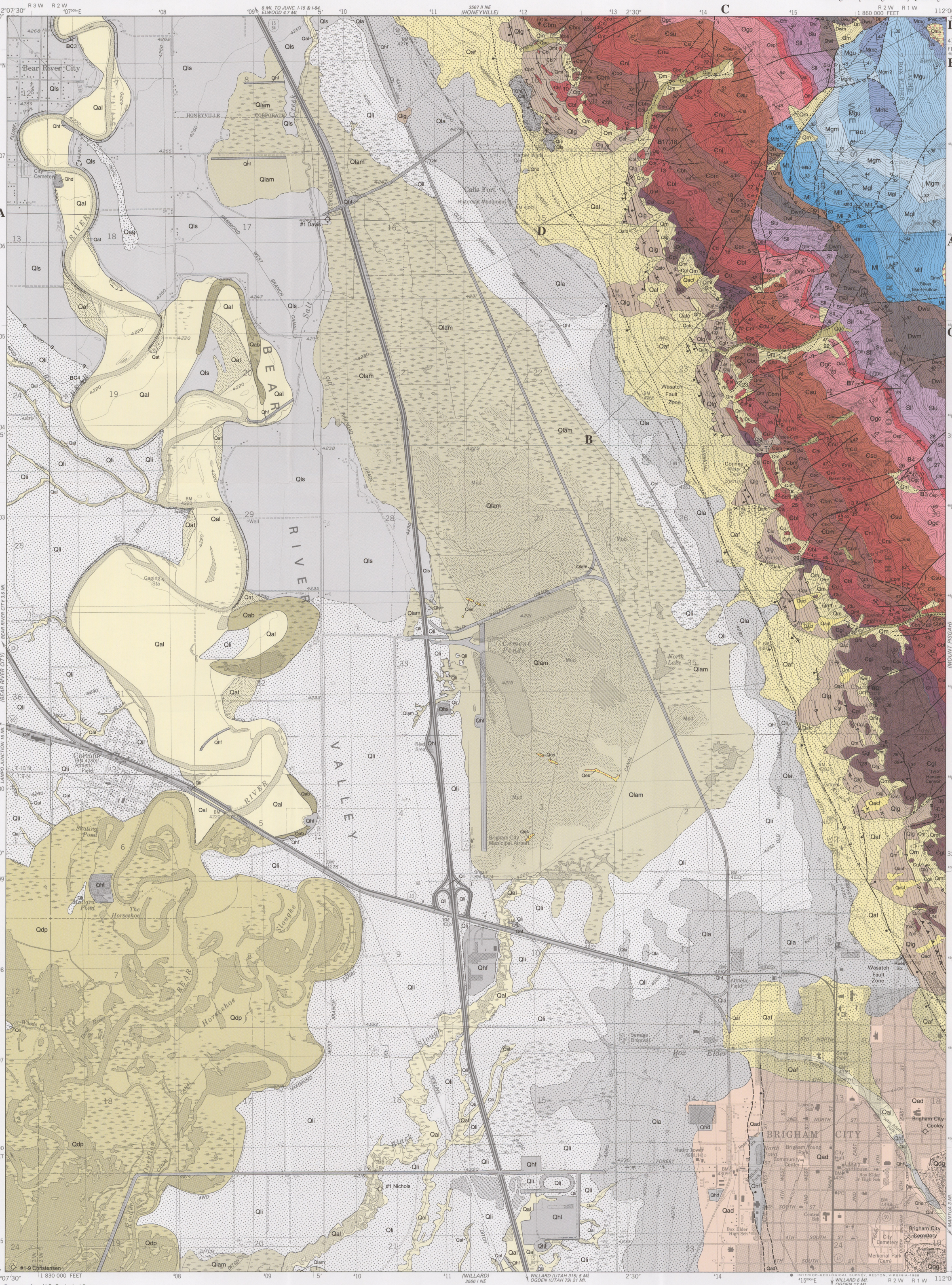
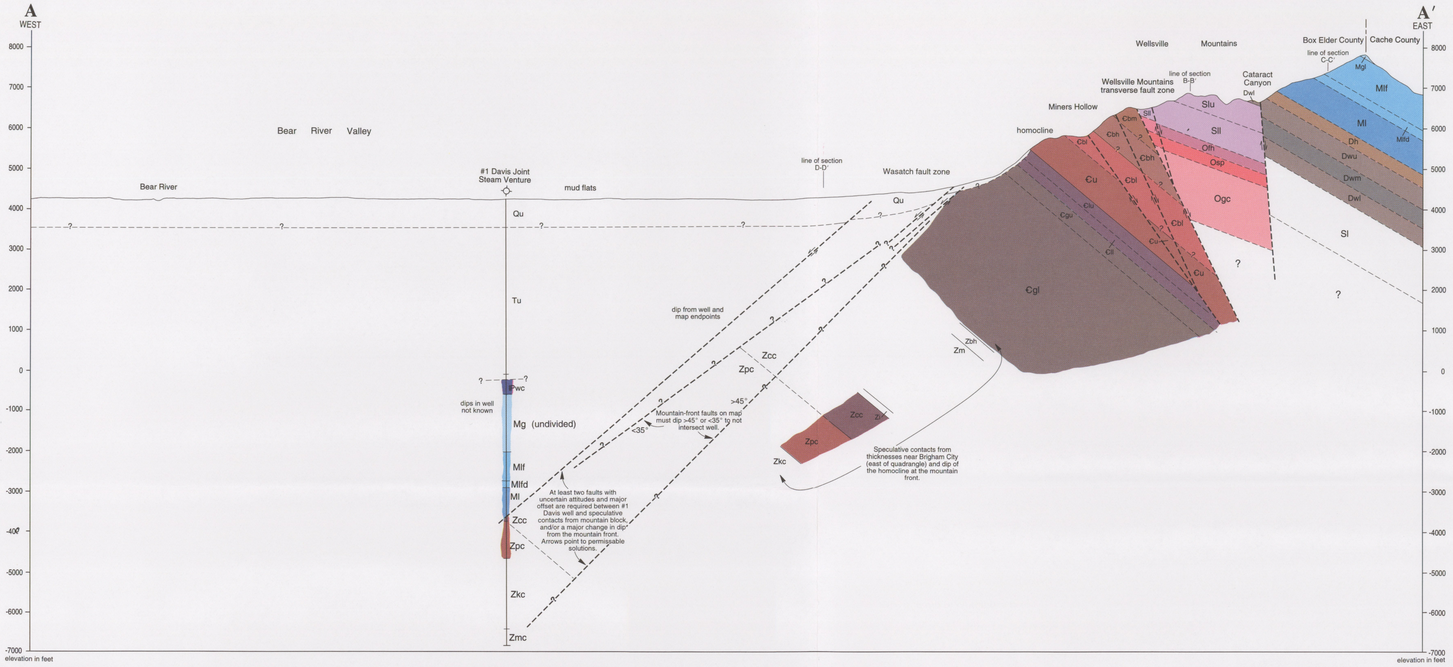
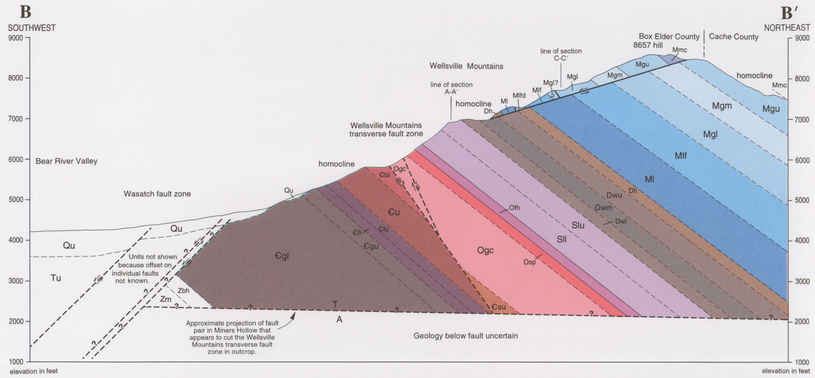
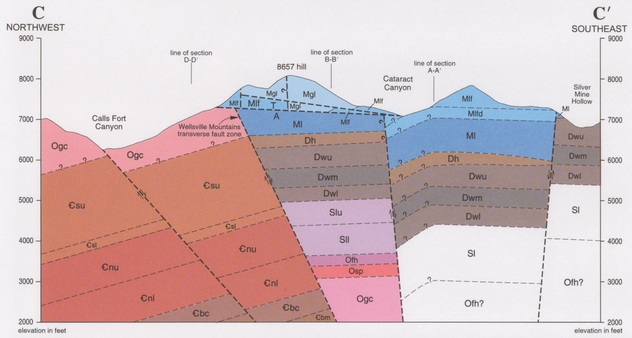
UTAH GEOLOGICAL SURVEY
a division of
UTAH DEPARTMENT OF NATURAL RESOURCES

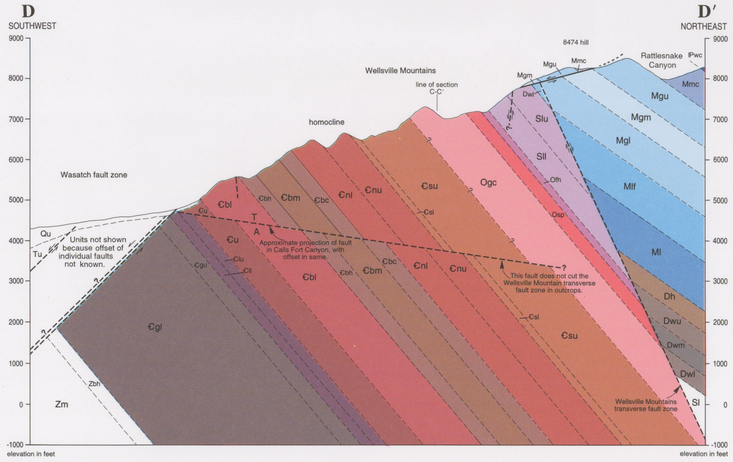

Bear River City
HONEYVILLE
CORPORATE
Calls Fort
Historical Monument
Harper Ward Cem
Wasatch Fault Zone
Corinne
Cement Ponds
North Lake
Brigham City Municipal Airport
Skating Pond
The Horseshoe
Horseshoe
Sloughs
Slough
Box Elder
Sewage Disposal
Radio Tower (KBUH)
BRIGHAM CITY
Brigham City Cooley
Brigham City Cemetery
Memorial Park (Cem)
Box Elder High Sch
Brigham Young Park
Community Center
City Hall
Library
Courthouse
Central Sch
Lincoln Sch
Athletic Field
Reservoir
#1 Davis
#1 Nichols
#1-9 Christensen
BEAR RIVER
BEAR RIVER VALLEY
Qal
Qls
Qli
Qla
Qlam
Qlg
Qaf
Qdp
Qhf
Qhd
Qhl
Qad
Qdg
Qes
Qag
Qab
Qat
Qacf
Qafo
Qm
Qmt
Qmf
Qmc
Qms
Qmg
Qmi
Qmd
Qmw
Qmy
Qmh
Qmp
Qmr
Qmu
Qmv
Qmx
Qmz
Qmb
Qmk
Qmn
Qmo
Qmq
Qmr
Qmt

UTAH GEOLOGICAL SURVEY
a division of
UTAH DEPARTMENT OF NATURAL RESOURCES









EXPLANATION

Contact, dashed where approximately located, queried where existence uncertain or location is very poorly constrained.

Faults, dashed where approximately located, queried where existence uncertain, dotted where concealed. Arrow indicates dip. Triangle arrow indicates trend and plunge of movement inferred from linear features in fault plane.

Moderately to steeply dipping normal fault, or fault with mostly dip slip movement. Bar and ball on downthrown side. Arrows show relative movement on cross sections.

Shallow-dipping normal fault (<30°). Open teeth on downthrown side. Teeth on both sides indicate abutting low-angle fault blocks. Arrows show relative movement on cross sections.

Strike-slip fault, or fault with mostly strike-slip movement. Arrows show relative movement.

Oblique-slip fault, approximate sense of movement shown by broken arrow. Only used when relative amounts of dip and strike slip are uncertain. Cross sections show movement by T-towards, and A-away.

Thrust fault (concealed trace near Kotter Canyon). Solid teeth on hanging wall.

Fault zone (map units uncertain)

Strike and dip of bedding in degrees

Strike and dip of fracture in degrees, offset uncertain

Lake Bonneville shorelines; dashed where approximately located.
- **Bonneville shoreline**
- **Provo shoreline**
- **Stansbury(?) shoreline**
- **Gilbert shoreline**
- **unnamed shoreline**

Headscarp of slide or slump

Spring with name when known (see table 6)

Tufa deposit

Fossil sample location (see table 2)

Location of cross section

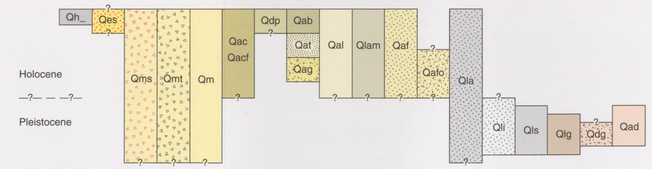
Location of measured section (see appendix)

Drill hole significant oil and gas exploration, geothermal and water wells, with name (see tables 5 and 6)

Outline of sand and gravel pit

Exploration and mine workings (numbers are those used in table 4)
- **Adit** (crossed where caved)
- **Glory hole**
- **Prospect**

CORRELATION OF QUATERNARY UNITS



DESCRIPTION OF MAP UNITS

Qhd Qhl Qhs Qhf Human disturbance - *Obscures natural deposits; origins uncertain or multiple* (Qhd); *landfill west of Brigham City* (Qhl); *sewage treatment ponds south of Corinne and northeast of the I-15 rest stop* (Qhs); *highway and railroad right-of-way fill, levees and dikes, building foundation fill, and other fill* (Qhf).

