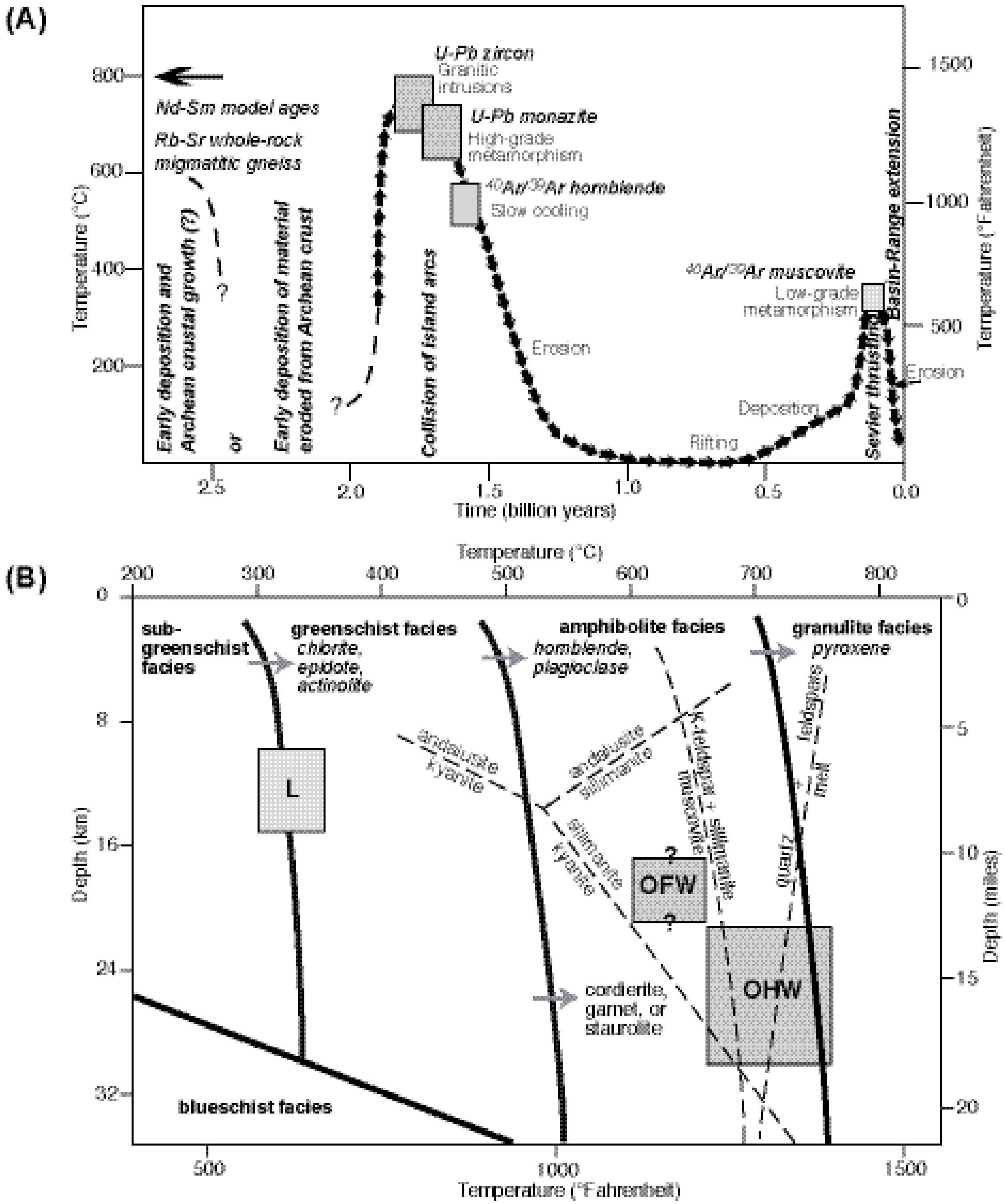

Figure 4. (A) Interpreted temperature-time history for the Farmington Canyon Complex based on data from Hedge and others (1983), Yonkee (1992), and Barnett and others (1993). Archean Nd-Sm model ages may record early crustal growth or inclusion of material eroded from Archean crust, U-Pb zircon and monazite ages record Early Proterozoic igneous intrusion and high-grade metamorphism, and $^{40}Ar/^{39}Ar$ muscovite ages from shear zones record Cretaceous low-grade metamorphism. (B) Estimated metamorphic conditions for the Farmington Canyon Complex, including Early Proterozoic high-grade metamorphism of rocks in the Ogden hanging wall (OHW) (from Barnett and others, 1993) and in Ogden footwall (OFW) (poorly constrained by presence of muscovite and garnet), and Cretaceous low-grade metamorphism (L) (from Yonkee, 1992). Index minerals found in mafic rocks (in italics) and in pelitic rocks at various grades are indicated. Solid lines show approximate boundaries between metamorphic facies. Dashed lines indicate stability fields of aluminosilicate minerals, and reaction of muscovite to K-feldspar and partial melting for water pressure equal to one-half of rock pressure (from Winkler, 1976).

the granitic gneiss of Ogden footwall, and only a limited number of samples are available for each unit. Overall, these data probably record widespread granitic intrusions, which may have incorporated material from radiogenic crust, approximately synchronous with Early Proterozoic regional metamorphism and deformation (Bryant, 1988a).

U-Pb data for metamorphic monazite from migmatitic gneiss and associated biotite-rich schist (as mapped in this study) give approximately concordant ages of about 1,700 to 1,650 Ma, which record the age of peak metamorphism or cooling to temperatures below about 650°C soon after peak metamorphism (Barnett and others, 1993). Nelson and others (2002) obtained similar monazite ages, and interpreted regional patterns to record metamorphism during collision of island arc terranes onto the southern margin of the Archean Wyoming Province. $^{40}Ar/^{39}Ar$ ages for hornblende range from about 1,650 to 1,580 Ma, and record slow cooling to about 500°C following peak metamorphism (Barnett and others, 1993).

Peak metamorphic conditions for rocks found in the hanging wall of the Ogden floor thrust are about 650 to 750°C at depths of about 20 to 30 kilometers (12-18 mi) (Barnett and others, 1993) (OHW, figure 4b). These conditions are consistent with uppermost amphibolite- to granulite-facies metamorphism, and with local presence of orthopyroxene in mafic rocks and granitic gneiss, and coexisting K-feldspar and sillimanite in biotite-rich schist. Peak metamorphic conditions for rocks found in the footwall of the Ogden floor thrust are lower (OFW, figure 4b), probably within middle amphibolite facies based on lack of orthopyroxene in mafic rocks and presence of muscovite-bearing schist.

We used these data, along with map relations and rock types described previously, to develop a simple model for the Precambrian history of the area (figure 5). A thick sequence of greywacke to variably feldspathic sandstone, with some clay-rich and quartz-rich layers, was deposited during either the Archean(?) or Early Proterozoic, incorporating material eroded from Archean crust (stage 1). This sequence was also intruded by a series of mafic dikes, possibly associated with basalt lava flows. Multiple foliations preserved in some fold hinges within migmatitic gneiss may record an earlier phase of deformation, during either Late Archean(?) metamorphism (Bryant, 1988b) or initial parts of protracted Early Proterozoic metamorphism (stage 2). This sequence was then intruded by large granitic plutons, approximately synchronous with the main phase of amphibolite- to granulite-facies metamorphism and intense deformation from about 1,800 to 1,650 Ma (stages 3 and 4). Plutons were transformed into large bodies of granitic gneiss, sedimentary rocks were transformed into migmatitic gneiss with layers of biotite-rich schist and quartz-rich gneiss, and mafic rocks were transformed into amphibolite. Gabbroic bodies in the granitic plutons may represent xenoliths of older amphibolite or mafic intrusions. Late-stage pegmatite dikes, as well as some late-stage granitic plutons in other parts of the Farmington Canyon Complex (Yonkee and others, 2000), were intruded after peak deformation (stage 5). These patterns are broadly similar to those found in the Mojave Province to the southwest, and may reflect a profound period of mountain building and crustal reworking associated with accretion of island arc terrains onto the margin of the North American continental core (Bryant, 1988b; Chamberlain and Bowring, 1990; Nelson and others, 2002). The entire complex then stayed at relatively high temperatures for about 100 million years, followed by a long period of uplift and erosion, now represented by a major unconformity, and then by deposition of Paleozoic to Mesozoic sedimentary rocks (stages 6 and 7). Hydrothermal alteration during Cretaceous deformation locally modified textures and mineralogy of basement rocks, especially along shear and fault zones (stage 8).

Overview of Paleozoic Sedimentary Rocks

Paleozoic sedimentary rocks are spectacularly exposed along Ogden Canyon in the northeastern part of the quadrangle (figure 6a). This sequence is transitional in thickness and character between a more eastern sequence deposited on the continental platform and preserved to the east and south toward the Salt Lake City area, and a more western sequence deposited along the continental shelf, and preserved in the Willard thrust sheet (Rigo, 1968; Hintze, 1988; Camilleri and others, 1997) (figure 1). This transitional nature, combined with a lack of intervening exposures, has resulted in a variety of formation names that were originally applied to both the eastern and western sequences being adapted to the Ogden area. Additionally, Mesozoic deformation has disrupted this sequence in the Ogden area, making accurate measurement of stratigraphic sections difficult. We have largely followed Rigo (1968) and Crittenden and Sorensen (1985) in our use of formation and informal member names.

Cambrian

Tintic Quartzite (€t)

The Tintic Quartzite consists mostly of well-cemented sandstone (orthoquartzite), but in detail displays minor variations with stratigraphic level, and can be crudely divided into a basal part and a main part. The basal part of the formation, which is up to 60 meters (200 ft) thick, consists of a heterogeneous package of purple- to green- to tan-weathering, interbedded conglomerate, sandstone, and siltstone. Conglomerate layers are medium to thick bedded, well to poorly sorted, and consist of subrounded to angular clasts in a fine- to coarse-grained, variably arkosic matrix. Clasts are up to 20 centimeters (8 in) in size, and consist of quartz, chert, and rare granitic gneiss fragments. Sandstone is fine to coarse grained, arkosic (especially near the contact with the Farmington Canyon Complex), and weakly to strongly cemented by hematite. Siltstone is micaceous and thin bedded. Conglomerate and sandstone layers are laterally discontinuous and some display trough cross-bedding and channels, possibly indicating fluvial deposition. The base of the formation is a major unconformity, with a fossil-weathering horizon locally present at the top of underlying Early Proterozoic igneous and metamorphic rocks.

The main part of the formation, which is about 330 to 390 meters (1,100-1,300 ft) thick, consists of laterally continuous layers of white to tan, well-cemented sandstone (orthoquartzite), with some lenses of quartz-pebble conglomerate and thin layers of argillite. Sandstone layers are mostly 0.3 to 2 meters (1-7 ft) thick, display widespread

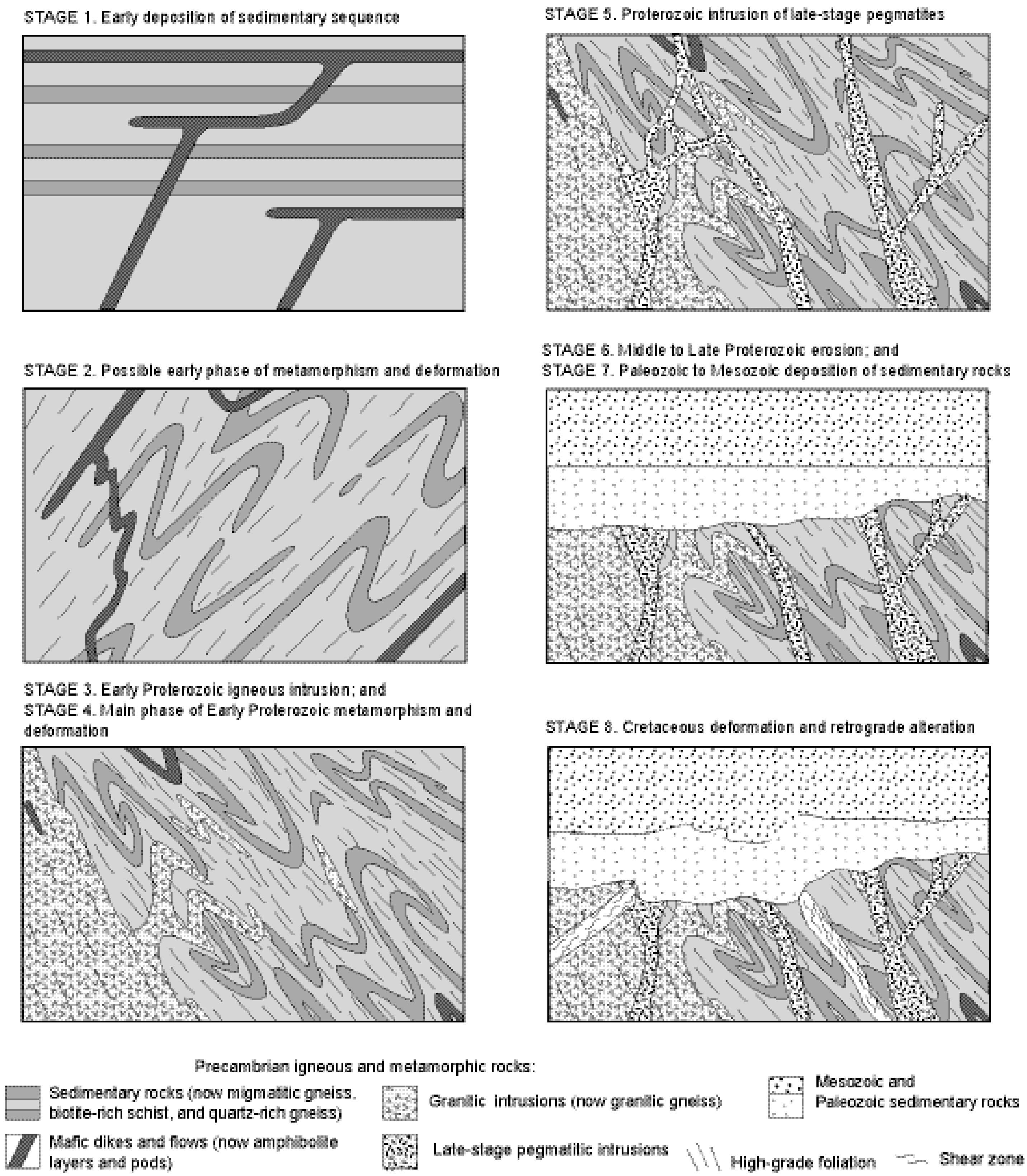

Figure 5. *Schematic diagram showing interpreted geologic history of the Farmington Canyon Complex (modified from Yonkee and others, 2000).*

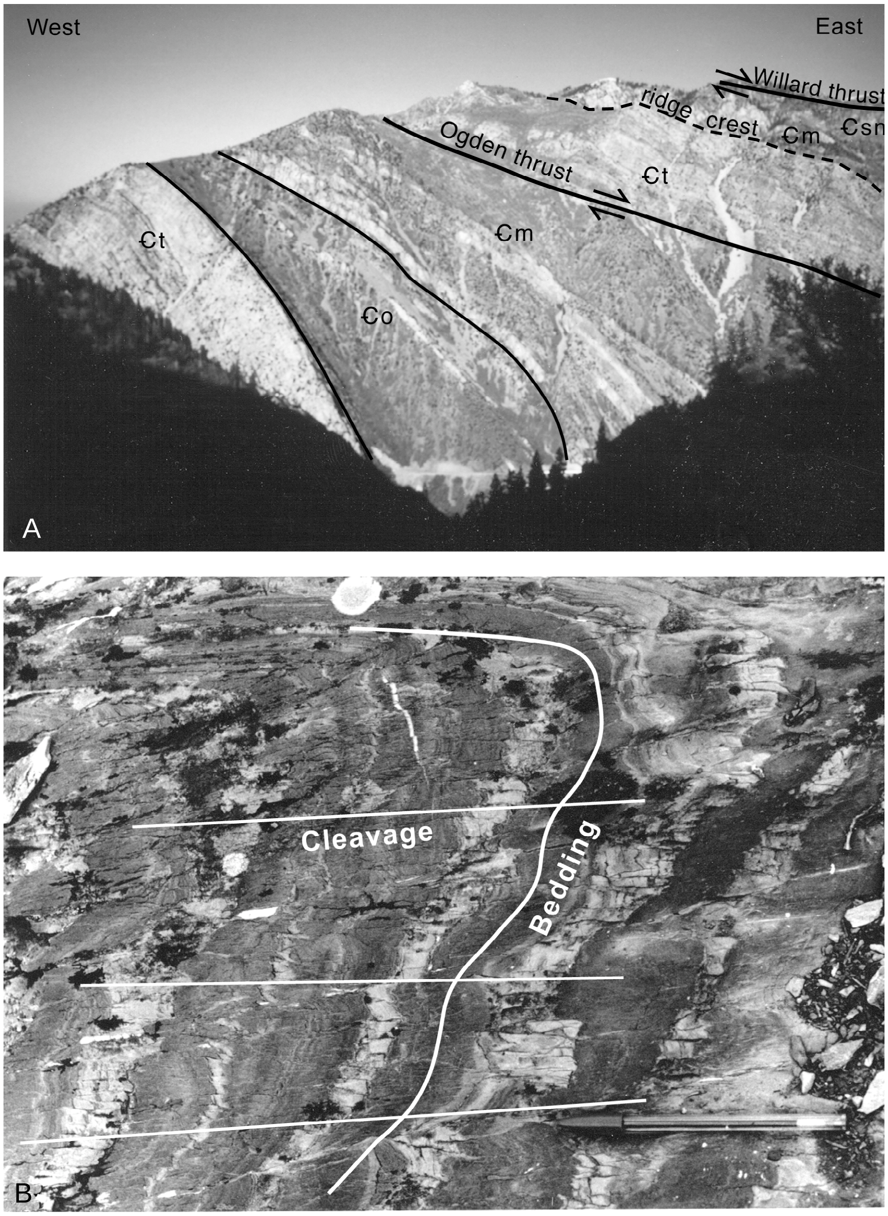

*Figure 6. **(A)** View to northwest of north side of Ogden Canyon where Cambrian units are repeated by the Ogden thrust fault. Units are: €t - Tintic Quartzite, €o - Ophir Shale, €m - Maxfield Formation, and €sn - St. Charles and Nounan Formations. Late Proterozoic strata within the Willard thrust sheet are exposed locally along the skyline. **(B)** Lower limestone member of Maxfield Formation just south of Taylor Canyon. Silty limestone beds (lighter colored) are folded and cut by spaced cleavage. Thrust-related deformation produced widespread variations in observed thicknesses of formations in the sedimentary cover.*

cross-bedding, and are bounded by discrete micaceous partings to thin layers of argillite. Sandstone is fine to coarse grained, quartz rich, and locally contains isolated quartz pebbles from 1 to 5 centimeters (0.4-2 in) in size. Conglomerate lenses up to 0.3 meters (1 ft) thick contain abundant rounded quartz pebbles. Argillite layers vary mostly from 1 to 15 centimeters (0.4-6 in) thick, and consist of olive-drab, finely laminated, micaceous siltstone, shale, and very fine-grained sandstone. Overall, sandstone becomes finer grained and forms thinner layers, quartz pebbles become less abundant, and argillite layers become more abundant and thicker toward the top of the formation. Trace fossils in the upper part of the formation include *Skolithus* tubes and rare *Plagiogmus* traces, indicating an Early to Middle Cambrian age (Peterson and Clark, 1974). Coarser grained sandstone and conglomerate layers were probably deposited in higher energy, near-shore, marine environments, whereas finer grained sandstone and argillite layers were probably deposited in lower energy, offshore marine environments.

Overall, the formation is resistant and forms large, light-colored, well-layered cliffs. Total thickness of the formation is about 400 to 450 meters (1,300-1,500 ft), but varies slightly due to minor faulting. This formation correlates lithologically with the Tintic Quartzite exposed in and south of the Salt Lake City area (Morris and Lovering, 1961), and with the Geertsen Canyon Quartzite of the Willard thrust sheet (Crittenden and others, 1971).

Ophir Shale (€o €om, €ou)

This formation is divided into the lower shale member (€ol), middle limestone member (€om), and upper shale member (€ou), following Rigo (1968). Undivided Ophir Shale (€o) is mapped in areas where the middle member cannot be traced.

The lower member consists mostly of brown to olive-drab, micaceous to silty shale (or argillite), with some orange-weathering, thin siltstone layers, and sparse, fine-grained sandstone layers. The member is non-resistant and forms covered slopes with shale float. The contact with the Tintic Quartzite is gradational over an interval of about 10 meters (30 ft), and is placed at the top of the last laterally continuous quartzite interval.

The middle member consists mostly of light- to medium-gray, thin- to medium-bedded, fine-grained limestone, with abundant thin, orange-gray-weathering, silty ribbons - a rock type referred to as ribbon limestone. This member also contains sparse lenses of oolitic limestone. The member is resistant and, where present, forms a thin, distinct ridge between the two shale members.

The upper member consists mostly of gray-brown to olive-drab, variably calcareous, micaceous to silty shale (or argillite), and rare limestone layers. Limestone layers are fine grained, light to medium gray, and less than 0.3 meters (1 ft) thick. The member is very non-resistant, rarely exposed, and generally forms brush-covered slopes.

Thicknesses of the overall formation and of individual members are highly variable due to intense deformation that led to widespread development of cleavage at varying angles to bedding, open to isoclinal folds, and shear zones. In areas having less intense deformation, the lower member is about 40 to 100 meters (130-330 ft) thick, the middle member is about 6 to 20 meters (20-70 ft) thick, and the upper member is about 40 to 80 meters (130-260 ft) thick, giving a total formation thickness of about 90 to 200 meters (300-700 ft). Rigo (1968) reported *Ehmaniella* sp., *Alokistocare* sp., and

Zacanthoides sp. from the lower member, consistent with an early Middle Cambrian age. This unit correlates lithologically with the Ophir Shale exposed in and south of the Salt Lake area (Morris and Lovering, 1961), and with parts of the Langston and Ute Formations in the Willard thrust sheet (Maxey, 1958; Rigo, 1968).

Maxfield Formation (€m, €ml, €ma, €mu)

This formation is divided into three map units, the lower limestone member (€ml), middle argillaceous limestone member (€ma), and upper limestone and dolomite member (€mu), partly following Rigo (1968). We map undivided Maxfield Formation (€m) in areas where members cannot be confidently identified due to complex deformation.

The lower member consists mostly of light- to medium-gray, thin- to medium-bedded, fine-grained, ribbon limestone with abundant orange-weathering, wavy, silty layers up to 2.5 centimeters (1 in) thick. A thin interval of less-resistant, argillaceous limestone is present near the middle of the member, and lenses of oolitic limestone exist locally. The lower member is overall resistant and generally forms a characteristic double ledge separated by a small slope along the argillaceous limestone interval. The contact with the underlying Ophir Shale is sharp and put at the base of the lower ledge.

The middle member consists of a distinct package of interlayered argillaceous limestone, shale, ribbon limestone, oncolitic limestone, oolitic limestone, and flat-pebble conglomerate. Argillaceous limestone consists of black, clay-rich layers and clay-filled cracks that surround thin beds to nodules of gray, fine-grained limestone. This rock type locally grades into flat-pebble conglomerate composed of fine-grained limestone and shale intraclasts in a variably shaley to calcareous matrix. Shale is olive drab to brown, and variably micaceous to silty. Ribbon limestone is thin bedded with abundant orange-gray silty layers. Layers of silty, oncolitic limestone with possible *Girvanella*(?) spherules, and layers of well-sorted oolitic limestone occur locally. The middle member is moderately to non-resistant and generally forms slopes with thin limestone ledges.

Our upper member corresponds to the combined upper limestone and overlying upper dolomite members of Rigo (1968). The lower part of this unit consists of light- to medium-gray, thin- to thick-bedded, fine-grained limestone with yellow-gray silty ribbons, oolitic limestone, and minor dolomite. Silty ribbons decrease in overall abundance and dolomitized areas increase in abundance upwards. The upper part of the member consists mostly of light- to dark-gray, medium- to thick-bedded, recrystallized dolomite and minor limestone. Some dolomite intervals are oolitic and some intervals contain thin, light-gray, slightly silty ribbons. White to light-gray, twiggy bodies up to 2.5 centimeters (1 in) long, which could represent fossils or burrows, are widespread. A distinct package of alternating dark-gray, chert-bearing dolomite, and light-gray, laminated boundstone forms a useful marker near the top of the member. The boundary between the limestone-rich lower part and dolomite-rich upper part of this member is locally irregular and corresponds to a complex diagenetic front.

Thicknesses of the overall formation and of individual members are variable due to deformation, with widespread development of cleavage at varying angles to bedding, open to isoclinal folds, minor faults, and brecciated zones (figure 6b). In areas of less-intense deformation, the lower member is about 40 to 80 meters (130-260 ft) thick, the middle member is about 40 to 80 meters (130-260 ft) thick, and the upper member is about 100 to 150 meters (330-500 ft) thick, giving a total formation thickness of about 180 to 300 meters (600-1,000 ft). Rigo (1968) reported *Bathyuriscus* sp., *Elrathina* sp., *Peronopsis* sp., and *Ptychagnostus* sp. from limestone that we map as part of the lower member, consistent with a Middle Cambrian age for the base of the formation. Overall, the three members mapped in the Ogden area are crudely similar to the Maxfield Formation in the Salt Lake City area (Calkins and Butler, 1943). The lower and middle members may correlate lithologically with part of the Ute Formation and the upper member may correlate lithologically with the uppermost Ute and Blacksmith Formations in the Willard thrust sheet.

Bloomington Formation (€b)

A heterogeneous interval of interlayered shaley limestone, flat-pebble conglomerate, shale, ribbon limestone, oncolitic limestone, and oolitic limestone comprise the Bloomington Formation. Shaley limestone consists of thin layers to nodules of fine-grained, gray limestone surrounded by discontinuous layers and filled cracks of black shale. Flat-pebble conglomerate is locally abundant and consists of light-gray, fine-grained limestone intraclasts in a calcareous to shaley matrix. Shale is olive drab to brown, variably micaceous to silty, and locally contains fragments of inarticulate brachiopods. Ribbon limestone is thin bedded and displays abundant orange-gray silty layers. Layers of silty, oncolitic limestone, and layers of well-sorted oolitic limestone occur locally and are up to 1 meter (3 ft) thick. This formation is overall non-resistant and forms a distinct slope between underlying and overlying cliffs of dolostone. The formation is cut by numerous minor faults that produce large variations in observed thickness; in areas of less intense deformation the formation is about 30 to 60 meters (100-200 ft) thick. Rigo (1968) reported *Eldoradia* sp., indicating a late Middle Cambrian age. This interval is temporally and lithologically similar to, but much thinner than the Bloomington Formation within the Willard sheet (Williams, 1948).

St. Charles and Nounan Formations, Undivided (€sn)

This map unit consists mostly of thin- to thick-bedded, but overall massive-weathering, light- to dark-gray dolomite of the St. Charles and underlying Nounan Formations. An interval of sandy dolomite and minor sandstone, less than 10 meters (30 ft) thick, near the middle of the unit probably corresponds to the Worm Creek Member of the St. Charles Formation, which marks the contact with the Nounan Formation. This thin interval, however, cannot be reliably traced in areas with minor faulting and poor exposure, and the two formations are mapped together. Dolomite is highly recrystallized, varies from fine to coarse grained, and locally displays lighter gray mottling. Some layers contain twiggy structures up to 2.5 centimeters (1 in) long, which could represent highly recrystallized fossils or burrows, and a few layers contain light-gray, slightly silty laminations. This unit forms large, relatively homogeneous cliffs to steep rocky slopes that contrast with the underlying non-resistant and heterogeneously layered Bloomington Formation. The thickness of the Nounan Formation is estimated to be about 150 to 220 meters (500-720 ft) and the thickness of the St. Charles Formation is estimated to also be about 150 to 220 meters (500-720 ft), with a total unit thickness of about 300 to 450 meters (1,000-1,500 ft), but thicknesses vary locally due to minor faulting. Fossils have not been recovered from this unit in the Ogden area, but the unit is correlated lihtologically with the Nounan and St. Charles Formations of the Willard thrust sheet, which contain a Late Cambrian fauna (Maxey, 1958).

Ordovician

Garden City Formation (Og)

Thin- to thick-bedded, light-gray to tan, flaggy-weathering dolomite, silty dolomite, silty limestone, and minor siltstone comprise the Garden City Formation. The formation is crudely divided into the following intervals: a lower interval of thinner bedded, lighter colored silty dolomite, silty limestone, and siltstone that forms less-resistant slopes; a middle interval of thicker bedded, medium-gray dolomite that forms larger ledges; and an upper interval of thin- to thick-bedded, light- to medium-gray, variably silty dolomite to dolomitic limestone that forms moderately resistant slopes with small ledges. Dolomite layers are recrystallized, generally fine to medium grained, and some layers contain fossil fragments of crinoids, brachiopods, and gastropods. Siltstone forms thin to discontinuous layers, and fills thin cracks in the dolomite at high angles to bedding, which may be related to desiccation cracking. The lower contact with the St. Charles Formation appears gradational over a short interval and is placed at a change from underlying massive-weathering dolomite, to well-bedded, silty dolomite. The undeformed thickness of the formation is estimated to be about 60 to 120 meters (200-400 ft), but thickness varies due to widespread minor faulting. This unit is lithologically similar to, but thinner than the Garden City Formation exposed within the Willard thrust sheet, which contains an Early Ordovician fauna (Ross, 1951).

Fish Haven Dolomite (Of)

Medium- to thick-bedded, medium- to dark-gray, massive-weathering dolomite comprises the Fish Haven Dolomite. The dolomite is strongly recrystallized, fine to coarse grained, and some layers contain fossil coral fragments. A few layers also contain possible oncolites and light-gray, slightly silty laminations. The unit is highly resistant and forms small cliffs. The lower contact is an unconformity, and corresponds to a distinct change from underlying well-bedded, lighter dolomite to more massive, darker dolomite. The upper contact is also an unconformity, and Silurian strata appear to be absent in the quadrangle, although biostratigraphic control is poor. The undeformed thickness of the formation is estimated to be about 40 to 80 meters (130-260 ft), but thickness varies due to minor faulting. This unit is lithologically similar to, but thinner than the Fish Haven Dolomite exposed within the Willard thrust sheet, which contains a Late Ordovician fauna (Williams, 1948).

Devonian

Hyrum Dolomite and Water Canyon Formation, Undivided (Dhw)

These two formations are grouped into a single map unit due to their relatively small thicknesses. The underlying Water Canyon Formation consists of a thin, overall light- to yellow-gray weathering interval of dolomite. Dolomite is thin to medium bedded, mostly fine grained, and silty to sandy. The base of the formation is an unconformity marked by an abrupt change from underlying massive dolomite to well-layered dolomite. The formation is about 10 to 30 meters (30-100 ft) thick, and generally forms a small, relatively less-resistant ledge, but is locally omitted by minor faulting. This interval is lithologically similar to, but much thinner than, the Water Canyon Formation exposed in the Willard thrust sheet, which contains Early Devonian fish fossils (Williams and Taylor, 1964).

The overlying Hyrum Dolomite consists of medium- to dark-gray, medium- to thick-bedded dolomite and minor silty limestone. Dolomite is medium to coarse grained, locally displays calcite-filled vugs and chert nodules, and some layers contain light-gray, slightly silty laminations. This formation is about 40 to 80 meters (130-260 ft) thick and forms a small, resistant ledge. This interval is lithologically similar to, but thinner than the Hyrum Dolomite exposed within the Willard thrust sheet, which contains a Middle Devonian fauna (Williams, 1971). Total thickness for the Hyrum Dolomite plus Water Canyon Formation in the Ogden area is about 50 to 100 meters (170-330 ft).

Beirdneau Formation (Db)

A heterogenous sequence of overall yellow- to red- to light-gray-weathering, silty to sandy dolomite and limestone, sandstone, shale, siltstone, flat-pebble conglomerate, and sedimentary breccia comprise the main part of the Beirdneau Formation. Limestone and dolomite are overall yellow- to light-gray weathering, thin to medium bedded, and contain variable amounts of medium-sand-sized, well-rounded quartz grains. Sandstone is orange-gray weathering, thin to medium bedded, fine to medium grained, moderately to well sorted, contains well-rounded quartz grains, and displays ripples and small-scale cross-bedding. Red to yellow shale and siltstone are variably calcareous to dolomitic, locally display soft-sediment folds, mudcracks, and sedimentary dikes, and grade into flat-pebble conglomerate composed of elongate carbonate clasts in a shaley matrix. Sedimentary breccia consists of angular dolomite, limestone, shale, and sandstone clasts up to 15 centimeters (6 in) in size in a finer grained matrix. The lower contact is placed at a change from underlying thicker bedded dolomite of the Hyrum Dolomite to thinner bedded limestone, dolomite, and sandstone. The thickness of the formation is probably about 50 to 100 meters (170-330 ft), but the formation is poorly exposed and deformed by widespread minor faults and folds that produce variations in observed thicknesses. This main part of the formation is lithologically similar to the Victoria Formation exposed south of the Salt Lake City area (Morris and Lovering, 1961), and to the Beirdneau Formation in the Willard thrust sheet, which is of Late Devonian age (Williams, 1971).

The uppermost part of the formation is poorly exposed in the Ogden quadrangle, but is exposed locally to the northeast in the Huntsville quadrangle where a distinctive, 10- to 15-meter-thick (30-50 ft) interval of purple to gray, argillaceous limestone and shale separates underlying sandy dolomite typical of the Beirdneau Formation from overlying fossiliferous limestone typical of the Gardison Limestone. Argillaceous limestone contains fossil shell fragments, and shale contains abundant trace fossils. The base of this interval is marked by a thin layer of purple quartzite, and the top of the interval is marked by a thin layer of black, organic-rich shale. This interval is lithologically similar to the Late Devonian Pinyon Peak Formation exposed near and south of the Salt Lake City area (Morris and Lovering, 1961).

Mississippian

Gardison Limestone (Mg)

Medium- to dark-gray, fossiliferous limestone and dolomitic limestone comprise the Gardison Limestone. Limestone consists of fine-grained matrix with sparse to abundant fossil fragments of crinoids, brachiopods, gastropods, and corals. The matrix is partly recrystallized to sparry calcite and dolomite. Pods and discontinuous stringers of gray to black chert, up to 10 centimeters (4 in) thick, increase in overall abundance upwards, and some fossil fragments are silicified. The lower part of the unit is thin to medium bedded and forms ledges, whereas the upper part is medium to thick bedded and forms more massive cliffs. The top of the formation is not exposed within the Ogden quadrangle, but in the nearby Huntsville quadrangle the formation is about 200 meters (660 ft) thick, and is bounded above by thin-bedded limestone and shale of the Deseret Limestone. This unit is lithologically similar to the Gardison Limestone described south of the Salt Lake area, which contains an Early Mississippian fauna (Morris and Lovering, 1961), and probably correlates with part of the Early Mississippian Lodgepole Limestone within the Willard thrust sheet.

Cretaceous Altered and Deformed Rocks

The Sevier orogeny produced a growing mountain belt within northern Utah during the Cretaceous, with multiple periods of large-scale thrusting and folding, significant erosion and development of a major unconformity at the surface, and local alteration and penetrative deformation at depth (Camilleri and others, 1997). Alteration and deformation produced new minerals and textures that overprinted various protoliths, forming the following rock types: chloritic gneiss, cataclasite, and mylonite (Kc); imbricated fault rocks (Kfx); and quartz veins and pods (K(?)q). These rock types are found in a wide zone along the Ogden floor thrust fault, in a series of shear zones that crosscut basement rocks of the Farmington Canyon Complex, and in diffuse altered zones associated with quartz pods that crosscut basement rocks (Yonkee, 1992; Yonkee and others, 1997). Available $^{40}Ar/^{39}Ar$ ages of fine-grained muscovite in shear zones and along the Ogden floor thrust range mostly from about 140 to 110 Ma, indicating that significant alteration and deformation occurred during the Early Cretaceous (figure 4a) (Yonkee, 1992). However, some chlorite alteration and quartz pods located away from the Ogden floor thrust and shear zones may be Proterozoic (Bryant, 1988a). Details of structural relations and deformation history are described in more detail in the Structural Geology section.

Chloritic Gneiss, Cataclasite, and Mylonite (Kc)

This unit consists of protoliths of the Farmington Canyon Complex that were variably overprinted by greenschist-facies alteration and deformation, resulting in growth of new minerals and development of new structures. We mapped only larger areas having more pervasive alteration. Chloritic gneiss displays moderate- to close-spaced fractures, local micaceous cleavage, minor fault and shear zones up to 0.3 meters (1 ft) thick, and local quartz veins. Chloritic gneiss grades into cataclasite within the fault zone of the Ogden floor thrust (figure 7a), and into mylonite plus phyllonite within basement shear zones (figure 7b). Cataclasite displays pervasive alteration, abundant angular fragments that lie in fine-grained, highly comminuted matrix, local scaly fabrics related to penetrative slip surfaces, and widespread quartz veins (figure 7d). Cataclasite along the Ogden floor thrust grades into mylonite plus phyllonite in southern exposures of the fault zone. Mylonite and mica-rich phyllonite display pervasive alteration, strong foliation defined by quartz ribbons and mica aggregates (figure 7f). Outcrops of chloritic gneiss, cataclasite, and mylonite are typically greenish, and vary from non-resistant where fracturing is intense, to resistant where quartz veins are abundant. Multiple sets of variably deformed veins record repeated episodes of fracturing, fluid influx, alteration, and deformation.

Alteration minerals include fine-grained muscovite (sericite), chlorite, biotite, epidote, and albite, with abundances that vary depending on protolith and extent of alteration. Chloritic gneiss generally contains 10 to 30 vol% combined chlorite, muscovite, and epidote, in addition to remnant plagioclase, K-feldspar, and quartz; cataclasite generally contains 20 to 40 vol% chlorite, muscovite, and epidote; and mylonite contains 20 to 60 vol% muscovite and chlorite. Geochemically, altered gneiss, cataclasite, mylonite, and phyllonite are depleted in alkalies, especially CaO, and enriched in MgO compared to basement rocks from which they were derived (table 1). Within chloritic gneiss, quartz grains display undulatory extinction but only limited plastic recrystallization, feldspar grains are partly fractured and altered to mica and epidote, and mafic minerals are largely altered to chlorite and biotite. Within cataclasite, fine-grained, micaceous matrix surrounds variably fractured and recrystallized quartz grains, highly fractured and altered feldspar grains, and clasts of previously cemented matrix. Within mylonite, quartz forms strongly recrystallized ribbons, feldspar is almost totally altered to foliated, fine-grained aggregates of mica, and original mafic minerals are entirely altered to chlorite.