Qes Eolian sand - *Small dunes of fine-grained sand present in the mud flats north of Brigham City; ≤5 feet (≤1.6 m) thick.*

Qm Mass-movement deposits, undivided - *Includes talus and colluvium, and possibly minor debris flows and landslides.*

Qms Landslide and slump deposits - *Derived from Manning Canyon Shale in Rattlesnake Canyon, and Little Flat Formation on the east edge of the quadrangle.*

Qmt Talus deposits - *Angular debris restricted to steep slopes in the Wellsville Mountains.*

Qac Colluvium and alluvium - *Mostly gravelly deposits mapped in canyons in the Wellsville Mountains; 0 to about 30 feet (0 to 9 m) thick.*

Qacf Colluvium and fan alluvium - *Mostly gravelly, fan-shaped deposits mapped on mountain-front slopes of the Wellsville Mountains.*

Qal Stream alluvium - *Sand, silt, clay, and gravel deposited in floodplains and stream channels, and terraces along the Bear River <20 feet (<6 m) above the floodplain.*

Qag Alluvial gravel - *Pebble gravel and sand, partially cemented with calcite or tufa; only present in a linear depression southeast of Bear River City, apparently in a paleo-channel; probably <10 feet (<3 m) thick.*

Qat Alluvial-terrace deposits - *Alluvial silt, sand and gravel deposited on terrace surfaces 20+ feet (6+ m) above present Bear River floodplain and below nearby lacustrine deposits; 0 to 15+ feet (0 to 4.5+ m) thick.*

Qab Oxbow lake deposits - *Fine-grained, organic-rich sediments deposited in oxbow lakes in the Bear River floodplain.*

Qdp Deltaic-plain deposits - *Sand, silt, and clay deposited in the Bear River delta of Great Salt Lake; includes deposits in marshes, oxbow lakes, channels, point bars, and natural levees.*

Qlam Lacustrine and alluvial mud-flat and marsh deposits - *Silt, clay, and sand deposited around North Lake and the Cement Ponds, and near the Bear River delta.*

Qaf Alluvial-fan deposits - *Active fans with debris-flow levees and distinct channels; contain poorly sorted, angular boulders, cobbles, pebbles, and finer grained sediments; 0 to 35+ feet (0 to 11+ m) thick.*

Qafo Older alluvial-fan deposits - *Remnants of older fans with higher and degraded surfaces; contain poorly sorted angular boulders, cobbles, pebbles, and finer grained sediments.*

Qla Mixed lacustrine and alluvial-fan deposits - *Lacustrine sand, silt, clay and some gravel that are interbedded with, reworked, and covered with alluvial gravel, sand and mud; present in the distal end of Box Elder fan-delta, and downslope from alluvial fans along mountain front; 0 to about 70 feet (0 to 21 m) thick.*

Qdg Deltaic gravel - *Clast-supported gravel with a sand and silt matrix, deposited in the Box Elder Canyon delta during the Provo stand of Lake Bonneville; 0 to about 250 feet (0 to 75 m) thick.*

Qad Fan-delta deposits - *Clast-supported gravel, with sand and finer grained sediment deposited in Lake Bonneville lacustrine delta and alluvial fan at the mouth of Box Elder Canyon; 0 to about 125 feet (0 to 38 m) thick.*

Qlg Lacustrine gravel and sand deposits - *Rounded pebbles, cobbles, and rare boulders, mixed with sand; deposited along the shore of Lake Bonneville and includes reworked material from pre-Lake Bonneville alluvial fans; 0 to about 30 feet (0 to 9 m) thick.*

Qls Lacustrine-sand deposits - *Fine-grained, organic-rich sand deposited in Lake Bonneville and during the Gilbert inundation, and coarser grained, clean beach(?) sand deposited in Lake Bonneville; exposed in the northwestern portion of the quadrangle and in the gravel pits north of Calls Fort Canyon, respectively; about 25 feet (7.6 m) thick.*

Qll Lacustrine-silt deposits - *Silt, clay, and fine-grained sand deposited in Lake Bonneville during the Gilbert inundation, and in Great Salt Lake; 24+ feet (7.3+ m) thick.*

Qu Quaternary deposits, undivided *(only on cross section)*

Tu Tertiary rocks and deposits, undivided *(only on cross section)*

IPwc West Canyon Limestone - *Interbedded cherty limestone, calcareous sandstone, and sandy limestone; basal 160 feet (49 m) in quadrangle.*

Mmc Manning Canyon Shale - *Interbedded silty, thin-bedded, gray limestone and olive-gray to black shale; fossiliferous; about 900 feet (275 m) thick.*

Great Blue Limestone - Divided into:

Mgu upper map unit - *Dark-gray, cherty, ledge- and slope-forming limestone; fossiliferous; 740 feet (225 m) thick.*

Mgm middle map unit - *Interbedded, olive-gray mudstone and shale, and gray limestone, that form slopes and ledges, respectively; 600 feet (183 m) thick.*

Mgl lower map unit - *Medium-to dark-gray, cliff-, ledge- and slope-forming limestone; fossiliferous; about 800 feet (245 m) thick.*

Mlf Little Flat Formation - *Brown-weathering, calcareous sandstone with sandy limestone and dolomite; about 900 feet (275 m) thick including Delle Phosphatic Member.*

Mlfd Delle Phosphatic Member of the Little Flat Formation - *Resistant, cherty limestone, with underlying less- resistant, calcareous sandstone.*

Ml Lodgepole Limestone - *Gray, typically cherty limestone; about 1,000 feet (305 m) thick.*

Dh Hyrum Dolomite - *Dark-gray, thick-bedded dolomite with some sandstone (quartzite) beds; thins rapidly to the south; 0 to 450 feet (0 to 137 m) thick.*

Water Canyon Formation

Dwu upper map unit - *Light-gray dolomite; 450 feet (137 m) thick.*

Dwm middle map unit - *Yellowish sandstone and interbedded sandy dolomite and limestone; 400 feet (122 m) thick.*

Dwl lower map unit - *Light-gray, relatively thin-bedded dolomite; about 400 feet (122 m) thick.*

Sl Laketown Dolomite, undivided - *About 1,100 to 1,200 feet (335 to 365 m) thick (only on cross sections).*

Laketown Dolomite - Divided into:

Slu upper map unit - *Dolomite, usually lighter colored than lower map unit; thickness variable.*

Sll lower map unit - *Medium- to dark-gray dolomite, interlayered light and dark color in lower part; thickness variable.*

Ofh Fish Haven Dolomite - *Very dark-gray dolomite; less resistant than overlying Laketown Dolomite; about 180 feet (55 m) thick.*

Osp Swan Peak Formation - *Quartzite, shale, and limestone, with capping, pale-orange, cliff-forming quartzite; 260 to 300 feet (79 to 91 m) thick.*

Ogc Garden City Formation - *Ledge-forming limestone, with some intraformational conglomerate; chert is common in lowermost and uppermost parts; 1,330 to 1,390 feet (405 to 424 m) thick.*

St. Charles Formation - Divided into:

€su upper map unit - *Dolomite, resistant, contains interbedded sand and silt, and in upper part chert; 980 feet (299 m) thick.*

€sl lower map unit - *Worm Creek Quartzite Member at base, overlying part is thin-bedded, sandy limestone; 170 feet (52 m) thick.*

Nounan Formation - Divided into:

€nu upper map unit - *Interbedded light-colored dolomite, sandy and silty dolomite, and limestone; about 545 feet (166 m) thick.*

€nl lower map unit - *Gray dolomite; about 650 feet (198 m) thick.*

Bloomington Formation - Divided into:

Calls Fort Shale Member - *Brown-weathering shale with some interbedded thin-bedded limestone; about 235 feet (72 m) thick.*

€bc Calls Fort Shale Member

€bm middle limestone member - *Gray, resistant limestone; 515 feet (155 m) thick.*

€bh Hodges Shale Member - *Brown-weathering shale with interbeds of silty limestone; fossiliferous; 335 feet (102 m) thick.*

€bl Blacksmith Formation - *Light- to medium-gray, cliff-forming dolomite; about 810 feet (245 m) thick.*

€u Ute Formation - *Interbedded limestone and shale, sandy in upper part; about 690 feet (210 m) thick.*

Langston Formation - Divided into:

€lu upper map unit - *Dolomite and limestone, forms ledges and cliffs; about 250 feet (76 m) thick.*

€ll lower map unit - *Shale and interbedded limestone (Spence Shale Member), with limestone and dolomite, and locally sandstone (Naomi Peak Member) at base; about 230 feet (70 m) thick.*

Geertsen Canyon Quartzite - Divided into:

€gu upper map unit - *Brown-weathering, medium- to coarse-grained, quartzite and interbedded argillite; contains cross-bedding, Skolithos (vertical burrows) and horizontal worm burrows; about 360 feet (110 m) thick.*

€gl lower map unit - *Light-colored, medium- to coarse-grained quartzite; contains cross-bedding, and pebble layers and lenses; estimated 3,500 feet (1,067 m) thick in the Wellsville Mountains.*

Zbh Browns Hole Formation (only on cross section)

Zm Mutual Formation (only on cross section)

Zi Inkom Formation (only on cross section)

Zcc Caddy Canyon Quartzite - *Gray-green quartzite; only exposure near Kotter Canyon; basal 100 feet (30 m) exposed.*

Zpc Papoose Creek Formation - *Interbedded dark-weathering quartzite and argillite; bedding surfaces are green and micaceous; only exposure near Kotter Canyon; top 30 feet (9 m) exposed.*

Zkc Kelley Canyon Formation (only on cross section)

Zmc Maple Canyon Formation (only on cross section)

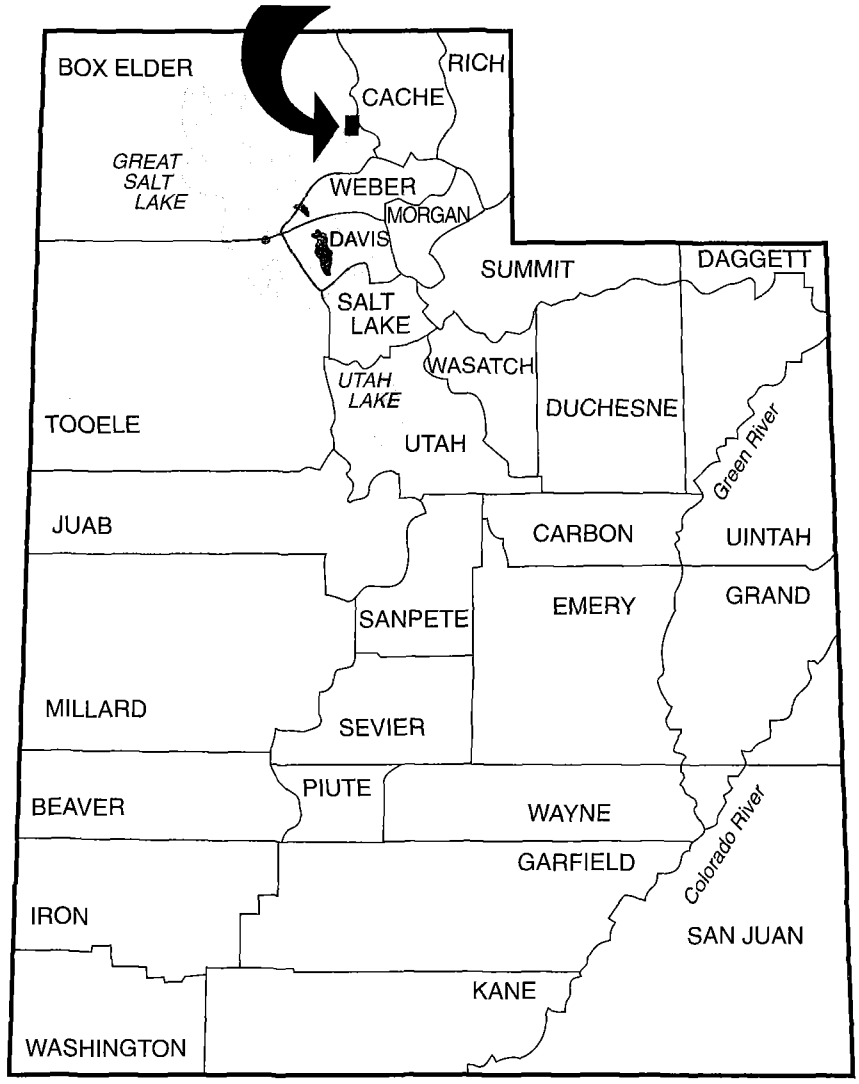
TIME STRAT. UNIT		FORMATION		SYMBOL	THICKNESS in feet		LITHOLOGY
PENN.	Lower	West Canyon Limestone		IPwc	160+		
MISSISSIPPIAN	Chesterian	Manning Canyon Shale		Mmc	~900		
		Great Blue Limestone	upper	Mgu	~2150	740	
			middle	Mgm		600	
			lower	Mgl		~800	
	?						
	Meramecian	Little Flat Formation		Mlf	~900		
		(Delle Phosphatic Mbr.)		(Mlfd)			
	Osagean	Lodgepole Limestone		Ml	~1000		
	Kinderhookian						
DEVONIAN	Middle	Hyrum Dolomite		Dh	0-450		
	?						
	Lower	Water Canyon Formation	upper	Dwu	~1250	450	
			middle	Dwm		400	
			lower	Dwl		~400	
SILURIAN	U.	Laketown Dolomite		(Slu)	1100-1200		
	?						
	Middle			Sl			
	Lower			(Sll)			
ORDOVICIAN	Upper	Fish Haven Dolomite		Ofh	180		
		Swan Peak Formation		Osp	260-300		
	Middle	Garden City Formation		Ogc	1330-1390		
	Lower						
CAMBRIAN	Upper	St. Charles Formation	upper	€su	1150	980	
			lower	€sl		170	
		Nounan Formation	upper	€nu	1195	~545	
			lower	€nl		~650	
	Middle	Bloomington Formation	Calls Fort Shale	€bc	~1085	~235	
			middle limestone	€bm		515	
			Hodges Shale	€bh		335	
		Blacksmith Formation		€bl	~810		
		Ute Formation		€u	~690		
		Langston Formation	upper	€lu	~480	~250	
			lower	€ll		~230	
	?						
	Lower	Geertsen Canyon Quartzite	upper	€gu	est. 3860+	360	est. 3500+
			lower	€gl			
PROTERZOIC	Upper	Browns Hole Formation		Zbh		covered/faulted shown only on cross section	
		Mutual Formation		Zm			
		Inkom Formation		Zi			
		Caddy Canyon Quartzite		Zcc	100+		
		Papoose Creek Formation		Zpc	30+		
		Kelley Canyon Formation		Zkc		covered/faulted shown only on cross section	
		Maple Canyon Formation		Zmc			