Imbricated Fault Rocks (Kfx)

This map unit consists of highly deformed and complexly imbricated rocks within fault-bounded slices along the Ogden floor thrust, which were derived from various protoliths. This unit includes highly deformed limestone and shale with intense cleavage and tight minor folds, and high-

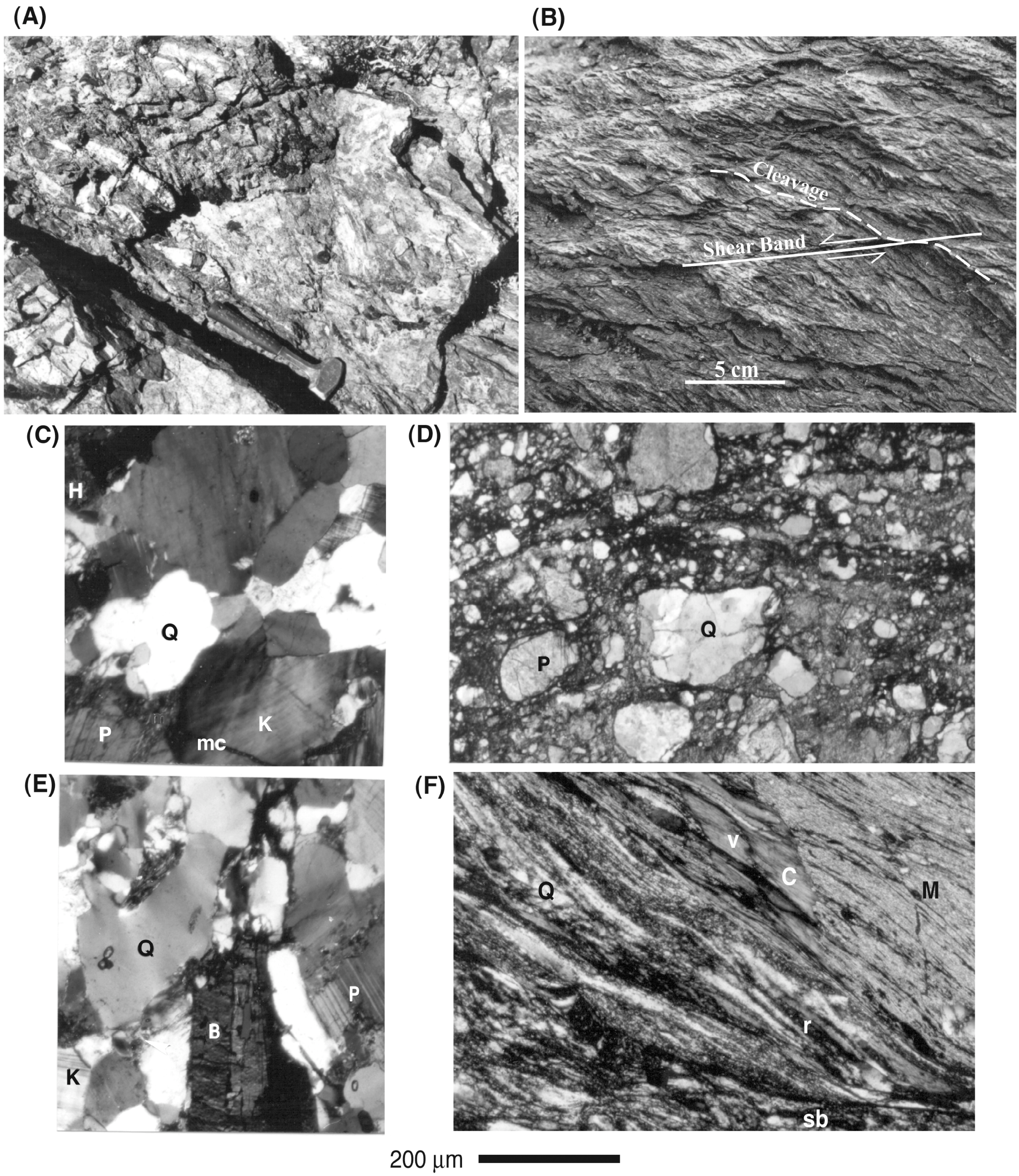

Figure 7. *(**A**) View looking north of minor fault zone and fractured, chloritic gneiss above the Ogden floor thrust along Taylor Canyon. Hammer for scale. (**B**) View looking south of shear zone along Weber Canyon. Cleavage dips gently west and rotates into parallelism with shear bands that have top-to-the-east slip. (**C and D**) Photomicrographs of granitic gneiss in wall rock (**C**) and cataclasite from Ogden floor thrust (**D**) along Taylor Canyon. Cataclasite contains abundant finely comminuted and altered material. Granitic gneiss is relatively undeformed and coarse grained. (**E and F**) Photomicrographs of migmatitic gneiss in wall rock (**E**) and phyllonite from shear zone (**F**) along Weber Canyon. Phyllonite contains abundant fine-grained mica and recrystallized quartz. Migmatitic gneiss is relatively undeformed and coarse grained.*
Labels are: Q- quartz, P- plagioclase, K- K-feldspar, H- hornblende, B- biotite, M- muscovite, C- chlorite, mc- microcrack, r- recrystallized quartz ribbons, sb- shear band, and v- vein.

ly fractured quartzite derived from Cambrian sedimentary rocks; and mixed cataclasite and mylonite derived from Precambrian basement rocks. Detailed stratigraphic relations of protoliths are obscure and individual slices are discontinuous due to complex minor faulting.

Quartz Veins and Pods (K(?)q)

This unit consists of larger quartz-filled veins and pods that crosscut granitic gneiss in the hanging wall of the Ogden floor thrust. Veins and pods consist dominantly of massive to fibrous quartz, with minor amounts of fine-grained chlorite, hematite, and muscovite. Granitic gneiss adjacent to quartz veins and pods displays red to green staining related to hematite and chlorite alteration, abundant fractures, and variable silicification. The age of quartz veins and pods is uncertain. Basement shear zones and cataclasite along the Ogden floor thrust that formed during the Cretaceous also display syntectonic quartz veins, local silicification, and chlorite alteration, and thus most quartz veins within the granitic gneiss are interpreted to be Cretaceous in age. However, Bryant (1988a) indicated that some quartz veins and pods may be related to Precambrian alteration.

Tertiary Igneous Dikes (Td)

Two small igneous dikes (NE 1/4 section 24 and N 1/2 section 25, T. 5 N., R. 1 W., Salt Lake Base Line and Meridian) crosscut rocks of the Farmington Canyon Complex. These dikes are non-foliated, dark colored, and consist of hornblende, biotite, and plagioclase phenocrysts in a fine-grained, altered matrix. These dikes are similar to other Tertiary lamprophyre dikes described in the Wasatch Range (Bryant, 1990).

Cenozoic Basin Fill

The Cenozoic marked a fundamental change in structural and sedimentation styles, from Cretaceous and Paleocene shorthening deformation and erosion, to Eocene and younger shortening deformation with sedimentation in locally developing basins. Regionally, basin fill in northern Utah includes (1) an older sequence of more tilted, Eocene to Oligocene strata preserved within half-grabens that began forming during initial collapse of the Sevier orogenic belt (Constenius, 1996), and (2) an unconformably overlying, younger sequence of less tilted, Miocene to Recent strata in grabens that formed during Basin and Range extension (Zoback, 1983; Bryant and others, 1989; Miller, 1991).

The older sequence is preserved in small half-grabens beneath parts of eastern Great Salt Lake, west of the Ogden quadrangle (Constenius, 1996). These half-grabens appear to be associated with listric normal faults, and are filled with mixtures of conglomerate, sandstone, reworked tuff, and minor lacustrine limestone, which are locally exposed on Antelope Island (Willis and Jensen, 2000).

The younger sequence is preserved within larger basins in northern Utah, including a major graben west of the Wasatch fault zone (Zoback, 1983). Miocene and Pliocene rocks in northern Utah are generally assigned to the Salt Lake Formation, which consists of heterogeneous mixtures of volcanic and sedimentary rocks deposited by streams and in lakes (Miller, 1991). Rock types include variably reworked tuff, local basaltic lava flows, mudstone, sandstone, conglomerate, lacustrine limestone, and minor carbonaceous shale. This late Tertiary basin fill is overlain by broadly similar, but less consolidated Quaternary basin fill.

Gravity, seismic, and limited drill-hole data indicate that a thick sequence of basin fill underlies the western part of the Ogden quadrangle within the large graben west of the Wasatch fault zone (Feth and others, 1966; Cook and others, 1967; Zoback, 1983; Glenn and others, 1980; McNeil and Smith, 1992). This sequence is subhorizontal to gently dipping, up to 3,000 meters (10,000 ft) thick in the central part of the graben, and includes both Tertiary and Quaternary basin fill.

Late Tertiary Basin Fill (Tb)

Late Tertiary basin fill is not exposed at the surface in the Ogden quadrangle, but probably includes a heterogeneous mixture of mudstone, sandstone, conglomerate, variably reworked tuff, and lacustrine limestone, based on limited, deep drill-hole data in nearby areas and regional lithologic patterns (Feth and others, 1966; Miller, 1991). Conglomerate-bearing intervals are more abundant in the eastern part of the graben near the Wasatch Range, whereas mudstone-rich intervals are more abundant to the west (Feth and others, 1966). Seismic imaging reveals widespread, gently dipping reflectors in the basin fill (Cook and others, 1967; Glenn and others, 1980), which appear related to downward increases in seismic velocity from about 1,800 to 2,500 meters/second (6,000-8,000 ft/sec) and to downward increases in specific gravity from about 1.8 to 2.3, based partly on geophysical logs from deep drill holes in nearby areas (McNeil and Smith, 1992). These changes are probably related to increasing lithification with depth. Total thickness of late Tertiary basin fill is estimated to be up to 2,400 meters (8,000 ft) in the central part of the Wasatch Front graben.

Quaternary Basin Fill (Qb)

Quaternary basin-fill deposits consist of weakly to nonlithified sediments and thin tuffaceous layers that accumulated during pre-Bonneville lake cycles, and have been encountered in wells in the Ogden area (Feth and others, 1966; Sprinkel, 1993). These deposits contain complexly interfingering, overall westward-fining intervals of gravel, sand, silt, and clay deposited in lacustrine and fluvial environments. The deposits can be crudely divided into a lower interval, the Delta aquifer, a middle confining interval, the Sunset aquifer, and an upper confining interval (Feth and others, 1966). The lower interval consists mostly of thin-bedded silt and fine sand partly deposited in marginal lacustrine environments (Sprinkel, 1993). The Delta aquifer consists mostly of interbedded cobble to pebble gravel and gravelly sand deposited in fluvial environments. Gravel contains subangular to subrounded clasts of quartzite, carbonate, and Precambrian igneous and metamorphic rock (Sprinkel, 1993). The top of the aquifer lies about 150 to 200 meters (500-700 ft) below the ground surface, and has an altitude decreasing from about 1,280 meters (4,200 ft) in the central part of the quadrangle to about 1,100 meters (3,600 ft) west of the quadrangle (Feth and others, 1966). The aquifer is about 15 to 60 meters (50-200 ft) thick and forms a westward-thinning wedge. The middle confining interval consists mostly of thin-bedded silt and fine sand with some gastropods and roots, and rare layers of pebbly sand, which were deposited in marginal lacustrine and fluvial environments (Sprinkel, 1993). The Sunset aquifer consists of pebble gravel, pebbly sand, and sand deposited in fluvial environments. Sand is quartz-rich, medium to coarse grained, and well sorted. The top of the aquifer lies about 60 to 120 meters (200-400 ft) below the ground surface, and has an altitude decreasing from about 1,310 meters (4,300 ft) near the central part of the quadrangle to about 1,220 meters (4,000 ft) west of the quadrangle (Feth and others, 1966). The aquifer is about 15 to 60 meters (50-200 ft) thick and forms a westward-thinning wedge. The upper confining interval consists mostly of thin-bedded silt and sand likely deposited in brackish lacustrine environments. The contact with overlying Lake Bonneville deposits probably lies about 30 to 100 meters (100-300 ft) below the ground surface in the western part of the quadrangle, but its position is uncertain near the mountain front (Feth and others, 1966).

The contact between Quaternary and Tertiary basin fill is interpreted to correspond to a widespread reflector observed along a seismic line near the southern boundary of the quadrangle (reflector B of Glenn and others, 1980), which may represent a downward change from weakly or non-lithified sediments to lithified deposits. This change, however, is probably gradational and may not correspond to the same stratigraphic interval in all areas. This reflector correlates with a downward decrease in caliper logs and increase in electrical resistivity below a depth of about 420 meters (1,400 ft) in the Hill AFB Test Hole #2 (section 5, T. 4 N., R. 1 W., Salt Lake Base Line and Meridian, in the adjoining Kaysville quadrangle), probably associated with an increase in lithification. For comparison, the Bureau of Reclamation Test Hole #5B (section 16, T. 5 N., R. 2 W., Salt Lake Base Line and Meridian, in the adjoining Roy quadrangle) first encountered thick lithified deposits at a depth of 480 meters (1,600 ft) (Feth and others, 1966). Quaternary (pre-Bonneville) basin fill is up to 400 meters (1,300 ft) thick, and is overlain by up to 100 meters (300 ft) of Lake Bonneville sediments.

Quaternary Surficial Deposits

Quaternary surficial deposits cover most of the western part of the quadrangle, and locally overlie bedrock in the eastern part of the quadrangle. The distribution and characteristics of these deposits were controlled by complex interactions of lacustrine, fluvial, mass-wasting, and glacial processes that changed over time, partly in response to climatic and tectonic controls during the late Pleistocene and Holocene. Repeated slip along the Wasatch fault zone, combined with erosion and mass-wasting processes, produced a steep, west-facing mountain front along the Wasatch Range with locally greater than 1,500 meters (5,000 ft) of topographic relief. Fault slip also down-dropped the basin to the west, where lacustrine, deltaic, and alluvial sediments accumulated during rising and falling lake and stream levels. Because of complex relationships between processes, a general discussion of the late Quaternary history in the Ogden area is presented to provide a framework, followed by descriptions of surficial map units.

Late Quaternary Geologic History

Many Quaternary surficial features in the Ogden area are associated with lacustrine processes during the transgression and regression of Lake Bonneville (figure 8). The following history is summarized from Currey and others (1984), Oviatt and others (1992), and Oviatt and others (1997). Overall, the lake had a transgressive phase from about 28 to 14.5 ka, and a regressive phase from about 14.5 to 10 ka. In detail, waters

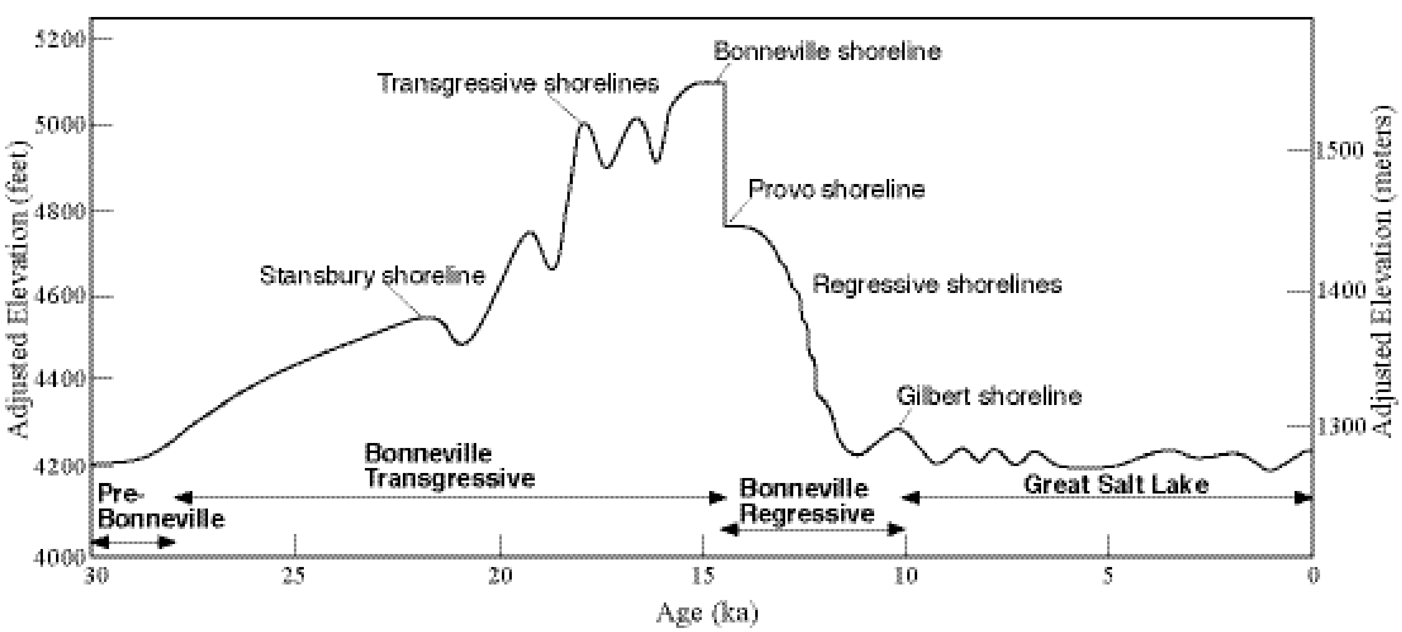

Figure 8. *Rise and fall of Lake Bonneville between about 28 and 10 ka, and of Great Salt Lake (modified from Oviatt and others, 1997). Elevations have been adjusted to remove effects of isostatic rebound.*

began rising at 28 ka from an initial level of about 1,280 meters (4,200 ft), then underwent a period of stabilization from 22 to 20 ka that formed the Stansbury shoreline. This was followed by continued overall rise with several minor oscillations that formed local transgressive shorelines. The lake reached its maximum extent from 15 to 14.5 ka at a level of about 1,550 meters (5,090 ft), forming the Bonneville shoreline. This lake level was controlled by a northern outlet to the Snake River drainage over a threshold in unconsolidated deposits near Red Rock Pass, Idaho. At 14.5 ka this threshold failed catastrophically and the lake level dropped rapidly. The lake remained stable from 14.5 to 14 ka at a level of about 1,445 meters (4,740 ft), controlled by an outlet over a bedrock threshold near Red Rock Pass, forming the Provo shoreline. From 14 to 11 ka the lake level decreased to elevations as low as about 1,280 meters (4,200 ft) due to climatic changes, forming multiple recessional shorelines. A small rise in lake level to 1,295 meters (4,250 ft) between 11 and 10 ka formed the Gilbert shoreline. During Lake Bonneville transgression and regression, widespread deposits of gravel-bearing lacustrine sediments accumulated and were reworked in environments of higher energy near shorelines, while fine-grained lacustrine sediments accumulated in quieter environments in deeper waters away from shorelines. During the past 10,000 years, the highly saline Great Salt Lake has fluctuated at levels between 1,274 and 1,286 meters (4,180 and 4,221 ft) (Murchison, 1989).

Shorelines produced during transgression and regression of Lake Bonneville are well preserved in the Ogden area, but current elevations have been modified by isostatic rebound and by deformation associated with slip along the Wasatch fault zone. The Stansbury shoreline is not present in the quadrangle. A transgressive shoreline and associated delta deposits near the mouth of Weber Canyon are at a current elevation of about 1,520 meters (5,000 ft). The Bonneville shoreline corresponds to a well-developed bench along the mountain front in the Ogden area at a current elevation of 1,590 meters (5,210 ft) in the footwall of the Wasatch fault zone. The Provo shoreline has a current elevation of 1,460 meters (4,800 ft) in the hanging wall of the Wasatch fault zone in the southern part of the quadrangle where the shoreline extends outward from the mountain front. The shoreline is more difficult to recognize in the northern part of the quadrangle due to its proximity to fault scarps near the mountain front, but appears to be at a current elevation of about 1,470 meters (4,840 ft) in the footwall of the Wasatch fault zone. The Gilbert shoreline is developed at lower elevations west of the quadrangle.

Episodes of deposition and erosion occurred along rivers and streams in the Ogden area in response to changing base levels during transgression and regression of Lake Bonneville, and tectonic activity along the Wasatch fault zone. The Weber and Ogden Rivers cut deep canyons across the Wasatch Range as the range was uplifted, starting in the Miocene (Naeser and others, 1983). During transgression of Lake Bonneville, sediments from these rivers were deposited in deltas that retreated eastward, reaching into Morgan and Ogden Valleys during the Bonneville highstand. During regression, base level was lowered and older sediments were locally eroded and redeposited in westward-prograding deltas west of the Wasatch mountain front. Mountain streams also cut smaller canyons as the range was uplifted, and alluvial fans of various ages formed from multiple runoff and debris-flow events at the mouths of these canyons. During the Holocene, rivers and streams continued to respond to lower base levels of Great Salt Lake by further downcutting into older lacustrine, deltaic, and alluvial deposits, leaving terraces and forming large channels.

Mass-wasting processes have been important in modifying slopes within the actively uplifting Wasatch Range, including development of large landslide complexes along some steeper slopes, episodic debris flows along some stream channels, and widespread creep within hillslope colluvium. Multiple faceted spurs along the mountain front may also be partly related to repeated slope failures. Earthquake-induced lateral spreads, some having undergone multiple periods of movement, formed locally in fine-grained lacustrine deposits west of the mountain front (Harty and Lowe, 2003). Additionally, younger landslides developed along slopes where rivers incised fine-grained lacustrine and delta deposits west of the mountain front.

Glacial processes were important in higher parts of the Wasatch Range during cooler Pleistocene episodes, with development of cirque basins and deposition of till. Madsen and Currey (1979) identified two ages of glacial deposits in the Little Cottonwood Canyon area near Salt Lake City: (1) locally preserved, much older till with highly weathered clasts and well-developed soil horizons that was probably deposited about 150 ka (Bull Lake glaciation); and (2) younger till with moderately weathered clasts that was deposited between 26 and 8 ka (late Pinedale glaciation). The maximum extent of late Pinedale glaciation probably occurred about 20 ka, with formation of terminal moraines, while recessional moraines formed during a deglacial pause at 13 ka; fresh-appearing, youngest till was deposited in upper parts of some cirque basins during another deglacial pause, probably at about 8 ka (Madsen and Currey, 1979). Several episodes of slightly cooler than average temperatures also occurred during Neoglacial time between 5 and 2 ka, with local development of rock glaciers at the heads of some cirque basins.

Quaternary map units in the quadrangle are described below. These map units are grouped based on dominant process, including lacustrine (l), deltaic (d), alluvial (a), mass-wasting (m), and glacial (g), and further subdivided based on deposit type and age, including pre-Bonneville (5), Lake Bonneville transgressive (4), Lake Bonneville regressive (3), Holocene (older) (2), and Holocene (younger) (1).

Lacustrine Gravel-Bearing Deposits, Bonneville Transgressive (Qlg$_4$)

This unit consists of gravel-rich layers with varying amounts of finer grained intervals that increase in abundance away from the mountain front and in interfluve areas. Gravel-rich layers are moderately to well sorted, medium to thick bedded, have primary dips locally greater than 10 degrees, and consist of pebble to cobble clasts with minor to moderate amounts of sandy matrix. Clasts are mostly subrounded to rounded, but subangular clasts are present locally where alluvial-fan and landslide deposits were reworked along shorelines. Clast types are mostly fragments of Precambrian metamorphic and igneous rock and Paleozoic sedimentary rock derived from the mountain front. Gravel-rich layers are best developed along the Bonneville shoreline at an elevation of about 1,590 meters (5,210 ft). Finer grained intervals consist of thin-bedded, pink to gray, calcareous silt, sand, and gravelly sand. This unit is exposed along the mountain front at elevations between the Provo and Bonneville shorelines, and grades westward into fine-grained lacustrine deposits (Qlf_4) that lack gravel layers. The unit may also locally include some fan-delta deposits near the mouths of mountain canyons. Total thickness of the unit is locally greater than 60 meters (200 ft) along the mountain front north of the mouth of Weber Canyon.

Lacustrine Fine-Grained Deposits, Bonneville Transgressive (Qlf_4)

This unit consists of varying amounts of sand, silt, and clay, and includes both very fine grained intervals deposited in quiet, deep waters, as well as intervals deposited as delta bottomset beds. Very fine grained intervals consist of pink to gray, laminated to thin-bedded, calcareous silt, clay, and minor marl, which contain fragments of ostracodes, including *Candona* sp. and *Limnocytherc* sp. (Feth and others, 1966). Bottomset intervals consist of rhythmically interlayered sand and silt beds with thicknesses of about 2.5 to 15 centimeters (1-6 in). Sand beds are moderately to well sorted, brown to gray, fine to medium grained, and display small-scale cross-bedding. Very fine grained intervals are most abundant farther northwest away from the mountain front, whereas bottomset deposits are more abundant near the mouth of Weber Canyon. The unit is well exposed near the mouth of Weber Canyon, above and east of the Provo shoreline, within a series of ridges up to 60 meters (200 ft) high and 1 kilometer (0.6 m) long. Farther north and west, the unit is largely covered by younger lacustrine and deltaic deposits, but is locally exposed in landslide main scarps along slopes cut by the Weber and Ogden Rivers. Total thickness of the unit may be as great as 150 meters (500 ft) near the mouth of Weber Canyon, which includes up to 90 meters (300 ft) of deposits preserved in the subsurface, but thickness of this unit appears to decrease toward the north and west.

Lacustrine Gravel-Bearing Deposits, Bonneville Regressive (Qlg_3)

This unit consists of gravel-rich layers with varying amounts of finer grained intervals, and formed partly by reworking of Bonneville-transgressive deposits. This unit is poorly exposed along the mountain front at elevations below the Provo shoreline in the northern part of the quadrangle. Gravel-rich layers are well to moderately sorted and consist of rounded to subangular, pebble to boulder clasts with variable amounts of sandy matrix. Finer grained intervals are thin bedded and consist of pink to gray, calcareous silt and sand, with some pebble clasts. This unit grades westward into fine-grained lacustrine deposits (Qlf_3) that lack gravel layers. This unit is probably less than 6 meters (20 ft) thick in most areas.

Lacustrine Fine-Grained Deposits, Bonneville Regressive (Qlf_3)

This unit includes sand-rich intervals that accumulated during reworking of older lacustrine deposits, as well as finer grained intervals deposited as delta bottomset beds and in deeper waters. Sand-rich intervals are well exposed in an area west of and below the Provo shoreline in the southern part of the quadrangle where the shoreline bends outward from the mountain front. Sand is brown to gray, moderately to well sorted, fine to medium grained, and is interlayered with some thin silt beds. The sand was probably deposited during reworking of older lacustrine deposits by nearshore waves and currents in moderate-energy environments near the Provo and other regressive shorelines. Farther north and west the unit consists of finer grained intervals with ostracodes of *Cytherissa* sp., and includes fine sand and silt deposited as bottomset beds, and pink to gray, calcareous silt and clay deposited in deeper waters (Feth and others, 1966). These finer grained intervals are largely covered by younger deposits, but are locally exposed in landslide main scarps along slopes cut by the Ogden and Weber Rivers. Thickness of the sand-rich deposits near the Provo shoreline is less than 6 meters (20 ft), but the thickness of finer grained deposits to the northwest is uncertain.

Deltaic Deposits, Bonneville Transgressive (Qd_4)

This unit consists mostly of clast-supported pebble and cobble gravel and gravelly sand deposited as topset beds. Gravel is moderately to well sorted with small amounts of sandy matrix, medium to thick bedded, and displays weak pebble imbrication and local channels. Clasts are mostly subrounded to rounded and consist of Precambrian metamorphic and igneous rock derived from the Wasatch Range, and some Paleozoic to Mesozoic sedimentary rock derived from the Weber River drainage basin. These deposits cover small areas northwest of the mouth of Weber Canyon at an elevation of about 1,520 meters (5,000 ft), which corresponds to a transgressive shoreline. Thickness of exposed topset beds in this unit is about 2 to 4 meters (7-13 ft).

Deltaic Deposits, Bonneville Regressive (Qd_3)

This unit consists mostly of sandy foreset and gravelly topset beds that form a large, gently west-sloping, composite delta between the Weber and Ogden Rivers. Foreset deposits consist of rhythmically interlayered beds of fine to medium, moderately to well-sorted sand with abundant ripples that are 2.5 to 15 centimeters (1-6-in) thick, and beds of silt to clay that are 1 to 5 centimeters (0.4-2 in) thick. Foreset beds have primary dips from about 5 to 10 degrees. Topset deposits consist mostly of clast-supported pebble and cobble gravel, with some gravelly sand. Gravel is moderately to well sorted with small amounts of sandy matrix, medium to thick bedded, and displays weak pebble imbrication and local channels. Clasts are mostly subrounded to rounded and have maximum sizes of about 30 centimeters (12 in). Clasts consist of Precambrian metamorphic and igneous rock derived from the Wasatch Range, Paleozoic to Mesozoic sedimentary rock derived from the Weber River drainage basin, and Late Proterozoic to Paleozoic sedimentary rock derived from the Ogden River drainage basin. The unit includes some fan-delta deposits near the mouth of Taylor Canyon and deltaic deposits that were reworked along recessional shorelines. Topset gravels are up to 6 meters (20 ft) thick, and foreset deposits vary from up to 25 meters (80 ft) thick in western parts of the quadrangle to being absent near the mouth of

Weber Canyon east of the Provo shoreline where gravel was deposited in channels incised in older lacustrine deposits.

The unit also includes gravels along multiple terraces that formed during downcutting of the Weber River. The terraces are 30 to 90 meters (100-300 ft) above the modern Weber River, and are graded to various lower delta levels and regressive shorelines exposed to the west in the Roy quadrangle. Gravel is moderately to well sorted with some sandy matrix, medium to thick bedded, and displays pebble imbrication and local channels. Clasts are mostly subrounded to rounded, pebble to cobble size, and consist mostly of Precambrian metamorphic and igneous rock derived from the nearby Wasatch Range and Paleozoic to Mesozoic sedimentary rock fragments derived from the upper Weber River drainage basin. Where exposed, terrace gravels are up to 6 meters (20 ft) thick.

Alluvial Gravel of Ogden Canyon (Qag_4)

The lower part of this unit consists mostly of clast-supported gravel, with sand intervals becoming increasingly abundant toward the upper part of the unit, recording an overall fining-upward sequence. Gravel is overall moderately sorted, thick bedded, and consists mostly of cobbles and pebbles with variable amounts of sandy matrix. Boulder clasts up to 1 meter (3 ft) in size are present at the base of the unit. Clasts include subangular to angular Paleozoic limestone and shale fragments locally derived from the Ogden Canyon area, and subrounded to rounded, Late Proterozoic to Paleozoic sedimentary rock fragments derived from the upper parts of the Ogden River drainage basin. Pebble imbrication and channels in parts of the unit indicate fluvial deposition. The gravel is weakly to strongly cemented by calcite. Sand intervals are coarse to fine grained, medium to thin bedded, and some finer grained layers near the top of the unit may have been deposited in shallow lake waters during transgression. This unit is preserved as small erosional remnants along the western part of Ogden Canyon, where one section of gravel capped by sand is about 60 meters (200 ft) thick. At the mouth of Ogden Canyon (SW1/4 section 23, T. 6 N., R. 1 W., Salt Lake Base Line and Meridian), remnants of gravels too small to show at map scale are displaced by the Wasatch normal fault zone and juxtaposed against fine-grained lacustrine deposits to the west, indicating that the gravels are older than the fine-grained deposits.

Older Alluvial Terrace Deposits, Holocene (Qat_2)

This unit consists mostly of clast-supported, pebble to cobble gravel and minor gravelly sand in terraces and benches about 9 to 15 meters (30-50 ft) above the modern Weber River. Terraces were deposited as rivers became graded to base levels below the Gilbert shoreline. Gravel is moderately to well sorted, medium to thick bedded, contains subangular to rounded clasts, and displays pebble imbrication and local channels. Clasts consist mostly of Paleozoic to Mesozoic sedimentary and Precambrian basement rock. Where exposed, this unit is less than 6 meters (20 ft) thick.

Stream Alluvium, Undivided (Qal)

This general unit consists mostly of gravel, gravelly sand, and finer grained overbank deposits along active stream channels and in inactive, low-level benches. Gravel is clast-supported, mostly pebble to cobble sized, moderately to well sorted with some silty to sandy matrix, medium to thick bedded, and displays clast imbrication and channels. Clasts range from subangular to rounded and have compositions that reflect source areas of different drainage basins, including abundant Precambrian basement rock along mountain streams, mixed Paleozoic to Mesozoic sedimentary rock and Precambrian basement rock along the Weber River, and abundant Late Proterozoic to Paleozoic sedimentary rock along the Ogden River. Thin-bedded sand to silt represent overbank deposits. The undivided unit is mapped along parts of rivers and streams where separate alluvial deposits are too narrow to map separately. The unit includes minor matrix-supported debris-flow deposits along mountain stream channels. The unit is up to 12 meters (40 ft) thick.

Older Stream Alluvium, Holocene (Qal_2)

This unit consists mostly of gravel and minor gravelly to silty sand. It forms inactive benches about 3 to 9 meters (10-30 ft) above the Weber and Ogden Rivers, and inactive margins along some ephemeral streams west of the mountain front. Gravels have characteristics similar to those described for undivided stream alluvium, with clast compositions that reflect source areas of the different drainage basins. Where exposed the unit is less than 6 meters (20 ft) thick.

Younger Stream Alluvium, Holocene (Qal_1)

This unit consists mostly of gravel and some finer grained overbank deposits along modern channels and recently active floodplains of the Weber River, Ogden River, and active streams west of the mountain front. However, parts of some floodplains are no longer active due to flood-control measures. Gravels have characteristics similar to those described for undivided stream alluvium. Overbank deposits consist of thin-bedded sand and silt that tend to support thicker vegetation. This unit is estimated to be about 3 to 6 meters (10-20 ft) thick.

Alluvial-Fan Deposits, Undivided (Qaf)

This general unit consists of complexly interlayered alluvial gravels and debris-flow deposits in fan-shaped landforms. In general, alluvial gravels are clast supported, thin to thick bedded, moderately sorted, and contain angular to rounded, pebble to cobble clasts with variable amounts of sandy to silty matrix. Debris-flow deposits tend to be matrix supported, unstratified, poorly to non-sorted, and contain angular to subangular, pebble to boulder clasts up to 2 meters (6 ft) in size with abundant muddy matrix. In general, fans were deposited at the mouths of most larger mountain streams, and locally where small ephemeral streams reworked lacustrine deposits. The undivided unit is mapped where morphologic and crosscutting relations of fans are ambiguous, such that relative age cannot be assigned. Exposed thickness of these fan deposits is less than 9 meters (30 ft).

Alluvial-Fan Deposits, Bonneville Transgressive (Qaf_4)

These deposits form fans that are graded to the Bonneville shoreline, generally display subdued morphology, and are deeply incised by modern streams. The fans consist of complexly interlayered alluvial gravels and debris-flow deposits, like those described for undivided alluvial fans. The transgressive fans, however, locally display increased rounding of clasts and decreased amounts of fine-grained matrix near the Bonneville shoreline, where fans were reworked by lake waves, and fan deposits grade locally into gravel-bearing lacustrine deposits (Qlg_4). Most fans accumulated during multiple runoff and debris-flow events over a long period of transgression. Total thickness of these fans may locally be greater than 60 meters (200 ft), but it is difficult to determine.

Alluvial-Fan Deposits, Bonneville Regressive (Qaf_3)

These deposits form fans that are graded to the Provo or recessional shorelines, display subdued channels and levees, and are locally incised into transgressive fans (Qaf_4), but are incised by modern streams. Regressive fans also consist of complexly interlayered alluvial gravels and debris-flow deposits, like those of the transgressive fans, but gravels contain more rounded clasts derived from reworking of older lacustrine gravels. Regressive fans locally display increased rounding of clasts and decreased amounts of fine-grained matrix near the Provo shoreline related to reworking by lake waves. Exposed thickness of these fans is less than 9 meters (30 ft).

Older Alluvial-Fan Deposits, Holocene (Qaf_2)

These deposits form fans that are slightly incised by modern streams and display moderately fresh channels and levees. These fan deposits also consist of complexly interlayered alluvial gravels and debris-flow deposits. Alluvial gravels contain a mixture of angular to subrounded stream clasts and reworked, rounded lacustrine clasts, with variable amounts of sandy to silty matrix. Debris-flow deposits contain mostly angular clasts with abundant muddy matrix. Exposed thickness of these fans is generally less than 6 meters (20 ft). Fault scarps are about 3 to 9 meters (10-30 ft) high where the Wasatch fault zone cuts this unit, indicating deposition prior to the last several surface faulting events on the Wasatch normal fault zone.

Younger Alluvial-Fan Deposits, Holocene (Qaf_1)

These deposits form active fans that are graded to modern stream or local base levels, and display relatively sharp channels and levees. These fans consist of interlayered gravel and debris-flow deposits. Alluvial gravels contain a mixture of angular to subrounded and reworked, rounded clasts, and debris-flow deposits contain mostly angular clasts with abundant muddy matrix. Boulders up to 2 m (6 ft) in size protrude above some fan surfaces. Thickness of these deposits is probably less than 6 meters (20 ft). Fault scarps are less than 3 meters (10 ft) high where the Wasatch fault zone cuts this unit, and in places fan deposits cover the fault trace without being offset, indicating active deposition within the past 1,000 years, as discussed in more detail in the Geologic Hazards section.

Landslide Deposits, Undivided (Qms)

This general unit consists of unsorted, unstratified, clay- to boulder-rich deposits and displaced bedrock blocks. Clasts are angular and have compositions that reflect local source materials. This undivided unit is mapped in the Wasatch Range where age relations are uncertain. Deposits display distinct hummocky topography, local seeps, and generally dense vegetation, and many are on steeper, northerly facing slopes. Areas with indistinct hummocky topography that may include older landslides and hillslope colluvium are mapped as Qms?. Many deposits probably have undergone recurrent movement, and movement has been characterized by sliding, slumping, flow, and ongoing creep.

Landslide Deposits, Pre-Bonneville to Bonneville Transgressive (Qms_5)

These deposits are locally cut by and reworked along the Bonneville shoreline, and toes of slides are locally covered by thin lacustrine deposits, indicating they moved before Lake Bonneville rose to its highest level. Parts of some slides were also active during Bonneville transgression, as recorded by interlayered landslide and fine-grained lacustrine deposits observed in trenches near Weber State University (west-central part of section 10, T. 5 N., R. 1 W., Salt Lake Base Line and Meridian), and parts of some slides may have been reactivated more recently. This unit consists of unstratified clay- to boulder-rich deposits with very large bedrock blocks that have been variably translated and rotated, and includes the Beus Canyon, University, and Dry Canyon slides of Pashley and Wiggins (1972). Deposits display subdued hummocky topography, have subdued main scarps, and lie along steeper slopes above and near the Bonneville shoreline. Thickness of deposits is likely highly variable and may locally be greater than 20 meters (70 ft). The particularly large Beus Canyon landslide complex extends about 1.2 kilometers (0.7 mi) west of the mountain front beneath a thin mantle of lacustrine sediments (Qlg_4/Qms_5 and Qlf_4/Qms_5 on plate 1). Areas that have randomly oriented bedrock blocks but lack distinct hummocky topography are mapped as Qms_5?. Parts of some landslides were reactivated along the mountain slope during the Holocene and are discussed below (Qms_2 on plate 1).

Landslide Deposits, Bonneville Regressive (Qms_3)

This unit represents a single large deposit consisting of clay, silt, fine sand, and minor gravel that was displaced in a liquefaction-induced flow slide and lateral spread, probably during one or more large paleoearthquakes. The unit displays disrupted bedding, locally developed sand dikes, landslide-related faults, and disharmonic folds. Geomorphic features of this landslide include main scarps, variably oriented internal scarps and ground cracks, closed depressions, hummocks, and transverse lineaments, suggesting complex failure by flow, translational sliding, and slumping (Harty and Lowe, 2003). The unit forms an overall gently northwest-sloping surface below the Provo shoreline. Recessional shorelines are slightly displaced and rotated on the slide, but the slide is deeply incised by modern stream channels, indicating ground failure occurred after regression from the Provo level and before major Holocene stream downcutting. The depth to the basal detachment under most of the slide is uncertain, and the unit may be as much as 20 meters (70 ft) thick.

Older Landslide Deposits, Holocene (Qms_2)

This unit includes (1) widespread slides that developed mostly within finer grained lacustrine and deltaic deposits along moderate slopes that have been incised by the Ogden River, Weber River, and other streams, and (2) reactivated parts of older slides in the Wasatch Range. Type 1 deposits consist mostly of sand, silt, and clay with locally disrupted bedding and landslide-related faults (Feth and others, 1966). These deposits have hummocky topography, subdued to moderately fresh main scarps, and locally form amphitheater-shaped regions. Springs and seeps exist where slides have cut perched water tables. Type 2 slides consist of unstratified clay- to boulder-rich deposits with large bedrock blocks. These slides display fresher appearing hummocky topography compared to the older slides they reactivated. Type 1 deposits formed by widespread slumping, flow, and local sliding, whereas type 2 deposits formed mostly by sliding with local flow.

Younger Landslide Deposits, Holocene (Qms_1)

This unit consists of slides that have experienced relatively recent movement and display fresh scarps, local ground cracks, and distinctly hummocky surfaces. This unit includes (1) recently reactivated parts of older slides within lacustrine and delta deposits, and (2) small reactivated parts of older slides and small slides in colluvium in the Wasatch Range and along the mountain front. Type 1 slides consist mostly of sand, silt, and clay, with highly disrupted bedding, local seeps, and denser vegetation compared to nearby areas. These slides tend to form in areas with shallow ground water, and have overall moderate slopes (Pashley and Wiggins, 1972; Lowe and others, 1992). Type 2 slides consist of clay- to boulder-rich diamicton, with compositions that reflect local source materials. These deposits formed by widespread slumping, earthflow, and sliding. Specific slides are further discussed in the Geologic Hazards section.

Debris-Flow Deposits (Qmf)

This unit consists of matrix- to clast-supported, cobble to boulder gravel with variable amounts of sandy to clayey matrix. Deposits are generally poorly to non-sorted, non-layered, and locally display levees and channels. The unit is present in some mountain canyons, and contains multiple flows of various ages, including flows graded to the Bonneville or Provo shorelines, Holocene flows inset into older flows, and historical flows. Because individual flows are small relative to map scale and correlating ages of flows between canyons is difficult, all flows are grouped into one map unit. This unit locally grades upslope into colluvium, talus, and older landslide deposits that were sources for flows in the upper parts of canyons, and downslope into alluvial fans at the mouths of the canyons. Thickness of debris flows is generally less than 9 meters (30 ft).

Talus (Qmt)

This unit consists of angular, pebble- to boulder-sized rock debris with little or no matrix. Talus forms rocky slopes with little or no vegetation at the base of bedrock cliffs and steeper slopes developed mainly in the Tintic Quartzite and Farmington Canyon Complex. Talus grades into colluvium that has been partly stabilized by vegetation. Thickness is uncertain, but is probably less than 15 meters (50 ft) in most areas.

Avalanche Deposits (Qma)

This unit consists of rock, soil, and vegetative debris within avalanche chutes along some higher-elevation, north-facing slopes. Deposits are unsorted, unlayered, and contain angular boulders to 2 meters (7 ft) in size, with variable amounts of matrix and debris. Avalanche deposits are only mapped along one large, distinct chute and include material reworked by slope wash. Smaller avalanche deposits are included with colluvium. Thickness is uncertain, but is probably less than 15 meters (50 ft) in most areas.