ISBN 1-55791-625-X

GEOLOGIC MAP OF THE BRIGHAM CITY 7.5-MINUTE QUADRANGLE, BOX ELDER AND CACHE COUNTIES, UTAH

by

Mark E. Jensen and Jon K. King



MAP 173 1999
UTAH GEOLOGICAL SURVEY
a division of
UTAH DEPARTMENT OF NATURAL RESOURCES

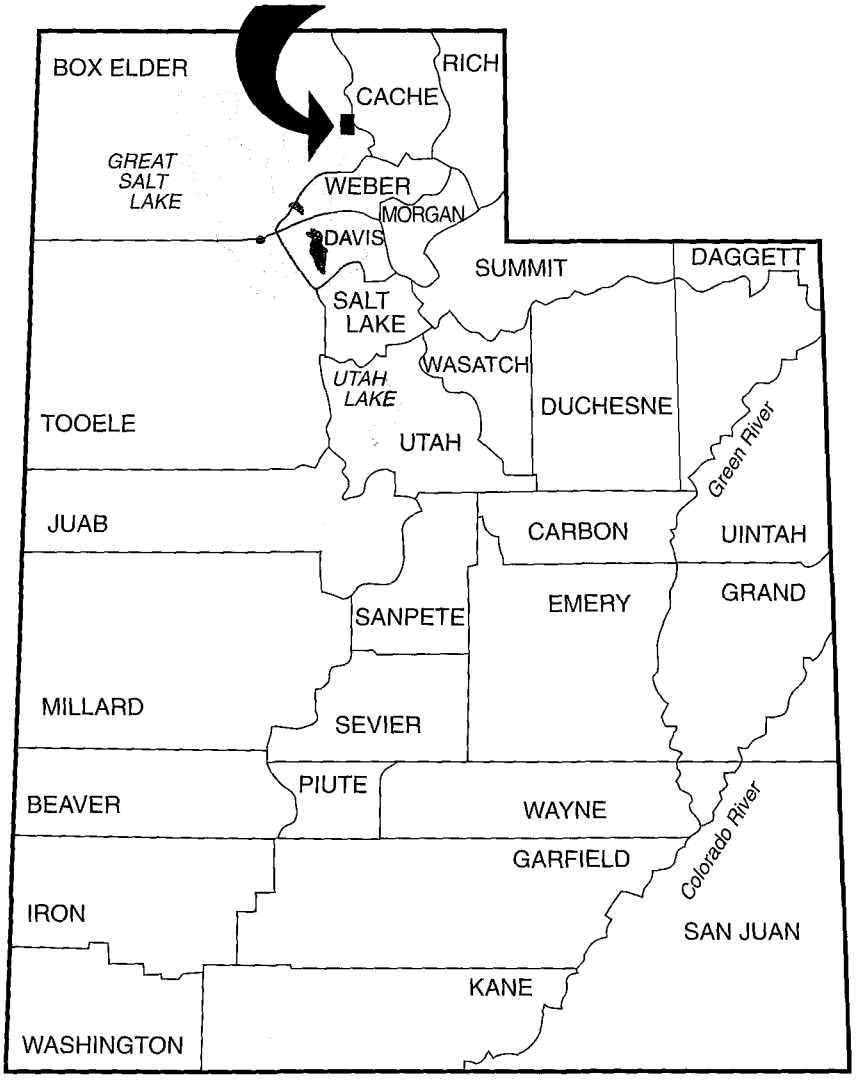
Jensen and King
GEOLOGIC MAP OF THE BRIGHAM CITY 7.5-MINUTE QUADRANGLE, BOX ELDER AND CACHE COUNTIES, UTAH
Utah Geological Survey Map 173

ISBN 1-55791-625-X

GEOLOGIC MAP OF THE BRIGHAM CITY 7.5-MINUTE QUADRANGLE, BOX ELDER AND CACHE COUNTIES, UTAH

by

Mark E. Jensen and Jon K. King



MAP 173 1999

UTAH GEOLOGICAL SURVEY

a division of

UTAH DEPARTMENT OF NATURAL RESOURCES

UTAH GEOLOGICAL SURVEY

The **UTAH GEOLOGICAL SURVEY** is organized into five geologic programs with Administration, Editorial, and Computer Resources providing necessary support to the programs. The **ECONOMIC GEOLOGY PROGRAM** undertakes studies to identify coal, geothermal, uranium, hydrocarbon, and industrial and metallic resources; initiates detailed studies of these resources including mining district and field studies; develops computerized resource data bases, to answer state, federal, and industry requests for information; and encourages the prudent development of Utah's geologic resources. The **APPLIED GEOLOGY PROGRAM** responds to requests from local and state governmental entities for engineering-geologic investigations; and identifies, documents, and interprets Utah's geologic hazards. The **GEOLOGIC MAPPING PROGRAM** maps the bedrock and surficial geology of the state at a regional scale by county and at a more detailed scale by quadrangle. The **GEOLOGIC EXTENSION SERVICE** answers inquiries from the public and provides information about Utah's geology in a non-technical format. The **ENVIRONMENTAL SCIENCES PROGRAM** maintains and publishes records of Utah's fossil resources, provides paleontological and archeological recovery services to state and local governments, conducts studies of environmental change to aid resource management, and evaluates the quantity and quality of Utah's ground-water resources.

The UGS Library is open to the public and contains many reference works on Utah geology and many unpublished documents on aspects of Utah geology by UGS staff and others. The UGS has several computer data bases with information on mineral and energy resources, geologic hazards, stratigraphic sections, and bibliographic references. Most files may be viewed by using the UGS Library. The UGS also manages a sample library which contains core, cuttings, and soil samples from mineral and petroleum drill holes and engineering geology investigations. Samples may be viewed at the Sample Library or requested as a loan for outside study.

The UGS publishes the results of its investigations in the form of maps, reports, and compilations of data that are accessible to the public. For information on UGS publications, contact the Natural Resources Map/Bookstore, 1594 W. North Temple, Salt Lake City, Utah 84116, (801) 537-3320 or 1-888-UTAH MAP. E-mail: nrugs.geostore@state.ut.us and visit our web site at http://www.ugs.state.ut.us.

UGS Editorial Staff

J. Stringfellow	Editor
Vicky Clarke, Sharon Hamre	Graphic Artists
Patricia H. Speranza, James W. Parker, Lori Douglas	Cartographers

2/99

GEOLOGIC MAP OF THE BRIGHAM CITY 7.5-MINUTE QUADRANGLE, BOX ELDER AND CACHE COUNTIES, UTAH

by
Mark E. Jensen[1] and Jon K. King
Utah Geological Survey

ABSTRACT

The Brigham City 7.5-minute quadrangle contains parts of the lower Bear River Valley and Wellsville Mountains. The mountain front is a part of the Wasatch Front, produced by displacement along the Wasatch fault zone. This fault zone is the most significant geologic feature in the quadrangle. The largest geologic feature in the Wellsville Mountains is a northeast-dipping homocline; it contains one of the more complete Cambrian sedimentary sections in northern Utah and a well-exposed record of Paleozoic continental shelf deposition. The mountains are broken by numerous faults and contain evidence for contraction during the Cretaceous to early Tertiary Sevier orogeny. A segmented major fault, transverse to the mountain front, divides the mountains into geologically different blocks. The mountain-front and subsurface data constrain the displacement during late Tertiary to present-day extension along the Brigham City segment of the Wasatch fault zone. Latest Pleistocene Lake Bonneville and two earlier Pleistocene lakes occupied the lower Bear River Valley. The Box Elder Canyon delta, a significant source of sand and gravel, formed in Lake Bonneville on the southeastern margin of the quadrangle. A deep borehole in the quadrangle provided additional data on Proterozoic rocks in northern Utah.

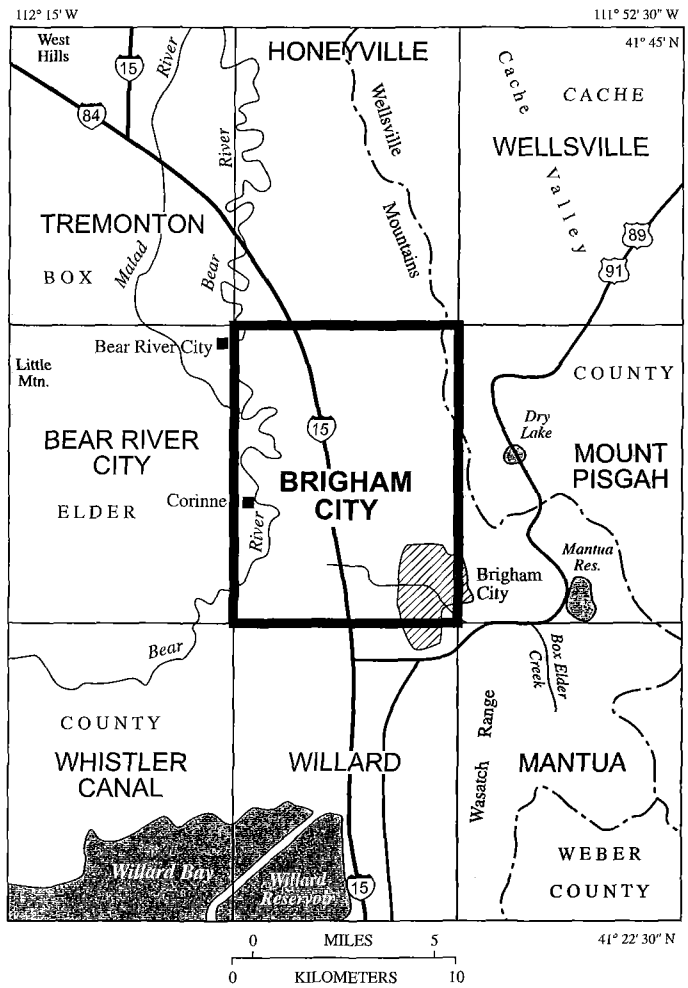


Figure 1. *Index map of the Brigham City area. Names of adjoining 7.5-minute quadrangles are in bold.*

INTRODUCTION

The Brigham City 7.5-minute quadrangle is located in northern Utah on the western side of the Wellsville Mountains and eastern side of the lower Bear River Valley (figure 1), along the northern Wasatch Front. The Wasatch Front is the eastern transitional boundary of the Basin and Range Province into the Middle Rocky Mountains Province (Stokes, 1986). Within the quadrangle, the Wasatch fault zone trends about N 25° W along the mountain front, from the southeastern border to the center of the northern edge (figures 1 and 2). East of the Wasatch fault zone, bedrock is exposed in a northeast-dipping (30° to 50°) homocline in the Wellsville Mountains. The rest of the quadrangle is in the Bear River Valley, where unconsolidated sediments are exposed and are presently being deposited. Another major structure in the quadrangle is a large-displacement (up to about 1 mile [1.6 km] of stratigraphic offset) fault that trends

[1] *currently with Utah Department of Environmental Quality, Division of Drinking Water.*

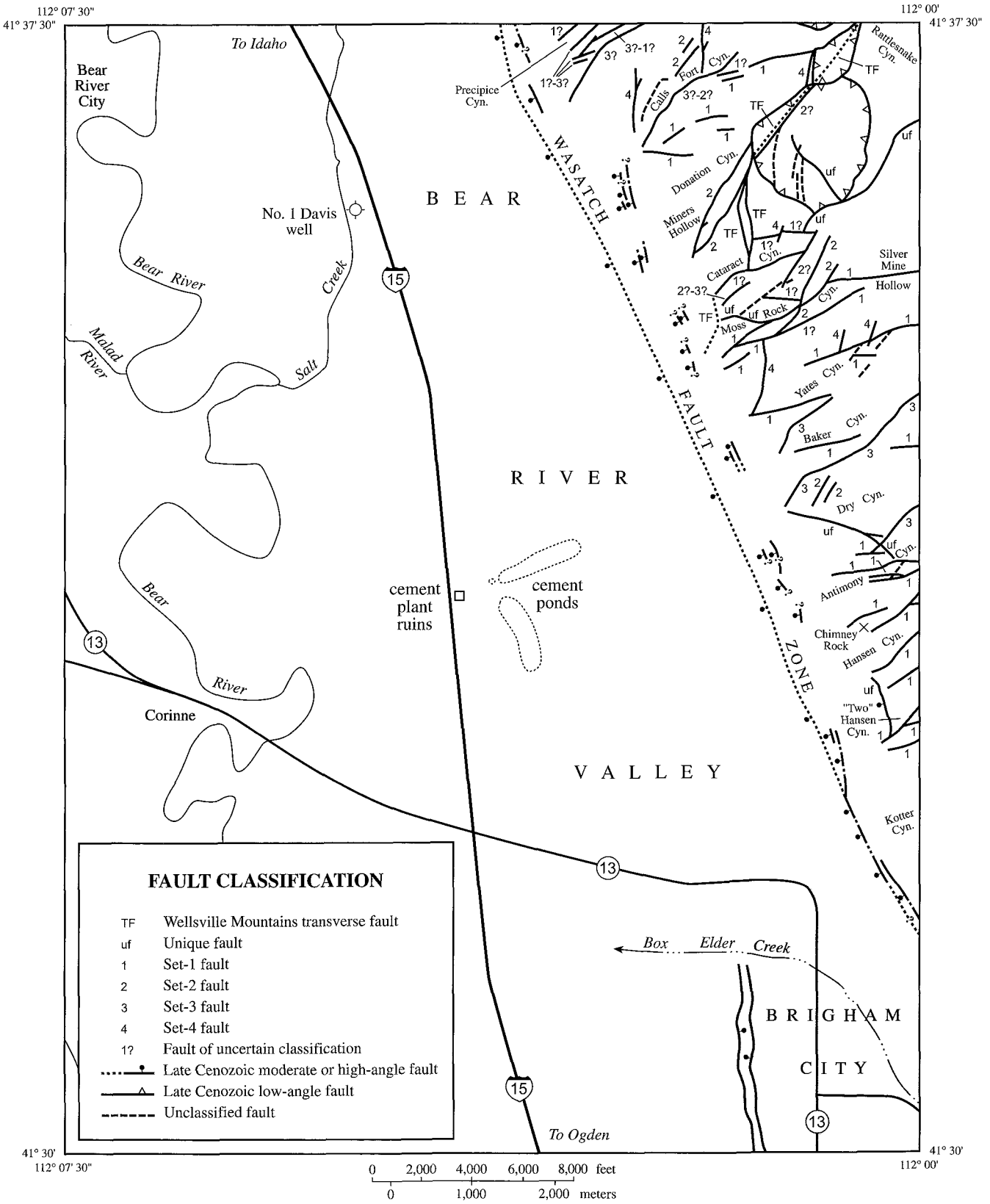


Figure 2. *Location map of various features and faults in the Brigham City 7.5-minute quadrangle, with fault classification.*

roughly N 25° E, transverse to the Wellsville Mountains. This structure, herein referred to as the Wellsville Mountains transverse fault zone, cuts the northeastern corner of the quadrangle and extends into the Honeyville and Wellsville quadrangles (plate 1; Davis, 1985). The Wellsville Mountains transverse fault zone is broken into several segments by other faults (figure 2), and divides the Wellsville Mountains into two blocks with different geologic characteristics. The most important difference is the absence of the Manning Canyon Shale north of the transverse fault zone.

Geographically, the quadrangle is mostly in Box Elder County; the northeastern edge is in Cache County. Parts of the communities of Brigham City, Corinne, and Bear River City are in the quadrangle. The Bear River flows through the western margin of the quadrangle and is joined by the Malad River south of Bear River City. Box Elder Creek flows through Brigham City.

The names used for several canyons in the Wellsville Mountains have changed on maps over time or are ambiguous (compare Williams, 1948; Gelnett, 1958; Brigham City 7.5-minute quadrangle topographic map, 1955, 1969 and 1988; Mount Pisgah 7.5-minute quadrangle topographic map, 1955, 1969, 1988 and 1991) such that the locations of some geologic features, and measured and type sections are uncertain (for example Walcott, 1908; Eardley and Hatch, 1940; Beus, 1958; Gelnett, 1958; Maxey, 1958). Almost all the names used in this report are those shown on the 1988 Brigham City 7.5-minute quadrangle topographic map (base map for plate 1). The exceptions, Silver Mine Hollow (NE$^1/_2$ section 19, T. 10 N., R. 1 W.) (all locations in this report are Salt Lake Baseline and Meridian) and Hansen Canyon (referred to as "two" Hansen Canyon in this report; NW$^1/_2$ section 6, T. 9 N., R. 1 W.), have been added on the base map, and are shown on figure 2, and on the 1991 Mount Pisgah, and 1969 and 1955 Brigham City 7.5-minute quadrangle topographic maps.

Several geologic maps covering the Brigham City and adjacent quadrangles were available to us. Gelnett (1958) mapped the southern half of the Wellsville Mountains, including the bedrock in the Brigham City quadrangle, and was the first to recognize the Wellsville Mountains transverse fault zone and the geologically different blocks. At smaller scales, Doelling (1980) studied and mapped the geology of Box Elder County (1:125,000), and Davis (1985) compiled a geologic map of the northern Wasatch Front (1:100,000) that encompassed the quadrangle. Surficial geologic maps that cover the Brigham City area include a small-scale (1:100,000), preliminary map by Miller (1980) and a small-scale (1:50,000) map by Personius (1990) that focused on the Wasatch fault zone. The soil survey of the eastern part of Box Elder County (Chadwick and others, 1975) covered the Bear River Valley in the Brigham City quadrangle, and was used to help delimit some Quaternary map units. The most detailed gravity map of the area, though regional in scope, was produced by Peterson (1974; see also Zoback, 1983).

Previous geologic mapping in adjacent 7.5-minute quadrangles provided control for our mapping (quadrangle names shown on figure 1). Adjacent maps at 1:24,000-scale cover the (1) Mantua and Willard (Crittenden and Sorensen, 1985), (2) Bear River City (Jensen, 1994), and (3) Honeyville (Oviatt, 1986a) quadrangles. Adjacent maps at other scales cover: (1) a small area just east of Brigham City in the Mount Pisgah quadrangle (Sorensen and Crittenden, 1976); (2) the Logan 30-minute quadrangle, which includes the Wellsville and Mount Pisgah quadrangles (Williams, 1948); and (3) the Logan 30 x 60-minute quadrangle, which includes the Wellsville and Mount Pisgah quadrangles (Dover, 1985).

Several discrepancies exist where our map of the Brigham City quadrangle (plate 1) adjoins the Honeyville quadrangle map of Oviatt (1986a). Differences in Quaternary mapping are discussed under the specific Quaternary unit. Differences in Cambrian contacts near Precipice Canyon occur because several previously unmapped faults on the south side of Precipice Canyon extend into the Honeyville quadrangle, and an outcrop of Bloomington Formation extends into Lake Bonneville deposits. Contacts of Ordovician and Silurian strata do not precisely match because it is difficult to plot contacts on steep slopes, and subdivision of the Laketown Dolomite is ambiguous (see description in stratigraphy section). The discrepancies in identification of Mississippian, Pennsylvanian, and Permian strata are due to different geologic relationships on opposite sides of the Wellsville Mountains transverse fault zone (see description in structural geology section), which barely enters the Honeyville quadrangle.

STRATIGRAPHY

Rocks exposed in the Brigham City quadrangle range in age from Precambrian to Pennsylvanian. Exposed Precambrian, Mississippian and Pennsylvanian rocks were penetrated by a deep borehole in the Bear River Valley, as were additional, unexposed Proterozoic and Tertiary rocks (table 1). Surficial deposits are Quaternary in age. Bedrock, from the earliest Cambrian Geertsen Canyon Quartzite to the Pennsylvanian West Canyon Limestone of the Oquirrh Group, is well ex-

Table 1.

Formation and unit tops in the #1 Davis, Utah Joint Steam Venture (Geothermal Kinetics) geothermal exploration well (SW1/4 SW1/4 SW1/4 section 16, T. 10 N., R. 2 W.). Formation picks are bold and tops used in cross section A-A´ (plate 2) are underlined.

Ground level - 4,251 feet
Surface material - Quaternary deposits
Total depth - 10,986 or 11,005 feet

UNIT TOPS BY SOURCE
[notes in brackets are by King]

DEPTH (in feet)	Campbell (in Doelling, 1980)	Morgan and Yonkee (unpublished, 1990-1)	King (this report)
580	**Salt Lake Formation**	**Salt Lake Formation**	no pick
680	no pick	no pick	**Salt Lake Formation** more consolidated Salt Lake - lithic sandstone of dark carbonate, Paleogene(?)
2,110	no pick	no pick	
4,295	no pick	no pick	
4,380	**Jefferson Formation** [Little Flat]	no pick	no pick
4,440	no pick	**West Canyon Limestone**	sandstone?, Great Blue (?)
4,790	no pick	**Great Blue Limestone** [40% too thick]	carbonate? or shale?, Great Blue(?)
5,360	thrust fault	no pick	no pick
5,360	**Manning Canyon Shale**	no pick	no pick
5,365	no pick	no pick	shale, Manning Canyon(?)
6,210	**Great Blue Limestone**	no pick	no pick
6,230	no pick [section incomplete-900 feet of Little Flat missing]	**Humbug Formation [Little Flat]**	carbonate?, Great Blue (?) or Little Flat(?)
6,870	no pick	Deseret Limestone	sandstone?
6,958	no pick	Lodgepole Limestone	**Delle Phosphatic Member of Little Flat(?)**
7,100	no pick	no pick	no pick
7,102	**Lodgepole Limestone** [section incomplete-at least 2,500 feet of Devonian and Silurian missing]	no pick	limestone, **Lodgepole(?)**
7,840	**Swan Peak Formation**	no pick	no pick
7,845	no pick	**FAULT**	**FAULT**
7,845	no pick	**Caddy Canyon Formation**	**Caddy Canyon Formation**
7,932	no pick	**Papoose Creek Formation**	no pick
7,970	no pick	no pick	**Papoose Creek Formation**
8,300	thrust fault	no pick	no pick
8,300	**Geertsen Canyon Quartzite** [Clem and Brown, 1985]	no pick	no pick
8,340	no pick	dolomite	no pick
8,850	no pick	no pick	**Kelley Canyon(?) Formation**
8,864	no pick	**Kelley Canyon Formation**	no pick
8,890	no pick	no pick	**Kelley Canyon Formation**
10,390	no pick	no pick	limestone
10,400-10,480 [samples missing]			
10,430	no pick	**Maple Canyon Formation**	no pick
10,570-10,590	no pick	no pick	dolomite
10,590	no pick	no pick	**Maple Canyon Formation**

posed in the Wellsville Mountains. Precambrian (Upper Proterozoic) rocks are exposed in a single isolated outcrop near Kotter Canyon (figure 2; plate 2, lithologic column). These Upper Proterozoic and Paleozoic rocks were deposited on a rifted and slowly subsiding continental-shelf margin (Hintze, 1988). The Cambrian section east of Calls Fort is probably as nearly complete as any section in northern Utah (see Maxey, 1958). Maxey (1941, 1958) measured sections from the base of the upper member of the Geertsen Canyon Quartzite to the Ordovician Garden City Formation. As noted in the following descriptions, some unit thicknesses are different on opposite sides of the Wellsville Mountains transverse fault zone.

Proterozoic

Several Upper Proterozoic formations were encountered in a deep borehole (#1 Davis, Utah Joint Steam Venture, geothermal borehole; section 16, T. 10 N., R. 2 W.) in the quadrangle (table 1). W.A. Yonkee of Weber State University first identified these formations from drill cuttings archived at the Utah Geological Survey (written communication, 1991; table 1, this report). During this study, King examined the cuttings, and geophysical and lithologic logs of the hole, and concurred with Yonkee's identifications. The borehole penetrated (in descending order) the Caddy Canyon, Papoose Creek, Kelley Canyon and Maple Canyon Formations. Because the contacts between some formations are gradational, the exact depths of these contacts are subject to interpretation. The Upper Proterozoic Inkom, Mutual and Browns Hole Formations that overlie the aforementioned formations in the adjacent Mantua, Willard and Mount Pisgah quadrangles (Sorensen and Crittenden, 1976; Crittenden and Sorensen, 1985) were not encountered in the borehole because of faulting. Rocks in the Inkom, Mutual and Browns Hole Formations are so unique that, if present, they would have been easily identified in drill cuttings. The Papoose Creek, Caddy Canyon, Inkom, Mutual, Browns Hole, and Geertsen Canyon Formations were formally defined to the east in the Huntsville, Utah area, and compose (in ascending order) the Brigham Group (Crittenden and others, 1971). The only Proterozoic formations exposed in the quadrangle are in an isolated outcrop near Kotter Canyon that contains the Caddy Canyon-Papoose Creek contact.

Maple Canyon Formation (Zmc; subsurface only)

Crittenden and others (1971) and Crittenden and Sorensen (1985) recognized three informal members in the Maple Canyon Formation. Only the upper member was encountered in the borehole. In outcrop, the upper member reportedly contains two, coarse-grained to conglomeratic, white quartzite units or two, coarse-grained to conglomeratic, green arkosic quartzite units. Olive-drab to green laminated siltstone or argillite separates the white or green quartzites. At the type locality near Huntsville, Utah this upper member is 60 to 500 feet (18 to 150 m) thick, but is typically 200 feet (60 m) thick. The middle member is a green arkosic quartzite (Crittenden and others, 1971; Crittenden and Sorensen, 1985). In the #1 Davis geothermal borehole (total depth 11,005 feet [3,354 m]), white quartzites were in drill cuttings from the last 415 to 575 feet (126 to 175 m) of the hole.

Kelley Canyon Formation (Zkc; subsurface only)

The Kelley Canyon Formation is dominantly thin-bedded, dark-gray to black argillite or phyllite that conformably overlies the Maple Canyon Formation. A distinctive bed 10 feet (3 m) thick of dolomite is present at the base of the Kelley Canyon at the type section near Huntsville. This dolomite and the lenticular, thin-bedded, silty limestones in the middle portion of the formation are examples of the rare carbonates in upper Proterozoic rocks in Utah. This formation is about 600 feet (180 m) thick in exposures near Brigham City (Crittenden and others, 1971; Sorensen and Crittenden, 1976; Crittenden and Sorensen, 1985). About 2,000 feet (610 m) of Kelley Canyon is exposed near Huntsville, where the overlying Papoose Creek Formation is absent (Crittenden and others, 1971; Sorensen and Crittenden, 1979).

In the #1 Davis geothermal borehole, King picked the Maple Canyon-Kelley Canyon contact at a depth of 10,590 feet (3228 m), based on dolomite in drill cuttings over an interval of about 20 feet (6 m). From cuttings, most of the Kelley Canyon is interpreted as dark phyllite containing scattered, unbedded calcite; other interpreted units are a well-indurated siltstone (quartzite) and limestone near the base, and a limestone near the top of the lower third of the formation. Yonkee (written communication, 1991) picked the basal Kelley Canyon at the top of the first quartzite, at a depth of about 10,430 feet (3,179 m).

Yonkee (written communication, 1991) picked the contact of the Kelley Canyon Formation with the overlying Papoose Creek Formation at a depth of 8,864 feet (2,702 m) in the borehole. This pick was apparently based on a change in the sonic logs, though the character of the geophysical borehole logs changes at several depths between 8,854 and 8,900 feet (2,699 and 2,713 m). From cuttings, a gradational change from dark-gray, argillitic (to phyllitic) siltstone and gray quartzite

(Papoose Creek) to dark-gray, almost black phyllite (or argillite)(Kelley Canyon) occurs over an interval of about 100 feet (30 m)(8,850 to 8,950 feet [2,697 to 2,728 m]). Therefore, the borehole penetrated 1,480 to 1,736 feet (451 to 529 m) of Kelley Canyon, far greater than its thickness (600 feet [180 m]) in nearby outcrops.

Papoose Creek Formation (Zpc)

In exposures near Brigham City, the Papoose Creek Formation is reportedly gray, brown, and greenish-brown siltstone with interbedded, similarly colored, fine-grained, quartzitic sandstone and medium- to coarse-grained quartzite (Sorensen and Crittenden, 1976; Crittenden and Sorensen, 1985). The unit is distinguished by fine-grained sandstone dikelets that fill apparent shrinkage fractures normal to bedding. The Papoose Creek Formation conformably overlies and is gradational into the Kelley Canyon Formation, and is 750 to 1,500 feet (225 to 455 m) thick in this area (Sorensen and Crittenden, 1976; Crittenden and Sorensen, 1985). Yonkee (written communication, 1991) placed the upper contact of the Papoose Creek Formation at a depth of 7,932 feet (2,418 m) in the geothermal borehole, apparently based on a change in gamma-ray response. King noted definite Papoose Creek siltstone fragments in the borehole cuttings at a depth of about 7,970 feet (2,429 m). Therefore, the borehole penetrated about 890 to 930 feet (271 to 283 m) of Papoose Creek, within the thickness range in outcrops near Brigham City.

The lower 30 feet (9 m) of an isolated outcrop just south of Kotter Canyon has been identified as the Papoose Creek Formation because this interval contains interbedded, light-gray to greenish-gray, fine- to medium-grained quartzite, and darker colored argillite or siltstone with greenish, micaceous bedding surfaces. Both quartzite and argillite weather dark yellowish brown, and bedding is largely defined by the argillite. The outcrop is mostly very thin bedded, though it varies from laminated to medium bedded. Bedding surfaces show apparent relict mud cracks filled with quartzite. The conformable contact with the overlying unit was placed at a sharp change to the lighter weathered colors and thicker bedding of the overlying Caddy Canyon Quartzite. This contact is apparently the same as the Papoose Creek-Caddy Canyon contact of Sorensen and Crittenden (1976) in the Mount Pisgah quadrangle, even though they stated that the contact is gradational rather than sharp.

Caddy Canyon Quartzite (Zcc)

In exposures near Brigham City, the Caddy Canyon Quartzite reportedly conformably overlies and grades into the Papoose Creek Formation, and is about 1,000 feet (305 m) thick (Sorensen and Crittenden, 1976; Crittenden and Sorensen, 1985). The Caddy Canyon is fine- to medium-grained, medium- to thick-bedded, vitreous quartzite that varies in color (tan, green, blue-green or purple, and locally light gray to white and pink)(Sorensen and Crittenden, 1976; Crittenden and Sorensen, 1985). Drill cuttings from a depth of about 7,880 feet (2,400 m) in the geothermal borehole are dominantly vitreous quartzite chips with the variety of colors found in the Caddy Canyon. Cuttings above this depth contain probable Lodgepole Limestone (table 1) and a fault has been inferred at a depth of about 7,845 feet (2,391 m). Therefore, only about 100 feet (30 m) of the basal Caddy Canyon Quartzite is present in the borehole.

The upper 100 feet (30 m) of the isolated outcrop south of Kotter Canyon is Caddy Canyon Quartzite. The rocks are light-gray and greenish-gray, medium- to thick-bedded, fine-grained quartzite that is not vitreous. The quartzite looks like the quartzite in the underlying Papoose Creek and weathers to dark-brown-stained outcrops. This darker staining distinguishes the Caddy Canyon outcrops from similar Geertsen Canyon Quartzite exposures upslope.

Inkom Formation (Zi; subsurface only)

Near Brigham City in the Mantua quadrangle, complete exposures of the Inkom Formation are about 150 feet (45 m) thick. The Inkom includes a lower, laminated, green-weathering siltstone, with lenses of silver- to gray-weathering, black tuff; and an upper, dark-green, very fine-grained sandstone (Sorensen and Crittenden, 1976; Crittenden and Sorensen, 1985).