Colluvium (Qc)

Colluvium consists of variably clayey to sandy, pebble to boulder gravel and diamicton, which has been moved and deposited mostly by slope wash and creep. The unit also includes small areas of debris and alluvial cones, talus, slides, alluvium, avalanche deposits, and bedrock exposures. Deposits are matrix to (rarely) clast supported, generally poorly to unsorted, weakly to non-stratified, and contain angular to subangular clasts with variable amounts of sandy to clayey matrix. This unit is mapped along vegetated slopes in the Wasatch Range, and along some scarps of the Wasatch fault zone. Although parts of this unit locally contain small landslides, it is distinguished from mapped landslide deposits (Qms) by a lack of well-developed hummocky topography. Total thickness of colluvium is probably less than 15 meters (50 ft) in most areas.

Colluvium and Alluvium, Undivided (Qac)

This unit includes hillslope colluvium and stream alluvium, with small areas of debris cones, slides, and bedrock exposures. Deposits consist of non-sorted, unstratified, clay- to boulder-rich diamicton, and moderately sorted, cobble gravel to sand with subangular to subrounded clasts. The unit is mapped along channels and slopes near some ephemeral streams in the Wasatch Range. Modern channels are locally incised as much as 6 meters (20 ft) into these deposits, indicating a long history of accumulation and recent local erosion. Total thickness of this unit is probably less than 15 meters (50 ft) in most areas.

Glacial Till, Older (Qgt_o)

This unit consists of unsorted, unlayered till containing clasts, mostly from 0.03 to 3 meters (0.1-10 ft) in size, with variable amounts of silty to sandy matrix. This unit contains moderately weathered clasts, displays distinct soil development, and has some subdued, partly eroded ridges that are too small to map at 1:24,000 scale. This unit is present in cirque basins along higher parts of the Wasatch Range. Older glacial till is also present to the east in the Snow Basin quadrangle within parts of the Mount Ogden, Middle, and Strawberry bowls. Clasts consist of Precambrian metamorphic and igneous rock and Tintic Quartzite derived from the cirque basins. In places, the unit is partly covered by small patches of unmapped colluvium. This unit is similar to glacial deposits elsewhere in the Wasatch Range that contain moderately weathered clasts and are related to late Pinedale glaciation, which reached its maximum during Bonneville transgression (about 20 ka) (Madsen and Currey, 1979).

Glacial Till, Younger (Qgt$_y$)

This unit consists of unsorted, unlayered till containing angular clasts, mostly from 0.1 to 6 meters (0.3-20 ft) in size, with small amounts of silty to sandy matrix. This unit contains fresh-appearing clasts, displays sharp ridges up to 10 meters (30 ft) high, contains large protruding boulders, and displays less soil development and is covered by less vegetation than older glacial till. This unit is mapped in the upper part of the Mount Ogden bowl and contains clasts derived from the Tintic Quartzite at the head of the bowl. This unit is similar to other fresh-appearing till found in the uppermost parts of some canyons along the Wasatch Range, and may have formed during a deglacial pause at about 8 ka (Madsen and Currey, 1979) or during a small Neoglacial advance (younger than 5 ka).

Rock-Glacier Deposits (Qgr)

This unit consists of unlayered, bouldery debris with very little to no matrix. The debris contains highly angular fragments, mostly from 0.1 to 6 meters (0.3-20 ft) in size, that were derived from nearby, steep exposures of Tintic Quartzite. Deposits display very sharp ridges up to 10 meters (30 ft) high, small depressions, and limited vegetative cover with little to no soil development. Rock-glacier deposits are above other glacial deposits along east- and north-facing slopes within the Mount Ogden and Strawberry bowls. These deposits are similar to rock glaciers described within high basins in Little Cottonwood Canyon (Madsen and Currey, 1979) and may have formed during Neoglacial time (younger than 5 ka and postdating younger glacial till).

Artificial Fill (Qf)

This unit consists of material that was excavated, reworked, or imported during construction of roads and railways along Weber Canyon, and near an abandoned landfill west of the Ogden River. Smaller areas of fill and disturbed ground were not mapped.

STRUCTURAL GEOLOGY

The Ogden area lies in a region with complex structural features, which are mostly related to three major episodes of mountain building (figures 1 and 9). The first episode occurred during the Early Proterozoic as island arcs were accreted onto the southern margin of the Wyoming Province, resulting in intense deformation, approximately synchronous with high-grade metamorphism and widespread igneous intrusion (Bryant, 1988b). The second episode occurred during mostly Cretaceous shortening and development of the Sevier fold and thrust belt (Camilleri and others, 1997). A third episode, which continues today, involves late Cenozoic extension and development of the Basin and Range Province (Smith and Bruhn, 1984).

Precambrian Structures

Precambrian structures within the quadrangle include foliation, gneissic layering, lineations, and complex minor folds within basement rocks of the Farmington Canyon Complex. A dominant, high-grade foliation, defined by preferred orientation of platy minerals and aggregates, is widely developed within both granitic gneiss and paragneiss [migmatitic gneiss, quartz-rich gneiss, and biotite schist (fig 3)]. Gneissic layering is generally developed parallel to the foliation, and likely formed by transposition of primary layering during isoclinal folding, partial melting, intrusion of igneous dikes, and metamorphic differentiation, such that evidence for primary stratigraphic markers has been almost completely obscured. Within paragneiss, an older foliation and parallel compositional layering are locally preserved in hinges of tight to isoclinal minor folds, but this foliation is transposed into parallelism with dominant foliation along fold limbs, forming a composite fabric. Locally preserved interference patterns of some minor folds also indicate a complex deformation history. The dominant foliation within paragneiss is parallel to that within granitic gneiss, but isoclinal folds are not found within granitic gneiss, possibly indicating a simpler deformation history. A dominant lineation, defined by preferred orientation of linear mineral aggregates and hornblende, is also widely developed, and is parallel to hinges of tight to isoclinal minor folds in paragneiss. The dominant foliation is associated with growth of biotite and sillimanite in migmatitic gneiss and biotite schist (paragneiss), and with hornblende in granitic gneiss. These relations indicate that the dominant foliation formed broadly synchronously with the main phase of Early Proterozoic metamorphism and intrusion of granite plutons.

The dominant foliation in basement rocks of the hanging wall of the Ogden floor thrust fault is overall east striking and steeply dipping in areas north of Weber Canyon, and overall east to southeast striking and moderately south to gently southwest dipping in areas along and south of the canyon (plate 1), with poles to foliation defining a diffuse girdle pattern having a gently southwest-plunging axis (figure 10). The dominant lineation and minor fold hinge lines are mostly gently southwest plunging in these basement rocks. In detail, the dominant foliation and lineation are locally rotated about younger, open to tight, mostly northwest-plunging minor folds, and a younger, weak foliation is rarely developed in younger fold hinges. The dominant foliation in basement rocks of the footwall of the Ogden floor thrust is overall gently dipping, but is rotated about younger, open to tight, mostly northwest-plunging minor folds, with poles to foliation defining a diffuse girdle pattern having a gently northwest-plunging axis (figure 10). A younger, mostly northwest-striking, weak foliation is also developed in some younger fold hinges. Regional warping also produced some variation in orientations of foliations and lineations in all basement rocks. Bryant (1988a) interpreted the presence of several large-scale folds based on outcrop patterns of granitic gneiss, assuming that the contact of granitic gneiss with other units is parallel to gneissic layering. Alternatively, outcrop patterns of granitic gneiss seen in plate 1 may be related to primary, variably cross-cutting igneous contacts.

Cretaceous Shortening

Cretaceous structures in the quadrangle include the Ogden thrust fault system, shear and fault zones in basement rocks, and minor folds, cleavage, and faults in the sedimentary cover, which all formed during growth of the Sevier orogenic belt. Regionally, this belt includes (1) a western hinterland with metamorphosed and poly-deformed basement and cover rocks exposed in northwest Utah, (2) a central region with thick shelf strata deformed by the Willard thrust system in north-central Utah, and (3) an eastern region with thinner platform strata deformed by closer-spaced thrusts in northeast Utah to southwest Wyoming (Camilleri and others, 1997). The hinterland had a complex history, including Late Jurassic to Early Cretaceous crustal thickening and metamorphism, followed by alternating pulses of Late Cretaceous to early Tertiary extension and contraction (Wells, 1997). The central region underwent large-scale thrusting and local low-grade metamorphism during the Early Cretaceous (Yonkee, 1997). The eastern region experienced significant thrusting and folding during the Late Cretaceous to early Tertiary, with synorogenic deposits accumulating in basins that formed partly in response to thrust loading (DeCelles, 1994).

The Ogden area lies near the transition between the central and eastern regions, and thus preserves a rich structural history (figures 1 and 9). The Willard thrust sheet probably covered much of the area during the Cretaceous, but was partly removed during subsequent uplift and erosion; parts of the sheet are preserved to the east and north in the adjacent Snow Basin, Huntsville, and North Ogden quadrangles (Sorensen and Crittenden, 1979; Bryant, 1984; Crittenden and Sorensen, 1985). Along the north side of Ogden Canyon, the Willard thrust fault places Late Proterozoic rocks over tectonized Cambrian to Mississippian strata along a major footwall ramp, and some structures along Ogden Canyon may be related to Willard footwall deformation (Evans and Neves, 1992). The Ogden thrust fault system, which is spectacularly exposed in the quadrangle (figure 6a), transferred slip to thrust faults of the eastern region. These eastern thrusts developed above a basal decollement in Cambrian strata, but the decollement and associated Ogden thrust system locally cut into basement rocks along a major ramp system in the Ogden area (Schirmer, 1988; Yonkee, 1992). Progressive slip along imbricates of this system formed the Wasatch anticlinorium, which has a moderately to steeply east-dipping eastern limb exposed in the Wasatch Range, and a gently west-dipping western limb exposed on Antelope Island (figure 9). Basement in the anticlinorium was internally deformed by a network of shear zones during the Early Cretaceous, prior to most slip on the Ogden thrust system, and sedimentary cover rocks were internally deformed by cleavage, minor folds, and faults (Yonkee, 1992).

Ogden Thrust Fault System

The Ogden thrust fault system, as well as bedding in the sedimentary cover, currently dips overall eastward on the east limb of the Wasatch anticlinorium, partly reflecting rotation associated with slip on structurally lower thrusts. The Ogden thrust system probably initiated with subhorizontal flats and west-dipping ramps. In detail, the thrust system displays a complex geometry. North of the quadrangle, the system consists of a single major thrust that strikes northwest, dips moderately northeast, and places Tintic Quartzite over tectonized Middle to Upper Cambrian strata (Crittenden and Sorensen, 1985). On the northern margin of the quadrangle, the system consists of an upper fault concealed along Johnson Draw that places Tintic Quartzite over Ophir Shale, and a lower fault to the west that places Tintic Quartzite over Maxfield to Nounan Formations (plate 1). South of Ogden Canyon, the Ogden thrust system branches into a floor thrust and roof thrust (Schirmer, 1988; Yonkee, 1992). The floor thrust strikes north-northeast and dips moderately east along an oblique ramp, which cuts down section southward from the Tintic Quartzite to deeper levels of the Farmington Canyon Complex in the hanging wall and from the Nounan Formation to Tinitc Quartzite in the footwall (plate 1), with stratigraphic separation increasing southward from about 1,500 to 4,000 meters (5,000-13,000 ft). The northern part of the roof thrust strikes north-northwest, dips moderately east, and places Tintic Quartzite over Ophir Shale along a flat. Farther south, the roof thrust dips moderately north along a

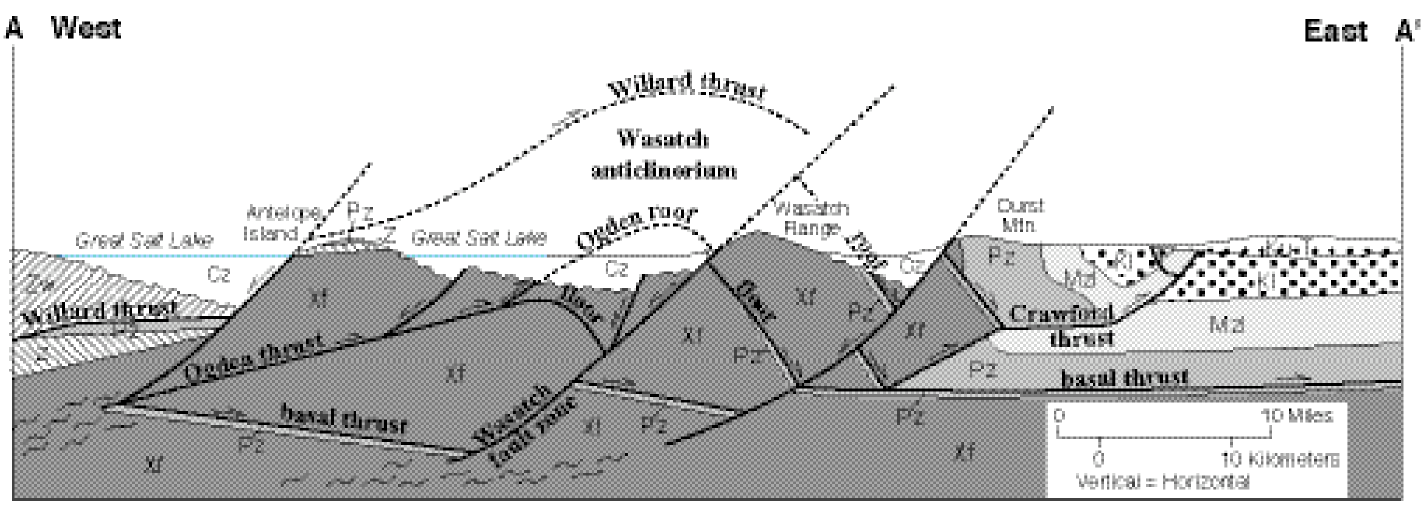

__Figure 9.__ Schematic regional cross section across the Wasatch Range and adjacent areas, showing relations between major structures, including the Willard thrust, Ogden thrust system, basal thrust, Crawford thrust, and Wasatch fault zone. Mostly Cretaceous thrust faulting and Cenozoic normal faulting have strongly influenced the geometry and outcrop patterns of various rock types. Units same as in figure 1.

lateral ramp, and cuts up section eastward from the Tintic Quartzite to middle Maxfield Formation in the hanging wall and from Ophir Shale to upper Maxfield Formation in the footwall, with stratigraphic separation ranging from about 300 to 500 meters (1,000-1,600 ft). A fault in the Ophir Shale branches away from the roof thrust and continues southeastward into the Snow Basin quadrangle.

The direction of net slip on the floor thrust is overall top-to-the-east, based on analysis of slip directions on minor faults (Bruhn and Beck, 1981; Yonkee, 1992). The net slip direction on the roof thrust is less well constrained, with varying slip directions on minor faults and shear veins indicating overall top-to-the-east slip. The magnitude of net slip across the floor thrust is estimated to be about 10 to 15 kilometers (6-9 mi), based on offset of projected Cambrian markers, but is poorly constrained. The net slip across the roof thrust is also poorly constrained and is estimated to be about 3 to 5 kilometers (2-3 mi). Although initial slip on the Ogden thrust system may have started during the Early Cretaceous, most large-scale slip, uplift, and cooling probably occurred during the Late Cretaceous, based on apatite fission track ages for rocks at high elevations along the Wasatch Range (Naeser and others, 1983) and relations of dated synorogenic conglomerates (DeCelles, 1994).

Basement Shear Zones

Basement rocks in the area are internally deformed by a complex network of shear zones, which are characterized by retrograde greenschist-facies metamorphism and development of mylonite, phyllonite, and chloritic gneiss (figure 4). Shear zones south of Weber Canyon include gently southeast- to northeast-dipping sets with top-to-the-east slip, and moderately southwest- to northwest-dipping sets with top-to-the-west slip, which define a conjugate to octahedral geometry (Yonkee, 1992). Cleavage within shear zones and in some regions of chloritic gneiss is overall gently dipping (figure 10). Fiber and stretching lineations on cleavage and associated shear band surfaces trend overall east-west. North of Weber Canyon, shear zones grade into fault zones that have similar chloritic alteration, but display more brittle features, are more widely spaced, and have more variable geometries. Shear zones include east-striking, moderately south-dipping sets with oblique slip, and north-striking, moderately east-dipping sets that are subparallel to the Ogden floor thrust and have top-to-the-east slip. Fault and shear zones are associated with abundant quartz veins and fractures.

$^{40}Ar/^{39}Ar$ ages of syntectonic muscovite from shear zones along and south of Weber Canyon are mostly between 140 and 110 Ma, recording internal deformation mostly prior to large-scale development of the Wasatch anticlinorium, which rotated beds in the sedimentary cover to currently observed east dips (Yonkee, 1992). If bedding is restored to horizontal, then currently gently east-dipping shear zones become steeply west-dipping zones with reverse slip and currently west-dipping shear zones become steeply east-dipping zones with reverse slip, consistent with early bulk shortening of the basement. Moderately east-dipping shear and fault zones subparallel to the Ogden thrust system become gently west-dipping thrust zones, and moderately south-dipping zones become oblique ramps.

Minor Folds, Faults, and Cleavage

The sedimentary cover displays widespread internal deformation, such that tectonic (observed) thicknesses of individual stratigraphic units are highly variable. Structural style varies between and within units, and is related to lithology and structural position relative to major thrusts. The Tintic Quartzite is overall less deformed than other units, but locally displays minor faults, minor folds, widely spaced veins, and fibrous slip surfaces. The Ophir Shale is highly deformed and acts as a detachment zone that separates underlying quartzite from overlying, more deformed strata. The Ophir Shale displays weak to intense slatey cleavage, widespread minor folds, minor fault and shear zones, and vein arrays. Limestone and shaley intervals of the Maxfield and Bloomington Formations display weakly to strongly developed spaced cleavage, open to tight minor folds (figure 6b), and vein arrays, whereas dolomite intervals contain abundant minor faults. Minor faults, bed-parallel slip surfaces, and open to tight minor folds are widespread in thinner bedded intervals of the Garden City, Water Canyon, and Beirdneau Formations, whereas more massive dolomite intervals in the St. Charles, Nounan, Fish Haven, and Hyrum Formations have widespread minor faults of varying orientations. Most minor faults are difficult to trace in areas of limited exposure and steep topography, and many faults do not display distinct slip lineations, making it difficult to determine structural relations.

Orientations of bedding, cleavage, and hinge lines of minor folds show systematic variations within different areas of the quadrangle, allowing structural domains to be defined (figure 11). In detail, domain boundaries are gradational, and structural patterns locally vary within domains.

Domain 1 is located in the footwall of the Ogden thrust north of Ogden Canyon where the thrust has a relatively simple geometry. Bedding is overall northwest striking and moderately northeast dipping, with some small-scale, northeast-verging minor folds. Hinge lines of minor folds plunge gently north-northwest/south-southeast. Cleavage dips overall gently northeast at acute angles to bedding, but locally forms partial fans about minor folds. These patterns are consistent with top-to-the-northeast slip parallel to bedding and minor tectonic thickening.