Mutual Formation (Zm; subsurface only)

In exposures near Brigham City in the Mantua quadrangle, the Mutual Formation is 2,200 to 2,600 feet (670 to 790 m) of medium- to coarse-grained, locally pebbly, gray quartzite that weathers to distinct dark shades of purple, grayish red, and less commonly green or brown. The quartzite is locally feldspathic and commonly cross-bedded (Sorensen and Crittenden, 1976; Crittenden and Sorensen, 1985).

Browns Hole Formation (Zbh; subsurface only)

The Browns Hole Formation rests conformably on the Mutual Formation at the type section near Huntsville, Utah (Crittenden and others, 1971), but this contact is unconformable in the Brigham City area (Mantua quadrangle) where the lower member is missing (Sorensen

and Crittenden, 1976; Crittenden and Sorensen, 1985). In the southeastern portion of the Mantua quadrangle, the informal lower (or volcanic) member of the Browns Hole is present, and contains basaltic or andesitic to trachytic flows and volcanic breccias that are locally reworked into volcanic conglomerates. The volcanic member is up to about 150 feet (40 m) thick. The informal upper (or quartzite) member is about 350 feet (105 m) thick in the Brigham City area and about 100 to 270 feet (30 to 85 m) thick to the south, and is a white to terra-cotta colored, well-sorted, medium- to fine-grained, medium-bedded, vitreous quartzite (Sorensen and Crittenden, 1976; Crittenden and Sorensen, 1985). A K-Ar date of 570 Ma was obtained from a cobble from the lower member, so the Browns Hole is considered latest Proterozoic in age (Crittenden and Sorensen, 1985).

Cambrian

Geertsen Canyon Quartzite (Ꞓgl, Ꞓgu)

The Geertsen Canyon Quartzite exposures northeast of Brigham City are at least part of the type locality of the Brigham Formation of Walcott (1908), and of measured sections of the Brigham Quartzite of Eardley and Hatch (1940). Maxey (1958) described, measured and correlated rocks we mapped as Geertsen Canyon with the Pioche(?) Formation and Prospect Mountain Quartzite. The exact locations of the type locality and measured sections are unknown. These incompletely described and vaguely located sections were replaced with type sections near Huntsville, Utah (Crittenden and others, 1971; Sorensen and Crittenden, 1976), when the Brigham was elevated to group status. The Geertsen Canyon Quartzite is the top formation in the Brigham Group. The Geertsen Canyon Quartzite is presently considered early Cambrian in age (Crittenden and Sorensen, 1985).

Near Huntsville, the Geertsen Canyon was divided into two informal members, and is about 3,900 to 4,200 feet (1,190 to 1,280 m) thick (Crittenden and others, 1971). The lower member is about 1,200 feet (365 m) of mostly coarse-grained, typically green or gray, or locally maroon or purple arkose. Grain size and feldspar content decrease upward such that the upper 800 feet (345 m) are white- to tan-weathering quartzite. The upper informal member is about 3,000 feet (915 m) thick, and is a pale-buff to white or pale-pink, medium- to coarse-grained, medium- to thick-bedded quartzite with local pale-red or pale-purple streaks. *Skolithos* tubes (vertical burrows) are abundant in the uppermost beds. Abundant cross-bedding and pebble conglomerates in the upper Geertsen Canyon indicate deposition in shallow water, possibly in a north-south elongate trough (Crittenden and others, 1971; Sorensen and Crittenden, 1976; Crittenden and Sorensen, 1985).

We divided the Geertsen Canyon Quartzite into two map units. Our units are not the same as the informal members of Crittenden and others (1971), because their reported change in grain size and feldspar content could not be mapped, and pebble conglomerates are present in most of the Geertsen Canyon. Our thick lower map unit (Ꞓgl) consists of light-colored, grayish-orange-pink, pale-reddish-orange, and medium-dark-gray quartzite. Our upper map unit (Ꞓgu) is brown-weathering quartzite, with interbedded argillite at the base and argillite partings higher in the unit. The Geertsen Canyon Quartzite is exposed along the base of the mountain from Brigham City to Antimony Canyon, and in scattered exposures from the mouth of Moss Rock Canyon northward to Miners Hollow. A stratigraphic section measured near Chimney Rock is presented in the appendix.

Our lower map-unit quartzites contain rounded, moderately sorted, medium to coarse grains, are medium to very thick bedded and cross-bedded, and form light-colored, blocky cliffs. Some purple, shaly (phyllitic) partings, and lenses and layers of pebble conglomerate up to about 1 foot (0.3 m) thick are present in the quartzites. Locally, scattered pebbles and pebble lenses that are one pebble thick are present along bedding planes. Pebbles are rounded, light-colored quartzite and some vein(?) quartz. Jensen measured nearly 1,600 feet (490 m) of the lower map unit in the quadrangle (appendix), and, with the exposures in the Mount Pisgah quadrangle, the complete lower unit is at least 3,500 feet (1,067 m) thick.

Our upper map unit (Ꞓgu) of the Geertsen Canyon Quartzite weathers much darker than the lower unit and forms dark cliffs below middle Cambrian rocks. Mapped contacts are based on these differences. Quartzite in the upper map unit is typically medium to coarse grained and medium to very thick bedded. In some outcrops, the upper map unit contains very fine- to fine-grained, thin-bedded quartzite with interbedded, laminated, argillite layers about 6 inches (15 cm) thick. The argillaceous material is micaceous and ripple marked. The upper unit is cross-bedded, and *Skolithos* tubes (vertical burrows) and horizontal worm burrows are present in the top portion. This unit is 356 feet (108.5 m) thick (appendix), and we correlate it with a *Skolithos*-bearing interval 375 feet (114 m) thick that Crittenden and others (1971) noted as being locally present at the top of the Geertsen Canyon. They reported abundant *Skolithos*, fucoidal structures in argillites, and some trilobite tracks in this interval.

Langston Formation (Ꞓll, Ꞓlu)

We divided the Langston Formation into two map units. Our lower unit (Ꞓll) contains the thin basal Naomi Peak Limestone Member and overlying Spence Shale Member, while our upper map unit (Ꞓlu) is dolomite and limestone that compose an unnamed member. The Langston conformably overlies the Geertsen Canyon Quartzite, and in the Brigham City area contains a fauna that is earliest Middle Cambrian in age (Maxey, 1958; table 2). Details on the lithology and depositional environments of the Langston are available in Buterbaugh (1982).

The Naomi Peak Limestone Member consists of medium-gray, medium-crystalline, ledge-forming, brown-weathering limestone and dolomite, with some light-brown weathering, poorly indurated sandstone. Locally, carbonates of the Naomi Peak Member are light gray when fresh, and weather pale brown with sugary surfaces. A basal fine-grained, yellowish-brown-weathering sandstone with dolomite cement is present south of Antimony Canyon and the Wellsville Mountains transverse fault zone. South of this canyon, the basal sandstone is 15 feet (4.6 m) thick and the overlying limestone is 21 feet (6.4 m) thick (appendix). North of the Wellsville Mountains transverse fault zone, Maxey (1958) measured 25 feet (7.6 m) of sandy limestone just north of Cataract Canyon, and Buterbaugh (1982) measured 24 feet (7.3 m) of dolostone (?) north of Miners Hollow. Maxey (1958) also listed the fossils he found in this member.

The Spence Shale Member consists of yellowish- to reddish-brown- and gray-weathering, silty shale, and lesser interbedded, silty limestone. The shale is dark and light gray when fresh, and highly fossiliferous. The limestone is medium dark gray when fresh, laminated to very thin bedded, very fine to finely crystalline, and locally fossiliferous. The Spence Shale is 225 feet (68.6 m) thick south of Antimony Canyon (appendix) and the Wellsville Mountains transverse fault zone. North of the Wellsville Mountains transverse fault zone, Maxey (1958) and Buterbaugh (1982) measured 175 and 159 feet (53.3 and 48.5 m) of Spence Shale, respectively. Using outcrop width, dip, and topography in unfaulted strata in the Cataract Canyon-Miners Hollow area (plate 1), the Spence Shale is about 200 feet (60 m) thick where they measured sections. This indicates that faults might be present in their measured sections, or different contacts were picked. The difference in thickness across the Wellsville Mountains transverse fault zone is therefore only about 25 feet (7 m). The Spence Shale Member in the Wellsville Mountains contains an abundant and diverse fauna that has been studied by numerous paleontologists (for example: Maxey, 1958; Gunther and Gunther, 1981; Babcock and Robison, 1988; and Conway-Morris and Robison, 1988).

The upper map unit of the Langston Formation is dolomite and limestone that weather to sugary textured surfaces that are light brown to light gray to medium gray in color.

Table 2.
Fossils collected by M.E. Jensen in the Brigham City quadrangle, with identifications.

Number	Identified by	Description
Stratigraphic unit/sub-unit		
	Age--zone	
	(Location)	
Langston Formation/Spence Shale Member		
	earliest Middle Cambrian - *Glossopleura* zone	
	(NW1/4 NW1/4 SW1/4 section 31, T. 10 N., R. 1 W.)	
B2a	L.F. Gunther	brachiopod-*Acrothele* sp. (immature)
B2b	L.F. Gunther	trilobite-*Athabaskia bithus*
B2c	L.F. Gunther	trilobite-*Spencia typicalis*
B2d	L.F. Gunther	trilobite-*Athabaskia bithus*
	L.F. Gunther	trilobite-*Bythicheilus typicum*
B2e	L.F. Gunther	brachiopod-*Acrothele* sp.
B2f	L.F. Gunther	trilobite-*Alokistocare* sp. (head)
	L.F. Gunther	trilobite-*Bythicheilus typicum*
B2g	L.F. Gunther	trilobite-*Bythicheilus typicum*
Bloomington Formation/Hodges Shale Member		
	Middle Cambrian - *Bolaspidella* zone	
	(SE1/4 SE1/4 SW1/4 section 11, T. 10 N., R. 2 W.)	
B17a	L.F. Gunther	brachiopod-*Acrothele affinis*
B17b	L.F. Gunther	brachiopod-*Acrotreta* sp.
B17c	L.F. Gunther	brachiopod-*Iphidella grata*
B18	L.F. Gunther	brachiopod-*Acrothele affinis*
Swan Peak Quartzite/lower part		
	Middle Ordovician (Whiterockian) - *Orthambonites michaelis-Orthidiella* zone	
	(NE1/4 SW1/4 NW1/4 section 30, T. 10 N., R. 1 W.)	
B3	L.F. Hintze	brachiopod-*Orthambonites swanensis*
	(SW1/4 NW1/4 NW1/4 section 30, T. 10 N., R. 1 W.)	
B4	L.F. Hintze	trilobite-*Eleutherocentrus petersoni*
	M.E. Jensen	orthocone cephalopod?
	(NE1/4 NW1/4 SE1/4 section 24, T. 10 N., R. 2 W.)	
B7	L.F. Hintze	brachiopod - *Orthambonites swanensis*

The dolomite is medium to light gray to yellowish brown when fresh, medium to coarsely crystalline, very thick bedded, and contains some fossil fragments and cross-bedding. The limestone is medium gray when fresh, fine to medium crystalline, thin bedded, and contains small shell fragments. The thickness of the upper member, measured south of Antimony Canyon and the Wellsville Mountains transverse fault zone, is 262 feet (79.9 m)(appendix), whereas from map portrayal (outcrop width, dip, and topography on plate 1), the upper member is about 210 feet (64 m) thick in the same area. The actual thickness is probably between these two figures because the measured section was offset across a fault. North of the Wellsville Mountains transverse fault zone the upper member is about 230 feet (70 m) thick; Buterbaugh (1982) measured 227 feet (69.2 m) north of Miners Hollow, and this seems reasonable given map portrayal (plate 1). Maxey's (1958) reported upper member thickness of 110 feet (33.5 m) does not appear accurate. Remembering that Maxey (1958) measured sections before the mountain was mapped, a fault might be present in his measured section, or he picked different contacts.

Ute Formation (Ꞓu)

The Ute Formation consists of interbedded, gray, sandy limestone and shale, with average limestone and shale bed thicknesses of 50 and 15 feet (15 and 4.6 m), respectively. The Ute conformably overlies the Langston Formation. The sand content increases upward in the Ute such that calcareous sandstone is present near the top of the formation. Most of the Ute weathers to slopes and thin ledges. However, two gray, resistant, nearly massive, 50- to 100-foot thick (15 to 30 m) limestone beds stand out, and a similar, thinner, gray limestone is present at the top of the Ute. This capping limestone grades irregularly upward into dolomite of the conformably overlying Blacksmith Formation, making it difficult to map this contact. Limestones in the upper Ute contain peloid and oncolite beds, cross-bedding and local intraformational conglomerate. The shales are olive gray and weather reddish to yellowish brown, and are variably fossiliferous. Maxey (1958) dated the fauna in the Ute Formation in the quadrangle as Middle Cambrian. Maxey (1941, 1958) and Deputy (1984) reported thicknesses of 621, 595 and 689 feet (189.3, 181.4 and 210 m) for the Ute north of Cataract Canyon and Miners Hollow, respectively, and provided additional details on the Ute. Deputy's (1984) measurement of 689 feet (210 m) is the most reasonable thickness, given map portrayal (plate 1), and the fact that Maxey (1941, 1958) measured sections before faults and contacts were mapped in the moutains.

Blacksmith Formation (Ꞓbl)

The Blacksmith Formation is exposed in conspicuous, easily traceable, light-gray- to almost-white-weathering, massive cliffs of dolomite and dolomitic limestone above the slopes and ledges of the Ute Formation, and below the slopes of the conformably overlying Hodges Shale Member of the Bloomington Formation. A distinct, almost-white-weathering carbonate is present in the middle of the Blacksmith. Parts of the lower half of the Blacksmith have lighter and darker layers that are a few tenths of inches to inches (mm to cm) thick. The Blacksmith carbonates are very fine to coarsely crystalline, very light to medium gray when fresh and very thick bedded, with some oolitic beds and fenestral fabric. Maxey (1958) and Hay (1982) measured 805 and 812 feet (245.4 and 247.5 m) of Blacksmith north of Cataract Canyon, respectively. The fossil-poor Blacksmith is Middle Cambrian in age based on its position between two Middle Cambrian units, whose ages are based on fossils (Maxey, 1958). Hay (1982) provided additional details on the lithology and origin of the Blacksmith.

Bloomington Formation (Ꞓbh, Ꞓbm, Ꞓbc)

Following Maxey (1958), the Bloomington Formation has been divided into three members for this study. The members, oldest to youngest, are the Hodges Shale (Ꞓbh), a middle limestone (Ꞓbm), and the Calls Fort Shale (Ꞓbc). Each member is easily mapped. The Hodges Shale Member (Ꞓbh) is mostly light-olive- to light-brown-weathering shale interbedded with light- to dark-gray, silty limestone. The limestones contain irregularly interbedded and intermingled thin beds and masses of siltstone and shale that are more resistant than the limestone. The middle limestone member (Ꞓbm) is dark to light gray, very fine to medium crystalline, argillaceous, and forms cliffs. This middle limestone is very thick bedded at the base and gradually becomes thin bedded at the top. The Calls Fort Shale Member (Ꞓbc) is mostly a light-olive- to light-brown-weathering shale with some thin beds of gray limestone. The shale contains distinctive, 1- to 2-inch long (2.5 to 5 cm), limestone nodules that weather out, leaving holes in the shales and littering gentle slopes. We placed the thin-bedded limestone that caps the Calls Fort Shale in the shale because it is more similar to the limestones in the Bloomington Formation than to the conformably overlying Nounan Formation dolomites. Based on fossil data, the Bloomington is Middle Cambrian in age (Maxey, 1958; Oviatt, 1986a; table 2). Maxey (1958) measured 335 feet (102.1 m) of Hodges, 515 feet (157.0 m) of middle limestone, 200 feet (61.0 m) of Calls Fort, and

35 feet (10.7 m) of capping limestone near Calls Fort Canyon, for a total of 1,085 feet (330.7 m). From map portrayal (plate 1), these thicknesses are reasonable. Therefore we probably used the same contacts as Maxey (1958) and faults are not present in his measured section.

Nounan Formation (Ꞓnl, Ꞓnu)

In the quadrangle, the Nounan Formation is divisible into two map units: a lower unit (Ꞓnl) of mostly light- to medium-gray, fine- to medium-crystalline, thick-bedded dolomite; and an upper unit (Ꞓnu) of gray and tan, interbedded dolomite, sandy and silty dolomite, and limestone. We mapped the contact between the Nounan units between a 10- to 20-foot-thick (3 to 6 m), lighter gray dolomite, and an overlying tan, sandy dolomite, which is the oldest Nounan sandy dolomite. This is evidently the same contact that Oviatt (1986a) used in the Honeyville quadrangle just to the north, and is the contact between Gardiner's (1974) middle and upper members of the Nounan. Our lower map unit weathers to light- and medium-gray, sugary surfaced outcrops that form crags and cliffs; these outcrops are generally lighter colored, thicker bedded and more resistant than the capping and middle limestones of the Bloomington Formation. Our upper Nounan map unit is mostly less resistant and thinner bedded than the lower map unit, though cliffs are present. The upper Nounan map unit forms continuous slopes in the Honeyville quadrangle where relief is lower. The upper map unit commonly contains nonmarine sediment that is more abundant at the base and near the top of the unit. This sand and silt form partings in the gray carbonates, and weather tan. Local brownish to reddish-brown lenses of quartzose dolomite in the upper unit contrast with the grays and tans. Because the top of the Nounan and bottom of the St. Charles Formation are lithologically similar, the Nounan contact with the conformably overlying St. Charles Formation is difficult to distinguish in the field. This is especially true in outcrops where the basal Worm Creek Quartzite Member of the St. Charles is absent. Williams (1948) reported that the Nounan was Late Cambrian in age, using unpublished fossil collections (in part from Maxey, 1941). Oviatt (1986a) reported the upper Nounan was Dresbachian (Late Cambrian) in age based on trilobite fauna. Gardiner (1974) and Maxey (1941) provided additional details on the formation. Away from faults and where contacts are most exact, the lower Nounan is about 650 feet (200 m) thick (plate 1 outcrop widths, topography, and dips from 3 sites). Gardiner (1974) and Oviatt (1986a) reported lower Nounan thicknesses of 601 and 729 feet (183.2 and 222.2 m) near Dry Canyon and just north of the quadrangle, respectively. The upper Nounan is about 545 feet (166 m) thick (this report; Gardiner, 1974; Oviatt, 1986a). Therefore, the total Nounan is about 1,200 feet (365 m) thick. The 828-foot (252.4 m) total thickness reported by Maxey (1941) is not used because it is one-third less, and the section was measured before faults and contacts were mapped.

St. Charles Formation (Ꞓsl, Ꞓsu)

The St. Charles Formation was divided into two map units. The lower unit (Ꞓsl) includes the Worm Creek Quartzite Member and about 100 feet (30 m) of slope-forming, interbedded, thin-bedded, silty and sandy limestone that are more like underlying carbonates in the Worm Creek than overlying carbonates in the upper St. Charles map unit. The Worm Creek Quartzite Member is at the bottom of the lower map unit; it comprises a basal 0 to 6-feet thick (0 to 1.8 m), light-gray to white quartzite with about 70 feet (21 m) of thin-bedded, sandy dolomite and limestone, and siltstone and shale. The upper map unit (Ꞓsu) is about 980 feet (300 m) thick, and is medium- to dark-gray, finely crystalline dolomite that typically weathers to gray, resistant exposures that were easily mapped along the mountain front. The middle portion of the upper map unit contains a distinct, almost-white-weathering, resistant dolomite. From map portrayal (plate 1), the upper map unit is at least 10 percent thinner south of the Wellsville Mountains transverse fault zone. The uppermost St. Charles contains light colored, commonly pink, elongate, 1- to 12-inch (2.5 to 30 cm) long, and 1-inch (2.5 cm) thick, chert nodules that are aligned parallel to bedding, and layers of clastic material that are much less resistant than the dolomite and weather into tan recesses. For additional information see Maxey (1941). As determined from trilobite and conodont fossils, the St. Charles Formation is Late Cambrian and earliest Ordovician in age in the Bear River Range (Taylor and others, 1981).

Ordovician

Garden City Formation (Ogc)

The Garden City Formation is mostly medium-gray, thin- to thick-bedded, finely crystalline to micritic limestone and silty limestone, with some intraformational conglomerate and silt partings. The formation is exposed in light-gray to tan ledges, cliffs and steep slopes, but is not massive. The basal part of the formation contains interbeds of less resistant, light-tan, calcareous sand-

stone, siltstone and some shale that are as much as 1 inch (2.5 cm) thick. The basal Garden City is also chert-bearing, and, therefore, looks much like the top of the underlying St. Charles Formation. They can be separated because the Garden City is slightly lighter in color and contains less clastic material higher in the section. Near the top of the Garden City, 1- to 10-inch-thick (2.5 to 25 cm) black chert nodules and stringers are abundant in the limestone. Above this cherty zone the uppermost Garden City is dark-gray dolomite and dolomitic limestone. The Garden City is 1,330 to 1,390 feet (405 to 424 m) thick both north of the quadrangle (Morgan, 1988; Oviatt, 1986a) and in the quadrangle south of the Wellsville Mountains transverse fault zone (Ross, 1951). Morgan (1988) reported additional information on the petrology and origin of the Garden City Formation. The Garden City is Early Ordovician to earliest Middle Ordovician in age as determined from its rich trilobite fauna, and disconformably overlies the St. Charles Formation (Ross, 1951; see also Taylor and others, 1981).

Swan Peak Formation (Osp)

Regionally, the Swan Peak Formation is divisible into three units (Francis, 1972; Oaks and others, 1977). We mapped the Swan Peak as a single unit because it is relatively thin in the quadrangle. Francis (1972) and Oaks and others (1977) provided details on the Swan Peak and its divisions. The Swan Peak is about 260 to 400 feet (80 to 120 m) thick in the Wellsville Mountains (Francis, 1972; Oviatt, 1986a; this report), and thickens to the north (260 to 300 feet [80 to 90 m] thick in the quadrangle). Because the Swan Peak also thickens to the north in the Bear River Range (Francis, 1972), the Wellsville Mountains transverse fault zone may not be a factor in this thickening. Beus (1958) and Gelnett (1958) reported a thickness of about 435 feet (133 m) in the Honeyville quadrangle, but it was measured in a structurally complex area and might be inaccurate. The Swan Peak contains quartzite, shale and limestone, and is typically visible as thick ledges and a capping cliff of quartzite. The lowermost unit is poorly exposed, and contains interbedded shale, quartzite and limestone. The middle unit is interbedded quartzite and shale, and contains abundant fucoidal trace fossils (horizontal feeding burrows) identified as *Annelidichnus* by Francis (1972). The uppermost unit is a distinctive, roughly 60-foot-thick (18 m), pink-orange-tan to white, fine- to medium-grained quartzite, in which the colors look like staining. Vertical burrows (*Skolithos* trace fossils) are abundant, and trace fossils on bedding are present (identified as *Scolicia* by Francis, 1972). The lower Swan Peak is earliest Middle Ordovician in age based on trilobites (Ross, 1951). Oaks and others (1977) showed a Middle Ordovician (early Champlainian) age for the entire Swan Peak, though this age has not been documented with fossil data. Table 2 contains other fossil information.

Fish Haven Dolomite (Ofh)

The Fish Haven Dolomite unconformably overlies the Swan Peak and is a dark-gray, almost black-weathering, finely crystalline, thick- to very thick-bedded, massive-weathering, cliff-forming dolomite. The contact with the overlying Laketown Dolomite is placed at the change to lighter gray dolomite, and is typically accompanied by changes to thinner bedding, greater resistance and weathering to pinnacles and spires in the Laketown. This is the contact that Williams (1948, 1958) mapped in the Bear River Range. Fish Haven thicknesses of 178 and 140 feet (54.3 and 42.7 m) have been measured in the Wellsville Mountains (appendix; Gelnett, 1958). From our examination of his field notes and aerial photographs, we apparently mapped the same Fish Haven--Laketown contact as Oviatt (1986a) did. However, we picked the contact at the base of the first thin-bedded dolomite in his unpublished measured section, making the Fish Haven about 185 feet (56 m) thick rather than the 197 feet (60.0 m) Oviatt (1986a) reported. The Fish Haven contains abundant corals, particularly rugose corals, and tabulate (*Favosites* and *Halysites* species) corals. Based on fossil corals collected in north-central Utah, the age of our Fish Haven map unit is probably late Late Ordovician (Cincinnatian) (after Williams, 1948; Gelnett, 1958). Budge and Sheehan (1980) presented more detailed data, but they used a different Fish Haven-Laketown contact.

Silurian

Laketown Dolomite (Sll, Slu, Sl - subsurface only)

We divided the Laketown Dolomite into two map units, but it was difficult to consistently map the contact between them. Both units are light- and dark-gray, medium- to very thick-bedded, massive-weathering, cliff-forming dolomites, with irregular blebs, stringers, and layers of chert at various horizons. The lower unit (Sll) is finely to coarsely crystalline, contains *Thalassinnoides* trace fossils, and is locally banded light and dark gray. In contrast, the upper unit (Slu) is sugary surfaced, medium crystalline, and contains more chert. Good exposures of the lower map unit are dark gray, or interbedded light and dark gray at the bottom, and dark gray higher in the unit. Good exposures of the upper unit are typically light gray in the bottom portion and dark gray in the top

portion. Therefore, the internal contact was mapped at a diffuse change from darker to lighter gray, as Oviatt (1986a) did in the Honeyville quadrangle. Because the upper map unit is noticeably thinner than the lower map unit south of the Calls Fort Canyon area (plate 1), this contact appears to climb or shift in the Laketown Dolomite in the Brigham City quadrangle. The Laketown Dolomite is about 1,100 to 1,200 feet (305 to 365 m) thick in the Wellsville Mountains on both sides of the Wellsville Mountains transverse fault zone (Oviatt, 1986a; after Gelnett, 1958). Using our Fish Haven-Laketown contact, the Laketown is late Late Ordovician and middle Early through Middle Silurian, and locally earliest Late Silurian in age in northern Utah (after Budge, 1966; Budge and Sheehan, 1980; Leatham, 1985).

We do not assign any member names to our Laketown map units because the Laketown members were defined biostratigraphically in the Bear River Range (Budge and Sheehan, 1980; Leatham, 1985). Further, they used an unmappable and different Laketown-Fish Haven contact than we used, and the lithologies present in the Wellsville Mountains are different from those reported in the Bear River Range by Budge and Sheehan (1980).

Devonian

Water Canyon Formation (Dwl, Dwm, Dwu)

The Water Canyon Formation was divided into three lithologically distinct map units using the same contacts that Oviatt (1986a) used in the Honeyville quadrangle. However, these contacts are difficult to map because the units are easily eroded and the resulting detritus mantles underlying units. The Water Canyon disconformably overlies the Laketown Dolomite (Taylor, 1963; Williams and Taylor, 1964). The Water Canyon is Early Devonian based on fish fossils found in the Wellsville Mountains (Oviatt, 1986a) and in northern Utah (Taylor, 1963; Williams and Taylor, 1964).

The lower map unit (Dwl) is a light-gray-weathering, finely crystalline, thin- to medium-bedded, ledge- and slope-forming dolomite that Oviatt (1986a) equated with the type Card Member of Williams and Taylor (1964). Our lower unit was apparently mapped as part of the Laketown Dolomite by Gelnett (1958)(figure 3). The lower map unit (Dwl) is lighter in color and less resistant than the underlying Laketown Dolomite, and contains detrital material. A change to thinner beds in the lower map unit has been widely reported but is not present everywhere. Oviatt (1986a) reported the lower map unit was 428 feet (130.5 m) thick, while Beus (1958) and Gelnett (1958) measured about 370 to 410 feet (113 to 125 m) of comparable rocks that they placed in the Laketown Dolomite (figure 3).

The middle map unit (Dwm) is a grayish-yellow-orange-weathering, slope-forming, fine-grained sandstone, and interbedded sandy dolomite and limestone. The middle map unit is closest lithologically to rocks in the type Grassy Flat Member of Williams and Taylor (1964), though in their reference section near Honeyville our middle map unit includes parts of both their two members (figure 3). Williams and Taylor (1964) apparently based their correlation on the Water Canyon-Laketown contact chosen by Beus (1958) and Gelnett (1958), which is stratigraphically higher than the contact used by Oviatt (1986a) and in our study (figure 3). Oviatt (1986a) placed the middle and upper map units in the Grassy Flat Member of Williams and Taylor (1964). The upper map unit (Dwu) is a light-gray- to white-weathering, slope-forming, fine-grained dolomite that is traceable along the mountain much like the lower unit. The middle and upper Water Canyon are 400 and 450 feet (122 and 137 m) thick, respectively, as calculated from topography, dip, and outcrop width on plate 1. These are about the same as the thicknesses reported by Oviatt (1986a). Thicknesses reported by Williams and Taylor (1964) and Gelnett (1958) were apparently based on different Water Canyon contacts (figure 3).

The Water Canyon-Hyrum Dolomite contact is not precisely defined (figure 3). Like Oviatt (1986a), we have used the darker color and greater resistance of the overlying Hyrum Dolomite to delineate this contact. This mapped contact might not be the same as the contact chosen by Williams and Taylor (1964) in their type section near Logan, Utah. Eliason (1969) reported that this contact was obscure, while Taylor (1963) noted that the Hyrum was darker in color and fossiliferous. Oviatt (1986a; written communications, 1983, 1984, 1985) and Gelnett (1958) did not see the intraformational breccias at the top of the Water Canyon that Williams and Taylor (1964) reported. However, the uppermost 175 feet (53.3 m) of Water Canyon rocks were covered in the section measured by Oviatt (written communication, 1983, 1984, 1985). Without this interval, Oviatt's (1986a) reported Water Canyon thickness (1,285 feet minus 175 feet=1,110 feet [338 m]) would be about the thickness measured by Williams and Taylor (1964) near Honeyville (683 feet [208 m]), plus the 370 to 410 feet (113 to 125 m) of probable lower Water Canyon rocks (1,053 to 1,093 feet [321 to 333 m]) that Beus (1958) and Gelnett (1958) previously assigned to the upper part of the Laketown Dolomite (figure 3).