Domain 2 is located in the footwall of the Ogden floor thrust south of Ogden Canyon where the floor thrust has an oblique ramp. Bedding is overall northwest striking and moderately northeast dipping, but small- to large-scale folds are widely developed. Hinge lines plunge gently west-northwest/east-southeast. Cleavage dips overall moderately southwest subparallel to axial planes of minor folds, but in detail is partly fanned about minor folds. A large-scale, basement-cored anticline is developed south of Taylor Canyon (plate 1). The fold has a steeply dipping to overturned northeast limb bounded by a south-dipping fault along the bottom of Taylor Canyon. The fault is interpreted to have initiated as an oblique ramp along a footwall imbricate, with top-to-the-northeast slip based on asymmetry of minor folds, but was later reactivated as a normal fault, as described in the section on Cenozoic extension. A large-scale, northeast-verging anticline-syncline pair is developed in Cambrian strata above a detachment fault at the base of the Maxfield Formation near upper Warm Water Canyon (NE$^{1}/_{4}$ section

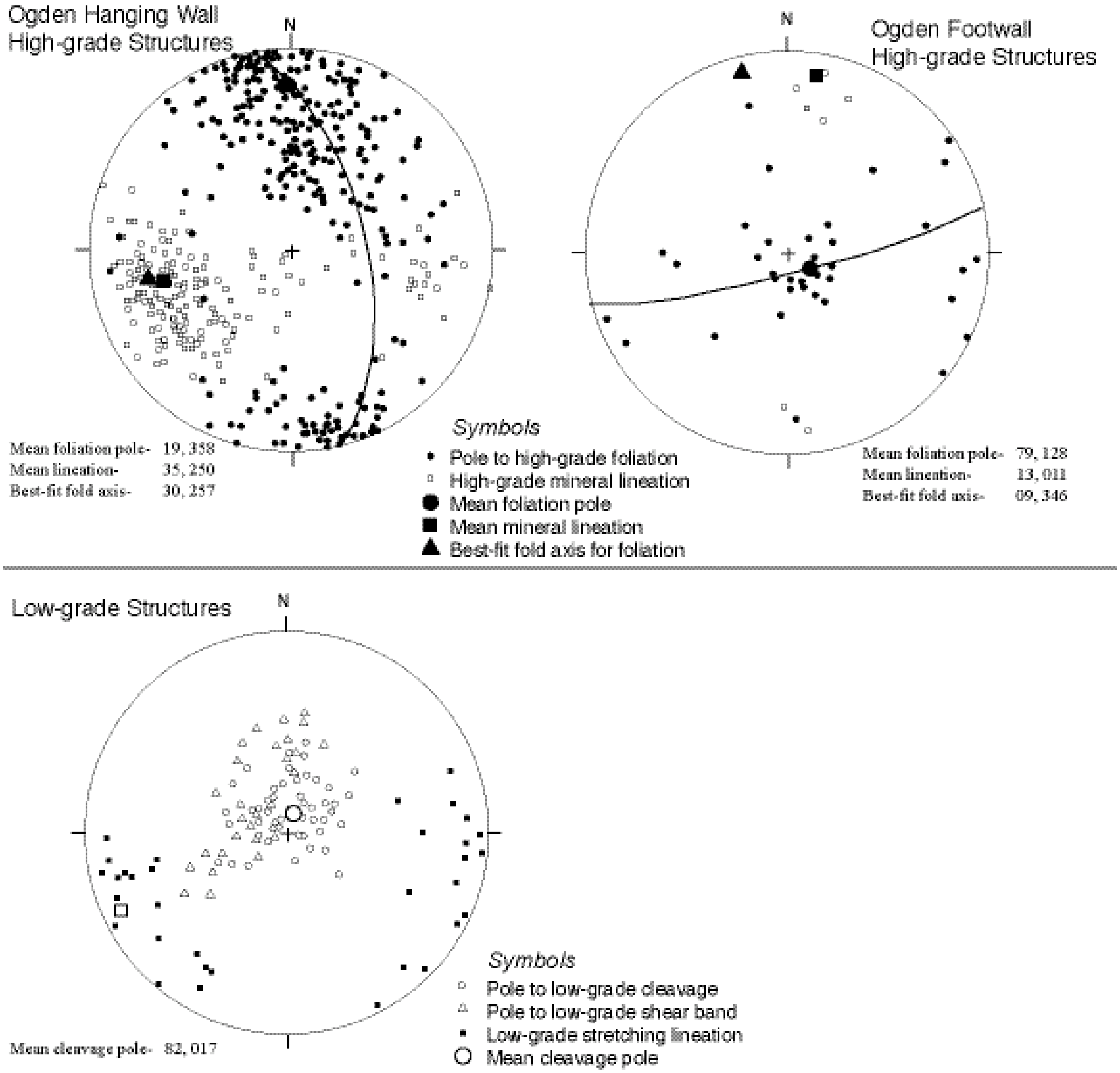

Figure 10. *Equal-area, lower-hemisphere stereograms showing geometric relations between Early Proterozoic high-grade structures and Cretaceous low-grade structures within the Farmington Canyon Complex. Plunge and trend of mean pole to high-grade foliation, is shown for basement rocks in hanging wall and footwall of Ogden floor thrust fault (to convert to average strike and dip, add 90° to trend and subtract plunge from 90°). Plunge and trend of overall fold axis for foliation also indicated, although patterns are complex due to local refolding. Low-grade structures include phyl - lonitic cleavage, shear bands, and stretching lineations.*

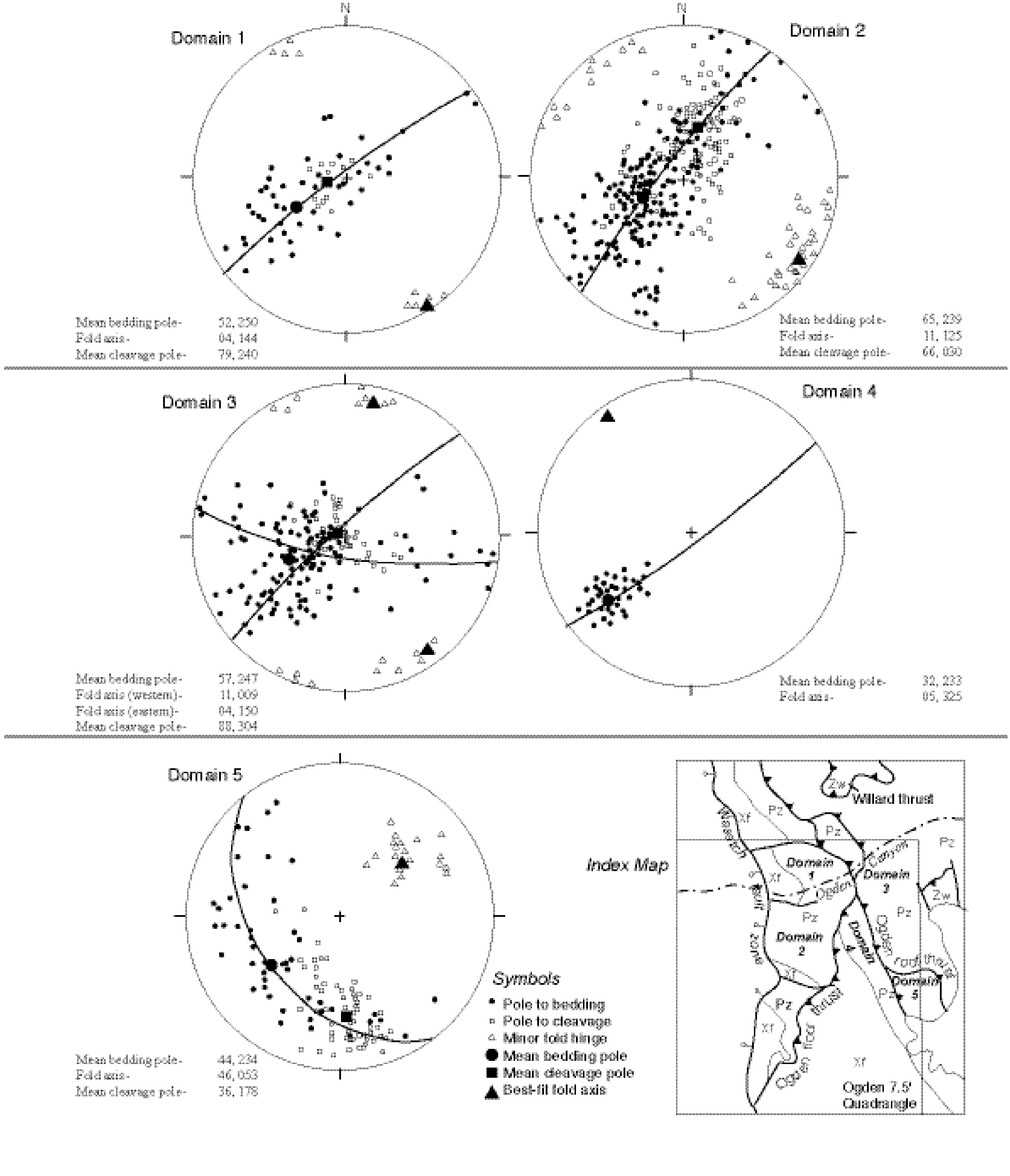

Figure 11. Equal-area, lower-hemisphere stereograms showing geometric relations between poles of bedding (small solid circles), poles to cleavage (small open squares), and hinge lines of minor folds (small open triangles) for domains within the Paleozoic sedimentary rocks. Index map shows approximate locations of domains. Plunge and trend of mean poles to bedding and cleavage are shown for each domain (to convert to average strike and dip, add 90° to trend and subtract plunge from 90°). Plunge and trend of best-fit fold axis also listed for each domain (note, folds in western and eastern parts of domain 3 tend to have different orientations).

26, T. 6 N., R. 1 W., Salt Lake Base Line and Meridian, plate 1). Although strata are thickened by minor folds and contraction faults in some areas, in other areas strata are thinned where cleavage rotates into low angles with bedding, and where detachment faults locally omit section. Complex relations in this domain probably record top-to-the-northeast shear, varying components of bed-parallel shortening to local extension, and slip along faults that variously cut down and up section across previously folded strata.

Domain 3 is located in the hanging wall of the Ogden thrust along Ogden Canyon. This domain is also located near a footwall ramp of the Willard thrust in the adjoining North Ogden quadrangle (Crittenden and Sorrensen, 1985), and some deformation features may be related to footwall deformation beneath the Willard thrust (Evans and Neves, 1992). Bedding is overall northwest striking and moderately northeast dipping, but varies significantly in orientation around widely developed open to tight, minor folds (figure 11). Fold hinge lines tend to plunge gently north-northeast/south-southwest in the western part of this domain, whereas folds tend to plunge gently northwest/southeast in the eastern part of the domain, possibly reflecting varying shortening and shear directions associated with the Ogden and Willard thrusts. In detail, minor folds show varying orientations, particularly within the Beirdneau Formation, possibly reflecting amplification of soft-sediment folds. Cleavage is well developed in parts of the Ophir and Maxfield Formations, and is overall gently dipping. The Ophir Formation displays particularly dramatic changes in tectonic thickness, being highly thickened by larger scale, tight folds in the northeast corner of the quadrangle (plate 1), but being thinned by bed-parallel cleavage in other areas. Ordovician to Devonian strata also display dramatic variations in thickness due to complex minor faulting in the northeast corner of the Ogden quadrangle (plate 1). The highly complex patterns in this domain may reflect multiple episodes of top-to-the-northeast to top-to-the-southeast shear near oblique ramps in the Ogden thrust and beneath the Willard thrust, and varying thickening and thinning of strata partly associated with detachment faults that locally cut up and down section.

Domain 4 is located between the floor and roof thrusts of the Ogden thrust system south of Ogden Canyon. This domain includes exposures of the Tintic Quartzite that display relatively consistent and simple geometric patterns. Bedding strikes overall north-northwest and dips about 40 to 70 degrees northeast in most exposures. Although minor folds are rare, slight variations in bedding orientations indicate an overall gently northwest-plunging fold axis (figure 11).

Domain 5 is located near a lateral ramp on the Ogden roof thrust south of Ogden Canyon. Bedding is overall northeast dipping, but strongly rotated by widespread, open to isoclinal minor folds that produce large variations in tectonic thickness of stratigraphic units. Hinge lines of minor folds plunge overall moderately northeast. A large-scale anticline cored by the Tintic Quartzite is developed above the roof thrust in the upper part of Cold Water Canyon (plate 1). Cleavage varies from steeply north dipping near the lateral ramp, to gently dipping away from the ramp. Limited data on slip lineations record complex combinations of top-to-the-northeast to top-to-the-southeast shear, partly related to internal deformation near the lateral ramp in the Ogden roof thrust.

Cenozoic Extensional Structures

Cenozoic extensional structures within the quadrangle include the Wasatch fault zone and associated normal faults, Wasatch Front basin, and other faults in the Wasatch footwall. Regionally, the Ogden area experienced two phases of Cenozoic extensional deformation, an older phase related to late Eocene to Oligocene collapse of the Sevier thrust belt (Constenius, 1996), and a younger phase related to Miocene to Holocene basin-and-range crustal extension (Zoback, 1983). The older phase was characterized by localized detachment and listric normal faulting, synchronous with volcanism and sedimentation in distinctly tilted half-grabens, which are preserved west and east of the quadrangle (Constenius, 1996) (figure 9). The younger phase is characterized by widely spaced, large-scale normal faults, gently tilted strata in basins, crustal thinning, and regionally elevated heat flow (Smith and Bruhn, 1984).

Wasatch Fault Zone

The trace of the Wasatch fault zone trends overall north to north-northwest along the base of the Wasatch Range in the eastern part of the quadrangle (plate 1). The fault zone consists of multiple fault scarps that offset Quaternary deposits (figure 12), including small-displacement antithetic faults, as well as highly fractured bedrock in the footwall. A shallow seismic-reflection survey conducted farther south in the Kaysville quadrangle showed the following: the main active fault zone consists of multiple, closely spaced fault surfaces that dip about 45 degrees west at depths greater than 40 meters (130 ft), but steepen near the surface; the footwall has thin alluvial-fan deposits over bedrock, whereas the hanging wall has thicker, mostly lacustrine deposits, with multiple fault-rupture-related colluvial wedges preserved in the subsurface; and other Quaternary normal faults lie west of the main active fault zone (Stephenson and others, 1993). These relations indicate that rupture may occur on various faults within the main active fault zone, and potentially active faults are also present in the hanging wall west of the main fault zone.

The Wasatch fault zone in the Ogden area is part of the Weber segment (Nelson and Personius, 1993). The Weber segment is about 60 kilometers (40 mi) long and is bounded by complexly deformed bedrock ridges (salients) at its northern end in the Pleasant View area, and at its southern end near Salt Lake City (figure 1) (Machette and others, 1992). This segment has had 6 to 10 surface-rupturing events over the past 12,000 to 15,000 years, including an event between 2.5 and 3 ka, and another event at about 1 ka (Nelson and Personius, 1993; McCalpin and others, 1994). Some of the surface-rupturing events produced 0.6 to 3.5 meters (2-11 ft) of vertical ground offset along the 60 kilometer (40 mi) length of the segment, giving estimated paleoearthquake magnitudes of 7 to 7.5 (Nelson and Personius, 1993). Microseismicity is limited along the Weber segment, but diffuse activity has occurred along the subsurface projection of the southern salient (Arabaz and others, 1979).

The Wasatch fault zone strikes north to northwest in the Ogden area, and is interpreted to dip about 40 to 45 degrees west, based on orientations of fault surfaces exposed in the Ogden and North Ogden quadrangles (this study; Crittenden

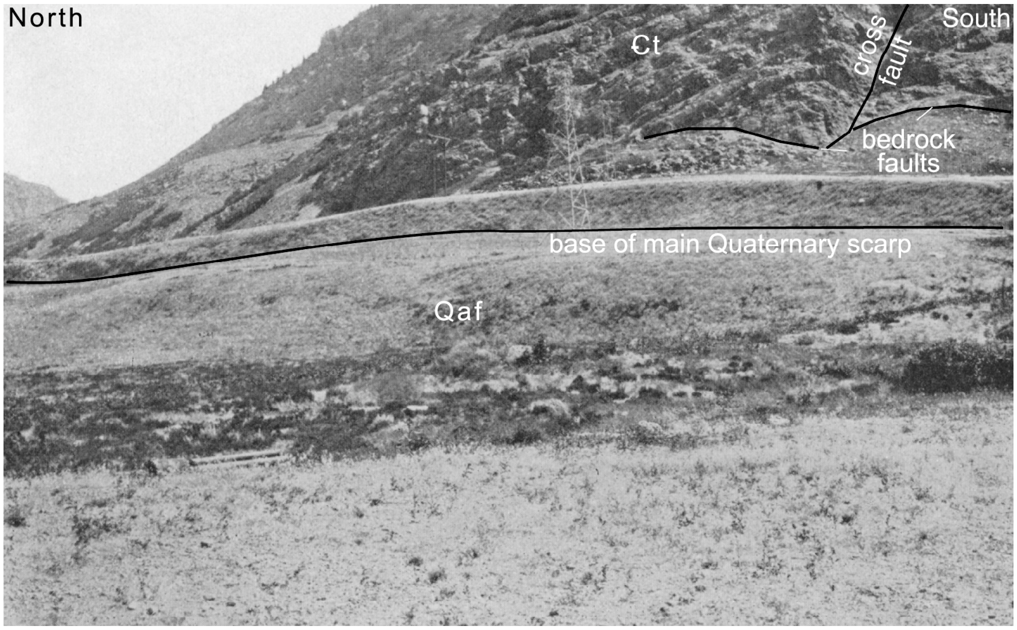

Figure 12. View looking east toward scarp along Wasatch fault zone (modified from Gilbert, 1928). Locations of abandoned bedrock fault traces, east-striking cross fault, and main active scarp indicated. Units are Ꞓt - Tintic Quartzite, and Qaf- alluvial-fan deposits.

and Sorensen, 1985, respectively), and on interpretation of seismic reflection lines reported by Glenn and others (1980). For comparison, deep drill-hole data from north of Brigham City indicate a fault dip of about 40 degrees (Jensen and King, 1999). The direction of net slip across the Wasatch fault zone in the Ogden area is interpreted to trend west-southwest, based on measured orientations of slip lineations along exposed fault surfaces, consistent with general orientations of slip lineations on other Holocene fault surfaces within north-central Utah (Zoback, 1983).

Initial slip on parts of the Wasatch fault zone may have begun by 17 Ma, based on a K-Ar age of muscovite along the fault zone south of Salt Lake City (Parry and Bruhn, 1986). However, regional basin-and-range extension may not have started until about 12 to 10 Ma, based on ages of older sediments in larger fault-bounded basins (Zoback, 1983; Bryant and others, 1989). Apatite fission-track data along the Wasatch Range between Ogden and Bountiful also indicate onset of significant unroofing at about 10 Ma, with an average uplift and erosion rate of about 0.4 millimeters per year (1.3 ft/1000 years) for the footwall of the Wasatch fault zone since that time (Naeser and others, 1983). Estimates of net slip, which are also based on the geometry of the associated hanging-wall basin, are described below.

Wasatch Front Basin

A large, sediment-filled basin, which is part of an asymmetric graben in the hanging wall of the Wasatch fault zone, underlies the western part of the Ogden quadrangle (Zoback, 1983). McNeil and Smith (1992) combined seismic reflection data west of the quadrangle with regional gravity data to constrain the regional, three-dimensional basin geometry. Their model indicates that lower-density Cenozoic deposits reach thicknesses of about 2,000 to 3,000 meters (7,000-10,000 ft) within the east-central part of the basin along the Weber segment, and that additional normal faults are likely present in the eastern part of the basin.

Detailed seismic and gravity data for traverses along the northern boundary of the quadrangle (Cook and others, 1967), and near the southern boundary of the quadrangle (Glenn and others, 1980), indicate (1) the basin contains gently dipping deposits that reach a thickness of about 2,400 meters (8,000 ft) in the western part of quadrangle, (2) other west-dipping normal faults are present in the subsurface within the eastern part of the basin, and (3) a bedrock block overlain by relatively thin basin deposits lies west of the main Wasatch fault zone (plate 2). This bedrock block is bounded in the subsurface by a major, west-dipping normal fault, labeled as Wasatch fault B on plates 1 and 2, which lies about 3 kilometers (2 mi) west of the main Wasatch fault zone. Seismic reflectors in basin fill above the block are subhorizontal, but the upper surface of the bedrock block appears to dip about 15 degrees west, slightly less than the slope of the modern range front. Lake Bonneville sediments do not appear offset across fault B, although the Quaternary-Tertiary contact may be slightly warped, and reflectors in the lower part of Tertiary basin fill appear truncated by fault B, indicating significant pre-Quaternary offset. The upper surface of the bedrock block is interpreted as a buried erosional surface that formed during pre-Quaternary uplift in the footwall of fault B, which was later downdropped and buried by subhorizontal fill as slip largely transferred to the main Wasatch fault zone. Another major, west-dipping normal fault, labeled as Wasatch fault C on plates 1 and 2, is located in the subsurface about 3 kilometers (2 mi) west of fault B. Fault C also has an associated antithetic fault, and bounds a secondary graben in the subsurface (Glenn and others, 1980).

Total extension across the main Wasatch fault zone and associated faults in the basin can be estimated by restoring the basal unconformity for basin fill, incorporating fission track, geologic, and geophysical data. Fission track data in the area indicate about 4 kilometers (2.5 mi) of uplift and erosion in the Wasatch footwall. Fission track ages also increase slightly eastward along Weber Canyon, probably from eastward tilting of the footwall (Naeser and others, 1983). Boulder lag that may represent remnants of a Tertiary basal conglomerate is preserved locally on the east side of the Wasatch Range in the Hunstville quadrangle (Sorensen and

Crittenden, 1979), and elevation variations of the lag indicate an average dip of about 15 degrees east. Projecting this unconformity westward over the range crest yields an estimated 4 kilometers (2.5 mi) of uplift and erosion in the Wasatch footwall, consistent with fission track data. The Tertiary basal unconformity is at an elevation of about 600 meters (2,000 ft) below sea level west of fault B, based on seismic data, and is at a projected elevation of about 5,400 meters (18,000 ft) east of the main Wasatch fault, giving a total vertical offset of about 6,000 meters (20,000 ft) for both faults (plate 2). The estimated total horizontal extension is about 6,000 meters (20,000 ft), and the total net slip is about 8,400 meters (28,000 ft), calculated for faults that dip 45 degrees west and have dominantly dip-slip motion.