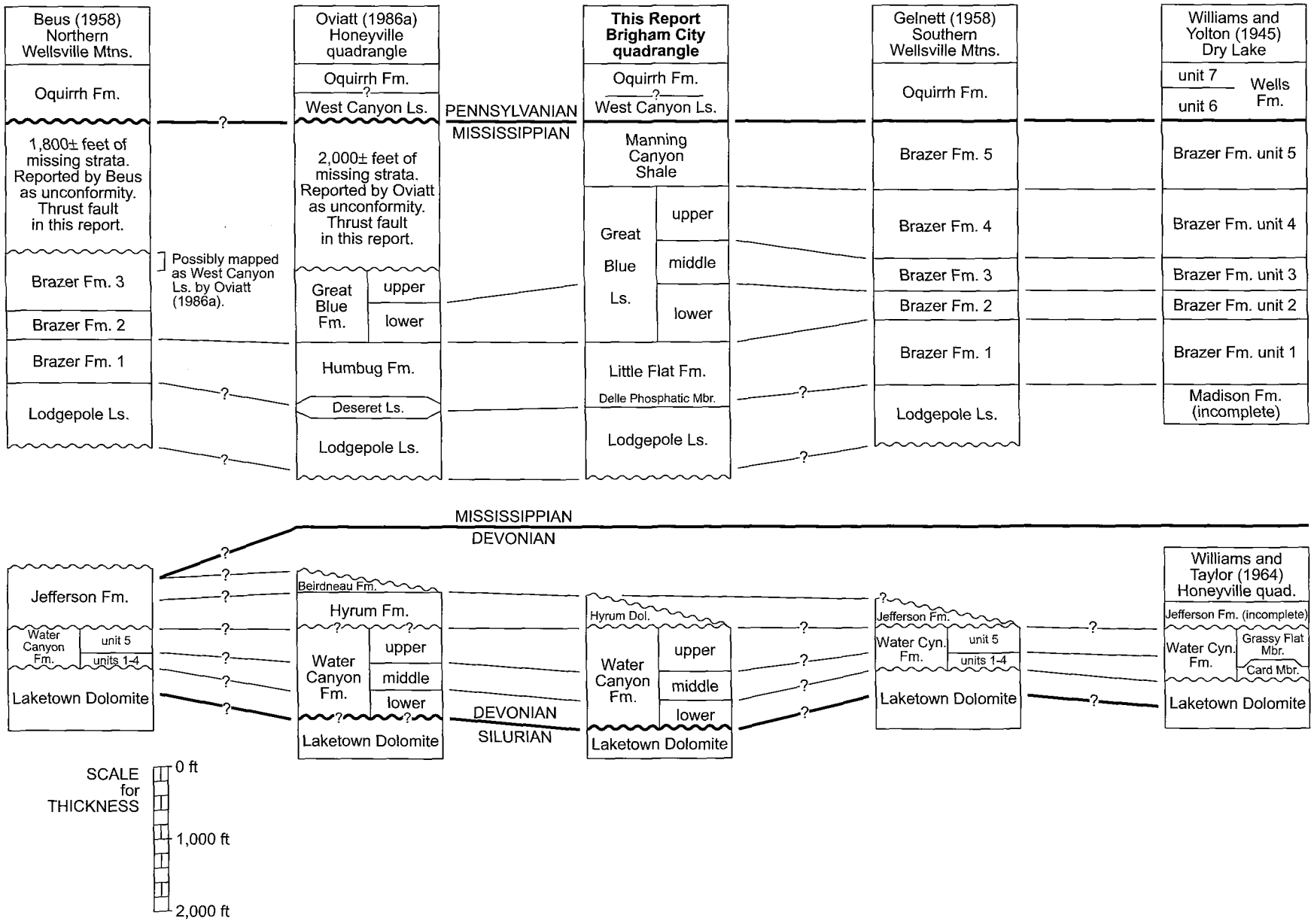


Figure 3. *Correlation chart for Devonian and Mississippi strata mapped in the Wellsville Mountains, and described at Dry Lake and Honeyville. Chart shows correlations used in this report (queried where uncertain). Stratal thicknesses are to scale. Upper chart hung on the base of the Oquirrh formation. Lower chart hung on the top of the Water Canyon Formation.*

Hyrum Dolomite (Dh)

The Hyrum Dolomite is a dark-gray, medium-crystalline dolomite that contains calcite-filled vugs. Quartzite strata are at two horizons in the formation, one near the base and another in the upper part. In the Brigham City quadrangle, the Hyrum Dolomite is unconformably overlain by the Lodgepole Limestone (figure 3), because the Beirdneau and Leatham Formations, which separate the Lodgepole and Hyrum in the Bear River Range (Williams, 1971; Sandberg and Gutschick, 1979), are absent. The Beirdneau is present to the west on Little Mountain (Jensen, 1994) and in the Honeyville quadrangle, and thickens to the north (Oviatt, 1986a)(figure 3). The Hyrum thins rapidly southward below the unconformity, from about 450 feet (138 m) thick northeast of Honeyville (Oviatt, 1986a) to about 50 feet (15 m) thick at the head of Moss Rock Canyon in the Brigham City quadrangle. The Hyrum Dolomite is absent on the eastern side of the Wellsville Mountains. Beus (1958) and Gelnett (1958) included the Hyrum strata in their Jefferson Formation (figure 3). However, their Jefferson-capping, cherty limestone probably belongs in the Lodgepole Limestone, and the underlying roughly 250 feet (76 m) of locally cherty dolomite is probably the Beirdneau Formation (figure 3). A Middle Devonian age was assigned to the Hyrum based on fossils from the base (and possibly middle portion) of the formation in the Wellsville Mountains, Bear River Range and West Hills, and the presence of Late Devonian (early Famennian) fossils in the upper portion of the overlying Beirdneau Formation in northern Utah (Williams, 1971; Oviatt, 1986a).

Mississippian

Lodgepole Limestone (Ml)

The Lodgepole is a medium- to dark-gray limestone and cherty limestone that commonly contains black chert nodules. The Lodgepole generally forms cliffs, but the lower portion is a slope former at the northern margin of the quadrangle. The Lodgepole is about 1,000 feet (305 m) thick in the Wellsville Mountains; it contains crinoid, coral, brachiopod, bryozoan, and some branch-like fossils. Based on conodonts, crinoids and corals, the Lodgepole is Kinderhookian and early Osagean (Early Mississippian) in age (Sandberg and Gutschick, 1979; Oviatt, 1986a).

Little Flat Formation (Mlfd, Mlf)

The Little Flat Formation is equivalent to rocks in the adjacent Honeyville quadrangle that Oviatt (1986a) mapped and labeled Deseret Limestone and Humbug Formation (figure 3). We called these rocks Little Flat because they are lithologically similar to the type Little Flat Formation in the Chesterfield Range in southeastern Idaho (W.J. Sando, written communication, 1988; see Dutro and Sando, 1963 for type descriptions).

Phosphatic rocks at the base of this stratigraphic interval are widespread in northern Utah and are the basal Delle Phosphatic Member of the Woodman Formation, Deseret Limestone and Little Flat Formation (Sandberg and Gutschick, 1984). Oviatt (1986a) reported phosphatic limestone at the base of this interval (his Deseret), but this is the only report of phosphatic rocks in the Wellsville Mountains (Williams, 1943, 1948; Williams and Yolton, 1945: Beus, 1958; Gelnett, 1958). We didn't find phosphatic rocks in the basal Little Flat sandstone or cherty limestone during our field work, but chemical and radiometric analyses were not performed. Near Dry Lake in the Mount Pisgah quadrangle, Williams (1943, 1948; Williams and Yolton, 1945) probably looked for phosphatic rocks in shales and may have missed a phosphatic limestone. Similarly, Gelnett (1958) and Beus (1958) didn't recognize phosphatic rocks and placed about 90 feet (27 m) of thin-bedded, black, chert-bearing limestone (Oviatt's [1986a] Deseret) in their uppermost Lodgepole Limestone (figure 3).

In the Brigham City quadrangle, the Little Flat Formation is divisible into what is probably the basal Delle Phosphatic Member (Mlfd) and overlying strata (Mlf). Our Delle contains a basal fine-grained sandstone and an overlying cherty limestone. Oviatt (1986a) mapped this sandstone and limestone as Deseret Limestone on his aerial photographs and plate 1, and noted it was about 90 feet (27 m) of phosphatic, cherty limestone and minor sandstone. The overlying Little Flat Formation strata (Mlf) are light-gray, medium- to coarse-grained sandstone, dolomitic and calcareous sandstone, and darker gray, sandy carbonate and limestone. These thin- to medium-bedded rocks weather to light-brown slopes and ledges. The entire Little Flat is probably 900 feet (275 m) thick in the quadrangle, but it is incompletely and poorly exposed. In the Bear River Range, the Little Flat is early Osagean to middle Meramecian (Early and Late Mississippian) in age, based on conodonts, and is approximately time-equivalent to the Deseret Limestone (Sandberg and Gutschick, 1979).

Great Blue Limestone (Mgl, Mgm, Mgu)

The Great Blue Limestone is only exposed in the northeastern part of the Brigham City quadrangle, and

was divided into three map units. The basal unit (Mgl) is a medium- to dark-gray limestone that forms cliffs, ledges, and steep slopes, and is about 800 feet (245 m) thick. Our middle map unit (Mgm) is interbedded olive-gray mudstone and shale, and medium-gray, thin- to medium-bedded limestone, with more limestone in the upper part. The unit forms pale-yellowish-brown slopes and light-gray ledges. The mudstones contain micrite nodules that are up to 5 inches (13 cm) in length. The limestones contain brachiopods, crinoid stems, horn coral, and dark chert. The upper map unit (Mgu) is dark-gray, fine- to medium-crystalline limestone that forms slopes and ledges, and commonly contains silicified brachiopods, crinoid stems, and horn and rugose corals. The unit contains chert as nodules and layers up to 1 foot (0.3 m) thick; chert is more abundant in the lower 200 feet (61 m). In upper Cataract Canyon, the middle and upper map units are 600 and 742 feet (182.9 and 226.2 m) thick, respectively (appendix). Their combined thickness (1,342 foot [409.0 m]) is roughly the thickness (1,420 feet [432.8 m]) reported for the same interval near Dry Lake (Williams, 1943; Williams and Yolton, 1945), about six miles (10 km) to the southeast in the Mount Pisgah quadrangle (figure 3). Regionally, the Great Blue Formation is Meramecian and Chesterian (middle to late Mississippian) in age from fossil data (Sando and Bamber, 1985; Oviatt, 1986a). Additional details on the Great Blue are provided in Lindsay (1977) and Sweide (1977). However, Lindsay's (1977) Great Blue includes parts of the Little Flat (Humbug) and Oquirrh formations of this and previous reports (Williams, 1948, 1958; Beus, 1958; Gelnett, 1958; Oviatt, 1986a) on the Wellsville Mountains. Sweide's (1977, figure 9) contacts remain unevaluated because he didn't examine the Dry Lake section of Williams and Yolton (1945), and Williams (1948, 1958) didn't map contacts of the Great Blue equivalent [Brazer] units shown in figure 3.

Our basal Great Blue unit appears to be equivalent to the lower Great Blue unit mapped by Oviatt (1986a) to the north in the Honeyville quadrangle (figure 3); however, his unit is 550 feet (167.6 m) thick (Oviatt, 1986a) compared to our 800 foot (245 m) thickness. The upper Great Blue unit of Oviatt (1986a) is not equivalent to either our middle or upper map unit, or to both units, despite similar lithologic characteristics. His upper unit is far thinner (475 versus 1,342 feet [145 vs. 409 m] thick) than our map units. The contacts on the two maps do not match due to these disparate thicknesses.

From these data, the Great Blue Limestone is much thinner north of the Wellsville Mountains transverse fault zone than south of it (about 1,025 feet [312 m] [Beus, 1958; Oviatt, 1986a] versus at least 2,100 feet [640 m] [Williams and Yolton, 1945; Gelnett, 1958; this report], figure 3). Because about 1,820 feet (555 m) of Great Blue equivalent rocks (Brazer units 2, 3 and 4) were measured in the Mount Pisgah quadrangle near Dry Lake by Williams (1943; Williams and Yolton, 1945), King attributes this thinning to faulting that omits strata (see Manning Canyon section). Previously, Beus (1975 personal communication in Lindsay, 1977, p. 117; see also Beus, 1958, p. 37-38) ascribed the thinning from Dry Lake to Honeyville to Mississippian and Pennsylvanian erosion, which completely removed the overlying Manning Canyon Shale in the Honeyville area (see below). Oviatt (written communication, 1995) reasserted in his review of this report that the Great Blue thickens from north to south, north of the Wellsville Mountains transverse fault zone. Note that the apparent thickness (outcrop width) of the Great Blue (Brazer) does increase where it crosses the topographic divide and forms the dip slope on the east side of the mountains (see Davis, 1985; Oviatt, 1986a).

Manning Canyon Shale (Mmc)

The Manning Canyon Shale is only present in the northeastern part of the Brigham City quadrangle, and consists of interbedded gray, silty, cherty, fossiliferous, thin-bedded, fine-crystalline limestone and light-olive-gray to black shale. The Manning Canyon is poorly exposed, and the shale weathers into depressions between limestone hills and ledges. Individual limestone and shale beds are 37 to 118 and 18 to 30 feet (11.3 to 36.0 and 5.5 to 9.1 m) thick, respectively (appendix). Jensen (appendix) measured 600 feet (180 m) of Manning Canyon in the best exposures, located on the western flank of the range. But, this measurement is probably a minimum thickness, because these exposures are in fault blocks. Based upon mapped contacts, topography, outcrop widths and dips (plate 1), the complete Manning Canyon is about 900 feet (275 m) thick in Rattlesnake Canyon. Williams and Yolton (1945) measured 950 feet (290 m) of equivalent strata (their Brazer unit 5) near Dry Lake in the Mount Pisgah quadrangle using the same contacts (figure 3). Sadlick (1955) used different contacts near Dry Lake, so his 1,130-foot (344.4 m) Manning Canyon thickness can not be used for comparison. Near Dry Lake, the Manning Canyon (Brazer unit 5) was assigned a Chesterian age based on fossils by Williams and Yolton (1945). Miller and others (1991) reported a Mississippian and Pennsylvanian age for the Manning Canyon to the west in the Blue Spring Hills (Lampo Junction quadrangle), but their upper Manning Canyon might be equivalent to our West Canyon Lime-

stone.