Partitioning of slip between the main Wasatch fault zone and faults B and C can only be bracketed with available data. The basal unconformity of basin fill has been eroded from the subsurface bedrock block east of fault B, and thus must have been at an elevation greater than about 1,500 meters (5,000 feet). Placing the contact at this minimum elevation yields a minimum slip of about 3,000 meters (10,000 ft) for fault B and a maximum slip of about 5,400 meters (18,000 ft) for the main Wasatch fault. Placing the contact at a higher elevation partitions a greater component of slip onto fault B. Fault C appears to offset the basal unconformity by about 300 meters (1,000 ft), with an estimated horizontal extension of about 250 meters (800 ft).

Other Faults

Bedrock in the Wasatch footwall is cut by secondary, north- to northwest-striking normal faults, and by east-striking cross faults. Ages of secondary normal faults are poorly constrained; some faults could be directly related to basin-and-range extension, but other faults could be related to extension during collapse of the Sevier thrust belt, localized extension during Sevier thrusting, or reactivation of Sevier-age faults. Slip on cross faults decreases eastward away from the main Wasatch fault zone, and some cross faults are associated with bends in the main Wasatch fault zone, indicating a geometric relation with extension, although some cross faults may have initiated during Sevier thrusting. Larger cross faults include a fault north of Ogden Canyon, a fault south of Ogden Canyon, and a fault along Taylor Canyon, which all place Precambrian basement rocks on their north sides against Lower to Middle Cambrian strata on their south sides. These faults dip 30 to 70 degrees south and display a range of slip lineations from about parallel to fault dip to oblique to fault strike. The Taylor Canyon fault may have initiated as an oblique thrust ramp with the south side up, followed by reactivation as a normal fault with the south side relatively downdropped.

MINERAL RESOURCES

Gravel and Sand

Relatively thick and widespread accumulations of gravel and sand in the quadrangle were deposited within the Weber delta of Lake Bonneville (Qd_3), as alluvium along the Weber and Ogden Rivers (Qat_2, Qal_2, and Qal_1), and locally in fans (various Qaf) and lake gravels (Qlg_4 and Qlg_3) along the Wasatch Range front. Some of these accumulations have been excavated, and larger gravel and sand pits are shown on plate 1. Alluvial and deltaic topset gravels are well sorted and contain abundant, rounded cobbles with limited amounts of fine-grained material. Alluvial-fan and gravel-bearing lacustrine deposits contain moderately to well-sorted gravels, as well as some poorly sorted debris flow deposits and some finer-grained lacustrine material. Deltaic foreset beds, and some lacustrine deposits near the Provo and other regressive shorelines, contain sand-rich intervals. General characteristics of some pits are summarized in commodity information sheets of the Utah Geological Survey Utah Mineral Occurrence System files. The largest pits, which are up to 60 meters (200 ft) deep and up to 40,000 square meters (400,000 ft^2) in area, are located in alluvial deposits near the mouth of Weber Canyon, and in deltaic topset beds north and south of the Weber River. Smaller pits have been excavated in slumped gravels northwest of the mouth of Ogden Canyon, lacustrine and fan gravels south of the mouth of Ogden Canyon, landslide deposits that contain large boulders northwest of the mouth of Beus Canyon, and delta deposits that contain well-sorted sand near the west edge of the quadrangle. Additional data on the larger deposits can be found in the inventory by the Utah State Department of Highways (1965).

Limestone, Dolomite, and Quartzite

Units containing intervals of limestone and dolomite that are exposed in the quadrangle include the Maxfield, Nounan, St. Charles, Garden City, Fish Haven, Hyrum, and Gardison Formations. Similar units have been used for aggregate and lime production in northern Utah (Tripp, 1991). Within the quadrangle, an abandoned lime kiln is located in Ogden Canyon near exposures of the Nounan Dolomite and upper member of the Maxfield Formation (SW1/4 section 24, T. 6 N., R. 1 W., Salt Lake Base Line and Meridian). The Tintic Quartzite is a potential source for silica, but has not yet been developed in the quadrangle. Limestone, dolomite, and quartzite, as well as gneiss from the Farmington Canyon Complex, could also be used for decorative stone.

Metallic Minerals

Gloyn and others (1995) described general characteristics of metallic mineral occurrences along the northern Wasatch Front, including quartz-chalcopyrite-pyrite veins associated with shear zones in basement rocks of the Farmington Canyon Complex, disseminated pyrite mineralization in basement rocks, and lead-zinc-silver replacement mineralization in Paleozoic sedimentary rocks. Rare quartz-pyrite veins and fracture zones appear associated with some shear zones and areas of diffuse chlorite-sericite alteration in the Ogden quadrangle. Sampled veins south of the quadrangle contained 1 to 8 percent copper, 1 to 11 ppm silver, and from less than 1 to 8 ppm gold (Gloyn and others, 1995). Lead-zinc-silver mineralization is mostly within fractured Paleozoic limestone and dolomite in areas outside the quadrangle (Gloyn and others, 1995), although a few exposures of carbonate in the quadrangle display iron-hydroxide alteration and very rare galena.

Several prospect pits have been excavated within the Ogden quadrangle. A prospect along Taylor Canyon is currently marked by a pile of iron-hydroxide-rich material (E$^1/_2$ section 35, T. 6 N., R. 1 W., Salt Lake Base Line and Meridian). The material was reportedly removed from an oxidized quartz-pyrite vein located along the Taylor Canyon fault, and ore was reported to have contained 15 to 4,000 ppm gold (Maguire, 1923). The Taylor Canyon fault is interpreted to have initiated as a Cretaceous thrust fault, and the reported mineralogy of the vein is similar to other quartz-pyrite veins associated with Cretaceous alteration described by Gloyn and others (1995). Total production from the prospect is uncertain. Other small pits (less than 3 meters [10 ft] across) have been dug in some exposures of the Farmington Canyon Complex that display quartz veins, chlorite alteration, iron-hydroxide alteration, rare pyrite, and rare malachite-azurite staining.

Oil and Gas

Oil and gas has not been produced in the Ogden quadrangle. In other areas along the northern Wasatch Front, however, minor amounts of natural gas have been produced from Quaternary marsh deposits (Doelling and others, 1980), and Tertiary basin-fill deposits drilled beneath parts of Great Salt Lake have had hydrocarbon shows (Bortz, 1984).

WATER RESOURCES

The Ogden quadrangle contains significant surface- and ground-water sources. The Wasatch Range receives about 50 to 125 centimeters (20-50 in) of average annual precipitation, mostly in the form of winter to early spring snowfall. The valley floor receives about 25 to 50 centimeters (10-20 in) of average annual precipitation (Feth and others, 1966; Anderson and others, 1994). Snowmelt provides recharge to the bedrock aquifers in the Wasatch Range, particularly at higher elevations, as well as runoff to streams.

Surface Water

The Weber and Ogden Rivers contribute the vast majority of surface water flowing into and through the quadrangle. Annual flow in the Weber River at a gaging station near Ogden averaged 0.32 cubic kilometers per year (260,000 acre-feet/year) from 1890 to 1993, and annual flow in the Ogden River at a gaging station below Pineview Reservoir east of the quadrangle averaged 0.07 cubic kilometers per year (57,000 acre-feet/year) from 1989 to 1995 (Utah Division of Water Resources, 1997, table 5-1). Flow along the Weber River increases in Weber Canyon from bedrock recharge and decreases west of the mouth of Weber Canyon where the river loses water into basin fill (Feth and others, 1966). Flow along the Ogden River also appears to increase slightly along Ogden Canyon, and decreases very slightly westward from the mouth of Ogden Canyon.

Perennial streams in the quadrangle include Burch Creek, which flows from the Wasatch Range westward across basin fill to the Weber River in the southern part of the quadrangle, and Mill Creek, which flows west of the mountain front in the northern part of the quadrangle. Intermittent streams, which have both permanently flowing stretches and stretches that are seasonally dry, drain Taylor, Waterfall, Strongs, Beus, and Spring Creek Canyons, and lose flow into basin fill west of the mountain front. Intermittent streams are present along Cold Water and Warm Water Canyons and drain northward into the Ogden River. Ephemeral streams, which are completely dry during much of the year, drain smaller canyons along the mountain front and side canyons of Ogden and Weber Canyons.

Ground Water

Bedrock Aquifers

Bedrock aquifers are likely present in the Wasatch Range, but hydrologic characteristics are poorly known. Potential bedrock aquifers include: fractured parts of the Precambrian Farmington Canyon Complex, from which small springs and seeps emanate along the mountain front; fractured parts of the Cambrian Tintic Quartzite, which is the source for a water well completed in the adjacent Snow Basin quadrangle; the Maxfield Limestone, which is the source of small springs along Taylor, Sardine, and Warm Water Canyons, and is also the source of a water well completed in the Snow Basin quadrangle; and fractured limestone and dolomite intervals in other Cambrian to Mississippian units, including the St. Charles and Nounan Formations that are the source of Wheeler Spring located in the adjacent Snow Basin quadrangle. Potential aquitards include shale-rich intervals in the Ophir, Bloomington, and Beirdnaeu Formations.

Fractured bedrock aquifers in the Ogden area likely have complex, highly variable permeability, overall low storage, and rapid flow rates, based on comparison to aquifers in the Park City, Utah area (Ashland and others, 2001). Quantitative data on hydrologic properties of bedrock aquifers in the quadrangle, however, are lacking. The Gateway tunnel, which penetrated the Farmington Canyon Complex in the Wasatch Range just south of Weber Canyon, encountered considerable water flow at various fractured intervals, with total discharge of the tunnel varying from 12 to 30 liters per second (180-450 gallons per minute [gpm]) during completion of the tunnel in 1955 (Feth and others, 1966). Discharge increased markedly during April to May, peaked in June, and then decreased from late summer to fall, likely reflecting recharge during snowmelt and limited storage. The Weber River gains in flow by about 130 liters per second (2,000 gpm) over a stretch of about 0.8 kilometers (0.5 mi) along lower Weber Canyon, probably related to inflow from bedrock of the Farmington Canyon Complex (Feth and others, 1966).

Water flow in the bedrock aquifers is probably overall westward from higher elevations near the mountain crest toward lower elevations along the mountain front on the west side of the Wasatch Range, with local flow toward canyon bottoms, especially along Weber and Ogden Canyons. Some ground water discharges into springs and gaining parts of streams along the mountain front, and a small amount of additional discharge into basin-fill aquifers may result from flow across the Wasatch fault zone at depth.

Major faults, such as the Wasatch fault zone, partly control fluid flow, with fractured zones preferentially transmitting water parallel to the fault, and fine-grained gouge zones tending to inhibit flow across the fault. Several warm springs are located near the Wasatch fault zone near the mouth of Ogden Canyon, including Ogden Hot Spring and a series of small springs in fractured footwall rocks of the Farmington Canyon Complex (SW1/4 section 23, T. 6 N., R. 1 W., Salt Lake Base Line and Meridian). Ogden Hot Spring has a flow of about 2 to 6 liters per second (35-100 gpm) and a water temperature of about 55°C (135°F) (Mundorff, 1970). Water from the spring contains 8,000 to 9,000 parts per million (ppm) total dissolved solids (TDS), and is geochemically of sodium-chloride type (Mundorff, 1970). Dissolved silica concentrations of the spring water indicate interaction with rocks at temperatures of about 100°C (210°F) (Glenn and others, 1980), which yields a circulation depth of about 3,000 meters (10,000 ft) for spring waters, using an estimated geothermal gradient of 30°C/kilometer. These springs may reflect relatively rapid upward flow along the fractured footwall of the Wasatch fault zone, with impermeable gouge zones that limit fluid flow across the fault core.

Basin-Fill Aquifers

The Ogden area has important ground-water resources in unconsolidated to semi-consolidated Quaternary basin-fill deposits (Feth and others, 1966; Clark and others, 1990). These deposits include coarser-grained alluvial sediments near the mountain front, and finer-grained lacustrine and alluvial sediments westward away from the mountains (Feth and others, 1966; Bolke and Waddell, 1972; Clark and others, 1990). Basin-fill aquifers in the Ogden area are part of the Weber Delta District (WDD) aquifer system, which covers an area of about 1,000 square kilometers (400 mi^2) and extends from the Wasatch Range westward to Great Salt Lake, and from North Ogden southward to Farmington (Feth and others, 1966; Clark and others, 1990; Gates, 1995). Deeper ground water in the aquifer system is predominantly confined, but unconfined conditions exist locally in recharge areas along a narrow band at the base of the Wasatch mountain front (Anderson and others, 1994). Two principal aquifers, the Sunset and Delta, have been delineated in the central part of the district (Feth and others, 1966). The Delta aquifer is the primary source of ground water for the Ogden area and is composed mostly of coarse-grained, pre-Bonneville fluvial and deltaic sediments (Clark and others, 1990). The top of the Delta aquifer is 150 to 200 meters (500-700 ft) below ground surface in the Ogden area, and the aquifer is about 15 to 60 meters (50-200 ft) thick (Feth and others, 1966). The shallower Sunset aquifer has a lower permeability and is used to a lesser extent as a source of ground water. The top of this aquifer is 60 to 120 meters (200-400 ft) below ground surface in the Ogden area, and this aquifer is about 15 to 60 meters (50-200 ft) thick (Feth and others, 1966). Fine-grained confining intervals overlie both aquifers away from the mountain front. A shallow unconfined aquifer is commonly present above the upper confining beds within Quaternary surficial deposits (Clark and others, 1990). Tertiary basin fill deeper than about 450 meters (1,500 ft) tends to be more lithified and less permeable, contains poorer quality water, and is not considered an important ground-water source (Clark and others, 1990).

Recharge to the WDD aquifer system includes channel seepage along losing stretches of streams; seepage from irrigated fields, lawns, and gardens; direct infiltration of precipitation; and subsurface inflow from bedrock of the Wasatch Range (table 2). Most recharge takes place in the primary recharge area along the mountain front, especially near the mouth of Weber Canyon (Anderson and others, 1994), where artificial ground-water recharge has been considered as an option to increase ground-water supplies (Feth and others, 1966; Clyde and others, 1984; Lowe and others, 2003). Subsurface inflow from bedrock along the mountain front and seepage from the Weber River are probably the dominant recharge sources.

Discharge from the WDD aquifer system includes flow into gaining stretches of streams and to small springs, water-well withdrawal, evapotranspiration of shallow ground water, and ground-water flow to Great Salt Lake (table 2). Water-well withdrawal and flow to gaining streams and springs are the main discharge components (Clark and others, 1990). Springs in basin fill in the quadrangle, including springs on the campus of Weber State University and within landslide complexes along bluffs above the Weber and Ogden Rivers, discharge up to 0.004 cubic kilometers per year (3,000 acre-feet per year) (Feth and others, 1966).

Ground-water flow in the WDD aquifer system is generally westward from recharge areas near the Wasatch Range toward Great Salt Lake (Feth and others, 1966). The horizontal hydraulic gradient for deeper wells in the Delta aquifer is about 1 meter per kilometer (5 ft/mi) in most areas, and the horizontal hydraulic gradient for shallow wells in the Sunset aquifer is about 2 meters per kilometer (10 ft/mi) (Feth and others, 1966). The vertical hydraulic gradient in the system is generally downward in recharge areas near the mountain front, and generally upward where confined conditions exist west of the mountain front, but vertical flow is probably relatively slow through low-permeability confining layers (Clark and others, 1990).

Seasonal ground-water levels in the WDD generally rise in the spring during net recharge and decline in the summer, with greatest declines near the mountain front (Clark and others, 1990). Long-term water levels in the aquifer system have declined slightly over time, probably related to increased withdrawals from wells for municipal and industrial use (Clark and others, 1990). From 1953 to 1985, ground-water levels declined an average of 8 meters (27 ft) for wells in the confined part of the aquifer system, with a maximum drop of 15 meters (50 ft) near the principal pumping center for the aquifer system (Clark and others, 1990). From 1953 to 1985, water levels in the unconfined part of the aquifer system declined as much as 12 meters (40 ft) in wells near the mouth of Weber Canyon (Clark and others, 1990), indicating that ground-water mining is a concern. This trend in declining water levels does not appear to have slowed; Burden and others (2000) document water-level declines of up to 9.4 meters (30.8 ft) from 1970 to 2000.

Ground-water quality in the Ogden area is generally good. Geochemically, ground water types in the quadrangle are calcium-magnesium-bicarbonate, sodium-chloride, and mixed (Smith and Gates, 1963; Feth and others, 1966; Bolke and Waddell, 1972; Clark and others, 1990). The calcium-magnesium-bicarbonate type is present south of central Ogden City, and generally contains less than 300 parts per million (ppm) total dissolved solids (TDS) (Feth and others, 1966, figure 14). The sodium-chloride type is present north of the Ogden River, and contains from 500 ppm TDS at the mouth of Ogden Canyon to more than 2,000 ppm TDS in the northwest corner of the quadrangle (Smith and Gates, 1963, figure 8; Feth and others, 1966, figure 14). Mixed-type water is present between the Ogden River and central Ogden City, and contains from 500 to 1,000 ppm TDS (Smith and Gates, 1963, figure 8; Feth and others, 1966, figure 14). Clark and others (1990, figure 44) extended the area where chloride concentrations exceed 250 ppm to include the entire area north of Burch Creek.

Concentrations of organic solvents, such as toluene and trichloroethane, exceeding ground-water-quality standards (U.S. EPA, 2002) have been identified in the shallow unconfined aquifer within the southern part of the Ogden quadrangle on Hill Air Force Base and are currently being remediated (Dalpias and others, 1989). Smaller plumes may also be present at other sites in the area, such as the Ogden Defense Depot.

Ground-water-quality data from Smith (1961, table 3), Smith and Gates (1963, table 4), Feth and others (1966, table 9), Bolke and Waddell (1972, table 2), Plantz and others (1986, table 5), and Clark and others (1990, table 13) indicate that water samples from wells in the Ogden quadrangle have not exceeded U.S. EPA (2002) ground-water-quality standards. However, wells in sections 30 and 29, T. 5 N., R. 1 W., Salt Lake Base Line and Meridian, have moderately high nitrate concentrations, with respective maximum values of 7.4 and 5.0 ppm (Bolke and Waddell, 1972, table 2).

Public Water Supplies

Hill Air Force Base uses five wells in sections 29 and 30, T. 5 N., R. 1 W., Salt Lake Base Line and Meridian, within the southern part of the quadrangle for military and culinary purposes (Smith, 1961, table 1; Bolke and Waddell, 1972, table 1). The cities of South Weber, Riverdale, Washington Terrace, and South Ogden obtain some of their culinary water from wells respectively located in sections 20 and 33, section 18, section 17, and section 8, all of T. 5 N., R. 1 W., Salt Lake Base Line and Meridian (Bolke and Waddell, 1972, table 1). The town of Uintah obtains some of its water supply from a spring, and the Uintah Highlands area obtains some of its water supply from springs and wells (Utah Division of Water Resources, 1997, table 11-1). Ogden City obtains most of its water supply from Pineview Reservoir and wells located in Ogden Valley the east of the quadrangle.

GEOLOGIC HAZARDS

Seismic Hazards

The Ogden quadrangle lies in the Intermountain seismic belt, a region of historical seismic activity that extends from northwestern Montana to southwestern Utah (Smith and Sbar, 1974). This belt contains major normal faults capable of generating large-magnitude earthquakes, including the Wasatch fault zone, as well as numerous other faults capable

Table 2. *Hydrologic budgets for the Weber Delta District aquifer system.*

	Feth and others (1966)[a] (km³/yr)	Feth and others (1966)[a] (acre-feet/yr)	Gates (1995)[b] (km³/yr)	Gates (1995)[b] (acre-feet/yr)	Clark and others (1990)[c] (km³/yr)	Clark and others (1990)[c] (acre-feet/yr)
Recharge type						
Channel seepage[d]	~ 0.025[f]	~21,000[f]	0.052	43,000	No separate estimate	
Other seepage[e]	0.007	6,000	0.007	6,000	No separate estimate	
Direct infiltration	0.012	10,000	0.008	7,000	No separate estimate	
Subsurface inflow	0.036	30,000	0.064	53,000	No separate estimate	
Total	~ 0.08	~70,000	0.131	109,000	0.130	107,000
Discharge type						
Flow to streams, springs	~ 0.023[g]	~19,000[g]	0.070	58,000	0.045	38,000
Water-well withdrawal	0.030	25,000	0.030	25,000	0.060	50,000
Evapotranspiration	0.007	6,000	0.008	7,000	0.007	6,000
Flow to Great Salt Lake	0.025	20,000	0.023	19,000	0.018	15,000
Total	~0.08	~70,000	0.131	109,000	0.130	109,000

[a] Representative of time period 1953-56 with well withdrawal for 1954; probably represents non-steady-state conditions
[b] Representative of time period 1953-56, with values adjusted to approximate steady-state conditions based on estimates of overall hydrologic budget for time period 1969-84
[c] Representative of time period 1969-84, based on modeling study with values adjusted for water removal from storage
[d] Includes losing stretches of stream channels and seepage from canals
[e] Includes irrigated fields, lawns, and gardens
[f] Approximate value, varies substantially between years
[g] Adjusted to maintain water balance with total discharge = total recharge

of generating moderate-magnitude earthquakes. Seismic hazards in the Ogden area include surface fault rupture, ground shaking, liquefaction, and seismically induced ground failure.

The Wasatch fault zone is of particular concern because of its potential for generating large earthquakes and its proximity to urban areas. Based on paleoseismic data for the past 6,000 years, the average recurrence interval for a large-magnitude (greater than 6.5) earthquake along the combined five central segments (Brigham City, Weber, Salt Lake City, Provo, and Nephi segments) of the Wasatch fault zone is about 320 years, and the average recurrence interval for a large-magnitude earthquake on an individual segment, such as the Weber, is about 1,600 years (Pechmann and Arabasz, 1995). Thus, there is a likelihood of a large-magnitude earthquake in the Ogden area in the future.

Moderate-magnitude earthquakes occur randomly along various faults in the Wasatch Front area, and may cause locally significant damage. For example, the largest historical earthquake in the Ogden area, which occurred in 1914, had an estimated magnitude of 5.5 and caused local damage (Arabasz and others, 1979). Based on historical seismicity, Pechmann and Arabasz (1995) estimate an average recurrence interval of 24 years for earthquakes having a magnitude between 5.5 and 6.5 along the Wasatch Front. Earthquakes having magnitudes less than 5.5 are more frequent, but generally do not produce significant damage.

Surface Fault Rupture

Surface faulting hazards in the Ogden area are probably greatest in belts that extend about 30 meters (100 ft) on either side of mapped scarp traces of the Wasatch fault zone. However, the Wasatch fault zone commonly consists of multiple subparallel faults that bound variably displaced blocks across a zone up to several hundred meters wide, and secondary faults locally branch away from the main zone (fault scarps in sections 10 and 15, T. 5 N., R. 1 W., Salt Lake Base Line and Meridian, plate 1), indicating that surface faulting hazards may exist over broader belts.

The last major surface faulting event on the Weber segment occurred sometime between about 700 to 1,400 years ago, based on studies along the southern part of the segment (Kaysville site; McCalpin and others, 1994) and northern part of the segment (East Ogden and North Ogden sites; Nelson, 1988; Forman and others, 1991), although limited evidence at the East Ogden site suggests a smaller event may have occurred locally about 600 years ago (Nelson, 1988). The penultimate surface-faulting event on the Weber segment occurred between 2,500 and 3,200 years ago, and the antepenultimate event occurred between 3,800 and 4,500 years ago (Nelson and others, 1987; Nelson, 1988; Forman and others, 1991). As many as six to ten surface-faulting events may have occurred along the Weber segment during the past 12,000 to 15,000 years (Nelson and Personius, 1993; McCalpin and others, 1994). Estimated magnitudes for these surface displacements and length of the Weber segment are about 7 to 7.5.

Ground Shaking

Ground shaking is the most widespread and frequently occurring seismic hazard and is responsible for the majority of earthquake-caused damage throughout the world. Significant ground shaking may occur at distances greater than 100 kilometers (60 mi) from the epicenter of a large-magnitude earthquake, and shaking may be locally amplified or dampened, depending on many factors including 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. Expected peak horizontal ground accelerations in the Ogden quadrangle are related to large earthquakes on the Wasatch fault zone. To address performance and safety issues related to earthquake ground shaking, buildings in the Ogden area should be constructed in accordance with the International Building Code (2000).

Liquefaction

Ground shaking can cause increased pressure in pore water between sediment grains and decreased intergranular stresses between grains, causing shear strengths of some sediments to decrease to near zero. When sediments undergo such liquefaction, foundations may crack, buildings may tip, buoyant buried structures may rise, and gentle slopes may fail (Lowe, 1993a). Liquefaction is most common in areas of shallow ground water (less than 9 meters [30 ft] 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 200 kilometers (120 mi) from the earthquake epicenter, based on analogy to other earthquakes (Youd and Perkins, 1987). Anderson and others (1982, 1990) produced liquefaction-potential maps that include the Ogden quadrangle, showing areas along the Weber and Ogden delta complex (Qd_3) having moderate potential, and stream alluvium (Qal) in the northwest corner of quadrangle having high potential, based partly on depth to ground water.

Earthquake-Induced Ground Failure

Local ground failure commonly accompanies earthquakes of magnitude 4.0 and greater (Keefer, 1984), and some form of ground failure (predominantly rock fall) has been noted in the descriptions of 12 earthquakes of magnitude 4.3 to 6.6 that occurred in or immediately adjacent to Utah between 1850 and 1986 (Keaton and others, 1987). Slope failure may occur as far as 300 kilometers (185 mi) from the epicenters of large-magnitude (greater than 6.5) earthquakes (Keaton and others, 1987).

Liquefaction may also induce ground failure of various types that can be very damaging. Four types of ground failure, which depend on slope of the ground surface, commonly result from liquefaction: (1) loss of bearing strength, (2) ground oscillation, (3) lateral-spread landslides, and (4) flow landslides (Youd, 1978a, 1978b, 1984; Tinsley and others, 1985). Loss of bearing strength may occur during ground shaking when underlying sediment liquefies and slopes are less than 0.5 percent (Anderson and others, 1982). The liquefied sediment is susceptible to deformation that allows buildings to settle or tilt (Tinsley and others, 1985). Ground oscillation takes place where liquefaction occurs below sediment layers that do not liquefy and slopes are too gentle for landsliding (Tinsley and others, 1985). Under these conditions, liquefaction at depth may decouple overlying sediment blocks that vibrate in different modes, causing fissuring and impacts between blocks that damage buried facilities (National Research Council, 1985; Tinsley and others, 1985). Failure by lateral spreading generally occurs on slopes between about 0.5 and 5.0 percent where surface sediment is displaced laterally downslope above a liquefied subsurface layer (Anderson and others, 1982; National Research Council, 1985). Surface sediment is commonly displaced by several to tens of meters and broken into blocks that are bounded by fissures and settle differentially, which can be especially destructive to buried facilities and structures with shallow foundations (Tinsley and others, 1985). Failure by flow slides generally occurs on slopes greater than 5 percent where liquefied surficial material containing intact blocks moves downslope above a failure plane (Anderson and others, 1982; National Research Council, 1985). Flow slides are the most catastrophic mode of liquefaction-induced failure, and masses can be displaced hundreds to thousands of meters at relatively high velocities (Tinsley and others, 1985), with potential for extensive damage to buildings and buried facilities.

A liquefaction-induced flow slide and lateral spread, the East Ogden landslide, covers approximately 10 square kilometers (4 mi^2) in the central part of the Ogden quadrangle (Qms_3 on plate 1). The slide was first identified by Pashley and Wiggins (1972) on the basis of offset and tilted beds, folds, and sand dikes exposed in deep utility trenches on the Weber State University campus. Geomorphic features, such as scarps, hummocks, closed depressions, and transverse lineaments within the landslide, suggest complex flow failure, translational sliding, and slumping (Harty and Lowe, 2003). Initial movement of the slide probably occurred in the early Holocene, but the deposit may have experienced multiple failure episodes, such as documented for some other liquefaction-induced flow slides along the Wasatch Front (Lowe and others, 1992; Harty and Lowe, 2003). Deposits related to ground oscillation and small lateral spreads may be present in the quadrangle, but would be difficult to recognize due to limited geomorphic expression.

Landslides

Many landslide deposits have been mapped in the Ogden quadrangle (various Qms on plate 1), and deposits include combinations of translational slides, rotational slides, and earth flows. Recently active slides in the quadrangle include the 1981 "railroad landslide" and 1983 “north pond” landslide in the Washington Terrace landslide complex (Gill, 1981; Lowe, 1988); the “Rainbow Gardens” landslide in the Ogden River landslide complex that underwent movement during 1987, 1988, 1992, and 1994 (Vandre and Lowe, 1995); and various small slides in the South Weber, Weber River, Ogden River landslide complexes (Pashley and Wiggins, 1972) and in older landslide complexes in the Wasatch Range (Qms_2 on plate 1). Overall, older landslides appear particularly susceptible to reactivation due to conditions that exist in previously displaced sediment masses, such as established failure planes and permeable zones (Robison and Lowe, 1993). The Weber County landslide hazards map (Weber County Planning Commission, 1988), which covers most of the Ogden quadrangle, identifies most of the recently active slides mapped on plate 1. However, other areas with relatively steep slopes may become active, particularly if ground-water conditions change or slopes are modified by construction.

Landslides may be triggered by increased pore-water pressure, oversteepening of slopes, loss of lateral support, weighting of the head, and earthquake ground shaking. Landslides are more likely to occur in years of abnormally high precipitation that tend to increase pore-water pressures, such as during the wet cycle of 1982-86, although slides also occur during drier periods. High pore-water pressure appears to be important in the “Rainbow Gardens” slide where water exits from a sand-rich interval above clayey layers in the upper part of the slide. Removal of support and oversteepening of slopes may have helped trigger several small slides along roadcuts, including a slide along part of Valley Drive that cut the Ogden River slide complex and a small slide along Utah Highway 32 in Ogden Canyon. Construction may increase the weighting of landslide heads, depending on how excavated materials are moved, and displaced fill may be susceptible to sliding. Irrigation and lawn watering may increase weighting as well as pore-water pressure, which can initiate slides. Landslides in the Ogden area may also be triggered by moderate to strong earthquakes.

Several geologic units in the quadrangle are susceptible to landslides. Slides and slumps are particularly common where incision by the Weber and Ogden Rivers has created high bluffs that expose lacustrine and deltaic sediments with locally perched water tables (Lowe and others, 1992; Robison and Lowe, 1993). Bedrock units susceptible to slides include the Precambrian Farmington Canyon Complex, which weathers to form relatively thick unstable hillside debris (colluvium), the Cambrian Ophir Shale, and the Cambrian Maxfield Limestone (Lowe and others, 1992).

The “Rainbow Gardens” landslide has been particularly active, with several periods of movement between 1987 and 1994, which resulted in movement of about 57,000 cubic meters (75,000 yd^3) of material and retreat of the main scarp by about 80 meters (250 ft) horizontally, requiring removal and relocation of two homes near the main scarp (Vandre and Lowe, 1995). Failure has been by undercutting and collapse of the upper part of the slide above springs at the base of sand-rich material, with earthflows and deposition in the lower part of the slide.

Rock Falls

Rock falls occur when erosion and gravity dislodge rocks from slopes. Large rocks may travel great distances by rolling, bouncing, and sliding down slopes at relatively high velocities, which may cause significant damage to structures and threaten lives. Potential rock-fall sources in the Ogden area include bedrock outcrops broken by bedding surfaces and fractures, which are common in the Cambrian Tintic Quartzite and Farmington Canyon Complex, and boulders on

Lake Bonneville shoreline benches. Case (1987, Utah Geological Survey unpublished mapping) mapped rock-fall sources on mountain-front spurs along the Wasatch Front, including the Ogden area. Triggering mechanisms for rock falls include water in outcrop discontinuities and ground shaking from earthquakes with magnitudes as small as 4.0 (Nelson, 1990; Keefer, 1984). In the Ogden area, rock falls have occasionally blocked traffic along canyon roads, struck vehicles, and damaged several homes in Ogden Canyon (Nelson, 1995).

Debris Flows

Debris flows are mixtures of water, rock, sediment, and organic material containing 70 to 90 percent solids by weight that form a muddy slurry much like wet concrete which flows downslope due to gravity, commonly in surges or pulses (Costa, 1984). Debris flows can form in at least two different ways: (1) overland flow and flood waters may scour materials from the ground surface and stream channels, increasing the proportion of solid materials to water until a mixture becomes a debris flow (Wieczorek and others, 1983); and (2) debris slides may reach a stream or have their water content increased by some other means until sufficient to permit flow (Lowe, 1993b). Debris flows generally remain confined to stream channels in mountainous areas (Qmf on plate 1), but spread out and deposit debris over large areas on fans (various Qaf on plate 1) beyond canyon mouths (Lowe, 1993b). Deposition of sediment takes place where flowing debris leaves constricted channels and enters fans, with a decrease in channel gradient and increase in channel area, resulting in decreased depth and velocity of flow and increased internal friction (Jochim, 1986).

Other types of alluvial-fan sedimentation are also considered in this section because debris flows, debris floods (hyperconcentrated streamflow), and normal streamflow form a continuum of mixtures that grade into each other as the relative proportion of sediment to water changes and as stream gradient changes (Pierson and Costa, 1987). Debris floods contain 40 to 70 weight percent solid materials transported by fast-moving waters, and can originate either through progressive incorporation of materials into flood waters or through dilution of debris flows (Wieczorek and others, 1983; Costa, 1984). In normal streamflow, solids account for less than 40 percent of the water-sediment mixture by weight (Costa, 1984). Because of difficulties in distinguishing debris floods from flood stages of streamflow, no adequate historical record separating such events exists for the Ogden area.

Debris-flow deposits of various ages in the quadrangle are found along parts of Cold Water, Taylor, Waterfall, Beus, Burch, and Spring Creek Canyons that drain larger mountain-front basins (Qmf on plate 1). Relatively large, likely late Holocene alluvial fans (Qaf_1 on plate 1), which probably record various combinations of debris-flow, debris-flood, and flood events, are associated with these and other canyons, and are the areas of greatest risk for debris flows and related damage. Many of these fans are variably inset into older fans, indicating multiple events over a long history from late Pleistocene through Holocene time. Smaller alluvial fans (Qaf), many of uncertain age, are also associated with most ephemeral streams that drain smaller mountain front basins, and may also pose debris-flow risks.

Recent debris flows in the Ogden area include a 1923 flow in Waterfall Canyon that was initiated by a cloudburst rainstorm falling on a watershed denuded by domestic-animal overgrazing (Croft, 1981). Many debris flows occurred along the Wasatch Front during 1983 and 1984, but none in the Ogden quadrangle. The 1983-84 debris flows were mobilized from debris slides during rapid melting of an unusually thick snowpack (Wieczorek and others, 1983, 1989; Keaton and Lowe, 1998), and damaged several homes. Recurrence intervals for debris-flow events of various magnitudes are not currently available for drainages in the Ogden quadrangle.

Flooding

Stream flooding may be caused by rain, melting snow, or a combination of both. For rivers with large drainage basins and many tributaries, like the Weber River, the primary cause of flooding is rapidly melting snow, usually occurring between late April and early July (U.S. Army Corps of Engineers, 1969; Federal Emergency Management Agency [FEMA], 1982). Snowmelt floods are characterized by large-volume runoff, moderately high peak flows, and marked diurnal fluctuation in flow (FEMA, 1982). Such floods are somewhat predictable because flood levels depend primarily on the volume of snow in the mountains and the rate of temperature increase in the spring. The largest snowmelt floods of record on the Weber River occurred in 1893, 1896, 1907, 1909, 1920, 1922, and 1952 (FEMA, 1980; Utah Division of Comprehensive Emergency Management, 1981), and more recently in 1983, 1984, and 1985.

Localized, high-intensity (cloudburst) thunderstorms are most effective in generating flooding in small drainage basins (Costa and Baker, 1981), such as those in the Wasatch Range. Such storms, which last from a few minutes to several hours, generally occur between mid-April and September, and can generate high-velocity, short-duration floods (FEMA, 1978; 1982). The flooding potential of such storms depends on intensity and duration of rainfall, distribution of rainfall over a drainage basin, soil characteristics, pre-storm soil-moisture, vegetation type, topography, and drainage pattern. Because many of these conditions are not known until rain is falling, the magnitude of flooding from a specific storm is difficult to predict. Communities in the quadrangle have experienced many historical cloudburst floods (table 3).

Flooding may also result from dam failure, which includes all unintentional releases of water from engineered dams. Four dams (Wilkinson, Echo, Wanship, and Smith-Morehouse) are located upstream of the quadrangle along the Weber River drainage, and two dams (Causey and Pineview) are located upstream along the Ogden River. Earthquake-induced ground shaking, liquefaction, landslides, and seiches could cause upstream dam failures and flooding (U.S. Bureau of Reclamation, 1982).

Shallow Ground Water

Ground water is considered to be shallow where the water table is within 9 meters (30 ft) of the ground surface. However, most problems arise only when the saturated zone

Table 3. *Historical cloudburst floods, Ogden 7.5-minute quadrangle, Utah, through 1980 (data from Utah Division of Comprehensive Emergency Management, 1981).*

City	Year
Uintah	1975, 1981
Riverdale	1956
Ogden	1888, 1901, 1905, 1908, 1912, 1913 (2), 1916 (2), 1917, 1920, 1921, 1926, 1929, 1930 (2), 1931, 1941, 1942, 1943, 1945, 1947, 1949, 1951, 1955, 1956, 1960, 1963, 1964, 1965, 1966, 1967, 1968, 1973, 1975, 1979

is within about 3 meters (10 ft) of the ground surface, because this is the depth to which many building foundations are excavated. Problems associated with shallow ground water are described in Robison and Lowe (1990) and include damage to foundations and contents of subsurface facilities such as basements; damage to underground utilities; failure of septic-tank soil-absorption fields; ground-water contamination from inundated landfills, waste dumps, storage tanks, and septic fields; buckling of roads and airport runways as bearing strengths in susceptible soils are reduced by saturation; and structural damage to foundations from wetting of collapsible or expansive soils. Shallow ground water is a particularly significant factor that must be considered when siting waste-disposal facilities and septic-tank soil-absorption systems, as pollutants can be easily introduced into shallow ground water, which may move laterally and eventually enter basin-fill aquifers, some of which are becoming increasingly contaminated (Waddell and Maxell, 1987). Shallow ground water may also cause dissolution of subsurface materials and soil piping, leading to development of sinkholes and collapse-induced depressions. Small sinkholes along the trace of the Wasatch fault zone south of the Ogden River (NW1/4 of section 26, T. 6 N., R. 1 W., Salt Lake Base Line and Meridian) may be related to movement of shallow ground water through conduits along the fault, which erodes unconsolidated sediments to create pipes that locally collapse.

Detailed data on depth to shallow ground-water are currently unavailable for the Ogden quadrangle, but regional maps indicate that depth to ground water may be less than 3 meters (10 ft) in the northwest part of the quadrangle (Hecker and others, 1988). Perched ground water is present at many locations in the quadrangle, especially in the Weber State University area and along bluffs above streams incised in the Weber River delta.

Problem Soils

Potential problem soils include collapsible (hydrocompactable) soils, compressible organic soils, and soils with a high shrink-swell potential. Problems with soils can also occur due to differential compaction when construction occurs on sediments having different characteristics. Erickson and others (1968) mapped the soils in the quadrangle. Most soils in the quadrangle have only low to moderate shrink-swell potential, but soils of the Kirkham series have a high shrink-swell potential (Erickson and others, 1968).

Radon

Radon is a colorless, odorless, tasteless, radioactive gas of geologic origin that is an environmental 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 distance due to both non-geologic (construction type, etc.) and geologic factors (geologic formation, ground-water levels, etc.), the geologic factors that influence indoor-radon levels can be quantified to assess the radon-hazard potential. Black and Solomon (1996) assessed the radon-hazard potential for much of the southern part of the Ogden quadrangle; they assigned moderate and high radon-hazard potentials to their mapped area, with most of the high radon-hazard potential areas being located along the mountain front where ground-water levels are deep. For the remainder of the Ogden quadrangle, radon-hazard potential has been assessed only in a general way (Sprinkel and Solomon, 1990; Black, 1993).

ACKNOWLEDGMENTS

The report and map benefitted from reviews by Sandy Eldredge, Bob Gloyn, Kimm Harty, Hugh Hurlow, Mike Hylland, Jon King, Greg McDonald, and Janae Wallace, Utah Geological Survey, and Jim Evans, Utah State University. Neil Storey, Weber State University, served as a field assistant for part of the work.

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