The Manning Canyon Shale is present in the Wellsville Mountains south of the Wellsville Mountains transverse fault zone (figure 2; plate 1), but is missing near Deweyville (Beus, 1958; Oviatt, 1986a), north of this fault (figure 3). This disappearance has been attributed to thinning between Dry Lake and Deweyville (Beus, 1958; Gelnett, 1958; Oviatt, 1986a; Jensen, 1988), due to a Mississippian-Pennsylvanian unconformity (see Great Blue Limestone text). However, from three lines of evidence, King here proposes that the disappearance is due to thrust faulting. First, the Manning Canyon Shale and Great Blue Limestone do not thin appreciably south of the Wellsville Mountains transverse fault zone. They are about as thick at Dry Lake as they are just south of this fault (preceding paragraphs; Gelnett, 1958, p. 47). Second, north of the Wellsville Mountains transverse fault zone, Oviatt (1986a) did not map any Manning Canyon, though he stated it could be present (written communication, 1995), and Beus (1958) did not depict thinning of his Brazer Formation (which includes the Manning Canyon). Finally, the Manning Canyon is commonly a glide plane for Mesozoic thrust faults in the area (Allmendinger and others, 1984). Therefore, the missing strata in the Honeyville quadrangle may be omitted by a thrust fault and the Wellsville Mountains transverse fault zone is an oblique or lateral ramp on this thrust fault.

Pennsylvanian

West Canyon Limestone (IPwc)

Poorly exposed, interbedded, thin- to medium-bedded, light-gray, cherty limestone, calcareous sandstone, and sandy limestone, that weather light gray to pale grayish yellow to yellowish brown, unconformably overly the Manning Canyon Shale in the extreme northeastern corner of the quadrangle. The entire unit is not present in the Brigham City quadrangle, but Oviatt (1986a) tentatively equated these strata with the West Canyon Limestone. He based this correlation on lithology, stratigraphic position, and identification of middle Morrowan (late Early Pennsylvanian) conodonts from the uppermost beds in the Honeyville quadrangle. The West Canyon Limestone is the basal formation of the Oquirrh Group in the southern Oquirrh Mountains (Welsh, 1983). The West Canyon contact with overlying Oquirrh Group strata isn't well defined in the Wellsville Mountains, so Oviatt (1986a) reported a West Canyon thickness of about 400 feet (122 m), while Jensen (this study) estimated a thickness of about 710 feet (215 m) where the corners of the Brigham City, Honeyville, Wellsville, and Mount Pisgah quadrangles meet.

Tertiary

Tertiary Undivided (Tu, subsurface only)

Tertiary rocks are not exposed in the quadrangle, but at least 4,295 feet (1,309 m) of Tertiary and Quaternary basin fill are present in the Bear River Valley. This estimate is from cuttings and geophysical logs of the #1 Davis, Utah Joint Steam Venture geothermal borehole, and the regional gravity map by Peterson (1974). Campbell, in Doelling (1980, p. 211), reported that 3,800 feet (1,160 m) of Tertiary Salt Lake Group rocks within a total of 4,380 feet (1,335 m) of Cenozoic basin fill were penetrated in this borehole. The borehole is located about two miles (3 km) southeast of Bear River City near Interstate 15, about 1.5 miles (2.4 km) west of the Wasatch fault zone (plate 1; figure 2), and is shown on cross-section A-A′ (plate 2). Before the borehole was drilled, Peterson (1974) prepared a 2-dimensional gravity profile and schematic cross section between the West Hills and Brigham City. He showed the thickest Cenozoic valley fill as about 7,000 feet (2,100 m) thick, northwest of Brigham City along Interstate 15 and 4.5 miles (7.2 km) west of the Wasatch fault zone. From the gravity map of Peterson (1974), about 5,000 feet (1525 m) rather than 4,380 feet (1,335 m) of Cenozoic valley fill should have been penetrated in the geothermal borehole. Therefore, the thickest valley fill in the quadrangle is probably somewhat less than 7,000 feet (2,100 m) thick.

Upper Tertiary rocks in northern Utah are commonly assigned to the Salt Lake Group or Formation (Hintze, 1988). The Salt Lake is a jumbled mixture of poorly consolidated strata in which individual rock types can not be traced laterally or vertically for any great distance. These rock types include: (1) bimodal volcanic rocks that vary from tuff to lava flows; (2) lacustrine deposits including limestone, marl, claystone, and volcanic ash; (3) conglomerates with pebble- to boulder-sized clasts; (4) carbonaceous shale and lignite; and (5) clastic rocks such as shale, mudstone, siltstone, and sandstone that contain varying amounts of reworked volcanic material. The Salt Lake Group is reportedly Miocene and Pliocene in age, but few well-documented isotopic dates are available (for example, Williams, 1962, 1964; Doelling, 1980; Oviatt, 1986b; Bryant and others, 1989; Miller and Schneyer, 1994). Cuttings from the #1 Davis geothermal borehole show Salt Lake strata are mostly reworked and altered tuff, with minor poorly to well-sorted, lithic sandstone and conglomerate, and calcareous siltstone and claystone. Cuttings also contain traces of shell fragments, limestone, pyrite, and organic material. Cuttings might contain datable material that could constrain the timing of late Tertiary extension.

Quaternary

Poorly consolidated to unconsolidated Quaternary (Pleistocene and Holocene) sediments cover most of the Brigham City quadrangle. These sediments include: (1) lacustrine deposits of Lake Bonneville, the Gilbert inundation, and Great Salt Lake; (2) deltaic and fan-delta deposits of Lake Bonneville; (3) mixed lacustrine and alluvial-fan deposits; (4) alluvial-fan deposits; (5) deposits in mudflats, marshes, deltaic plains and oxbow lakes; (6) alluvial deposits of the Bear River and smaller streams; (7) colluvium and alluvium; (8) mass-movement deposits; and (9) eolian deposits. In addition, small, poorly exposed Quaternary tufa deposits on bedrock and cementing Quaternary sediments were noted near the mouths of Cataract, Yates and Baker Canyons, and at two sites on the mountain front between Moss Rock and Yates Canyons. These deposits are along shorelines, above the Bonneville shoreline, and next to springs. They are shown by a T on plate 1 since their exact extent could not be mapped. Human activities have filled and disturbed some areas so that natural deposits are obscured.

The thickness of Pleistocene and Holocene basin fill in the Bear River Valley in the quadrangle is uncertain. Campbell, in Doelling (1980, p. 211), reported 580 feet (177 m) of Quaternary deposits (his Lake Bonneville Group) in the #1 Davis geothermal borehole. From geophysical logs of this borehole, basin fill becomes more consolidated at a depth of about 680 feet (207 m). King (this study) believes this change defines the contact between less-consolidated Quaternary deposits and more-consolidated Tertiary basin fill. However, the borehole cuttings do not exhibit a distinct lithologic change from 200 feet (60 m), where sampling began, until a depth of about 2,100 feet (640 m)(table 1). A log of a water well about 1 mile (1.6 km) west of the geothermal borehole (Bjorklund and McGreevy, 1973, p. 17) penetrated about 600 feet (180 m) of interbedded sand and clay of probable Quaternary age. Another water well on the southern edge of the quadrangle (section 22, T. 9 N., R. 2 W.) (Bjorklund and McGreevy, 1973, p. 16) penetrated about 700 feet (210 m) of probable Quaternary deposits, comprising interbedded lacustrine silt and sand.

Though we mapped independently using a different approach, many of our Quaternary units and contacts are the same as those of Personius (1990). Minor differences exist in unit names, and contact and compositional details rather than in locations and kinds of deposits. The greatest differences are that Personius (1990) separated Provo-shoreline deposits from Bonneville-shoreline deposits, mapped some debris flows separately, and assigned different ages to some alluvial-fan deposits. We were unable to consistently identify his distinctions.

The Quaternary deposits in the Brigham City quadrangle are largely the product of lake processes in the Bonneville basin, including Great Salt Lake. At least two Pleistocene, pre-Bonneville lake cycles occupied the Bear River Valley (Scott and others, 1983; Oviatt and others, 1987; Oviatt and Currey, 1987), but no evidence for these lake cycles is exposed in the quadrangle. Limestone, shell fragments, and well-sorted, coarse, sand-sized Paleozoic carbonate grains (beach? sands) are present in Quaternary cuttings from the #1 Davis geothermal borehole. The ages and interpretations of regional, Lake Bonneville, Gilbert inundation, and prehistoric Great Salt Lake events in the following paragraphs are from Currey, Oviatt, and Czarnomski (1984); Currey, Atwood, and Mabey (1984); Currey and Oviatt (1985); Murchison (1989); and Oviatt and others (1992). Ages are in approximate radiocarbon ^{14}C years. The Bonneville-, Provo-, and Gilbert-shoreline elevations are from this study and mapping in nearby quadrangles (Oviatt, 1986a, 1986b; Jensen, 1994).

Lake waters in the Bonneville basin began to rise about 30,000 years ago. Water levels stabilized or oscillated for about 2,000 years, beginning about 22,000 years ago. This stillstand formed the Stansbury shoreline at an elevation of about 4,500 feet (1,372 m). The Stansbury shoreline is not prominent or well preserved in the Brigham City quadrangle, but might be present in the SE¼ SW¼ section 36, T. 10 N., R. 2 W. at an elevation of about 4,480 feet (1,366 m). Oviatt and others (1990) reported fine-grained, Stansbury-stillstand deposits in a cut-bank in the Bear River near Bear River City (base of unit 2 in measured section BC3, appendix; C.G. Oviatt, written communication, 1985). From about 20,000 to 15,300 years ago, Lake Bonneville rose to its highest level. For the next 1,000 years lake levels were largely controlled by the elevation of the outlet into the Snake River drainage near Preston, Idaho (Zenda threshold). The Bonneville shoreline formed at an elevation of about 5,165 feet (1,574 m) during the highest stand. Most of the Brigham City quadrangle was under water from 15,300 to about 14,300 years ago. Small remnants of the Bonneville shoreline have been mapped in the quadrangle (Personius, 1990; plate 1, this report).

Prior to 14,300 years ago, the threshold at Zenda failed, resulting in a catastrophic flood in the Snake River drainage, and the water level in Lake Bonneville dropped about 360 feet (110 m). The Box Elder Canyon delta probably formed soon after this rapid drop in lake level (Personius, 1990; written communication, 1995). The lake remained at this level until about 13,900 years

ago, forming the Provo shoreline at an elevation of about 4,780 to 4,790 feet (1,457 to 1,460 m). This shoreline is visible many places along the mountain front in the quadrangle. Numerous lower shorelines, labeled X on plate 1, apparently formed during retreat of Lake Bonneville from the Provo shoreline.

Lake levels in the Bonneville basin have been much lower since the Provo stillstand. Between approximately 12,000 to 11,000 years ago lake levels were at least as low as historic lowstands in Great Salt Lake, marking the end of the Bonneville lake-cycle. A small lake-level rise followed this decline, so that between roughly 10,900 and 10,300 years ago, the Gilbert shoreline formed at an elevation of about 4,250 feet (1,295 m). Gravel along a slight change in slope at this contour south of Bear River City is the only manifestation of this shoreline in the Brigham City quadrangle. Lake waters receded from the Gilbert shoreline about 10,000 years ago. This rise and fall is referred to as the Gilbert inundation in this report. In the past 9,500 years, Great Salt Lake has fluctuated below the level of the Gilbert shoreline. A level as high as about 4,220 feet (1,286 m) elevation was reached between 3,400 and 1,400 years ago. A prehistoric, "Little Ice Age," late-Holocene shoreline formed at an elevation of approximately 4,217 feet (1,285 m) (age estimated at 1600 to 1700 A.D.) (Murchison, 1989). Though valley-floor elevations are low enough, this shoreline has not been documented in the quadrangle. Great Salt Lake rose to historic high elevations of 4,211.5 feet (1,283.7 m) in 1873 (estimated by Arnow and Stephens, 1990) and 4,211.85 feet (1,283.8 m) in 1986 (Harty and Christensen, 1988), flooding the lower reaches of the Bear River Valley.

Lacustrine Silt Deposits (Qli)

Lacustrine silt deposits of Lake Bonneville, the Gilbert inundation, and Great Salt Lake cover most of the Bear River Valley, and therefore most of the western half of the Brigham City quadrangle. Remnants of this unit (Qli) are present in the Bear River deltaic plain (Qdp) and floodplain (Qal) as isolated topographic highs. These sediments consist of interbedded silt, clay, and very fine- to fine-grained sand that are laminated to thin bedded. The deposits are medium dark to dark gray when fresh, and oxidize to light and dark yellowish brown, pale olive and light olive gray. This unit locally contains ostracodes and is cross-bedded in some sand layers. The sand is subrounded to rounded and moderately sorted. These sediments were deposited in deep or relatively quiet lake water. The deposits are at least 24 feet (7.3 m) thick (appendix).

Lacustrine Sand Deposits (Qls)

Lacustrine sand deposits of Lake Bonneville and the Gilbert inundation are present in the northwest part of the quadrangle. These deposits consist of very fine-grained, subrounded to rounded, moderately sorted, laminated to medium-bedded, and cross-bedded sand. Locally, the sand is fine to medium grained. This unit overlies and interfingers with unit Qli (interbedded clay, silt, and very fine sand). Both map units are exposed in the banks of the Bear River east of Bear River City (appendix). On the surface, the lacustrine sand unit grades into the lacustrine silt map unit (Qli) by becoming finer grained. The soils map of Chadwick and others (1975) aided in differentiating this sand unit from the lacustrine silt unit. Some of the sand may have been deposited in a paleo-Bear River delta when Lake Bonneville was receding far below the Provo shoreline. The lacustrine sand is up to 25 feet (7.6 m) thick.

Lacustrine sand deposits are also exposed in the gravel pits northeast of Calls Fort, below about 2 to 10 feet (0.5 to 3 m) of lacustrine and alluvial gravel (Qlg, Qaf). The pits have been recontoured and the walls have sloughed, so pit margins have been used as contacts where natural contacts are obscured. The sand is mapped as Qh/Qls (human disturbance over sand) for these reasons. The sand in the pits lacks organic material, is very light yellow to off-white in color, and is better sorted and coarser grained than the other lacustrine sands in the quadrangle. Personius (written communication, 1995) suggested these are fan-delta sands at and below the Stansbury shoreline. Because the elevation fits (4,500 feet [1,372 m]), the deposits are transgressive lacustrine, and the delta source is obscure, we think these are Stansbury beach deposits. Though poorly exposed, the sand is apparently 20 or more feet (6+ m) thick.

Lacustrine Gravel and Sand Deposits (Qlg)

Lacustrine gravel and sand deposits of Lake Bonneville are present along the mountain front in the eastern part of the quadrangle. The unit comprises subrounded to well-rounded pebbles, cobbles, and rare boulders that are mixed with sand. The gravel is locally cemented by calcareous tufa (T on plate 1). This unit was deposited in beach and nearshore environments of the lake. The lacustrine gravel and sand deposits are commonly slightly modified by later mass movements on steeper slopes, having undergone mass movement or been covered by mass-movement deposits that can not be delimited at map scale. From exposures and drilling records in northern Utah (for example Case, 1985; Lowe, 1987), lacustrine gravels overlie pre-Lake Bonneville

alluvial fans and some of these lake gravels are probably reworked older alluvial fans. Alluvial-fan gravels are typically more angular and show rounding where they grade into the lacustrine gravels. A log of a water well (Case, 1985, well no. 141) is here interpreted as penetrating 30 feet (9 m) of Pleistocene lacustrine gravel below a Holocene alluvial fan.

Deltaic Gravel (Qdg)

These deposits slope downward from the Provo shoreline and contain more gravel than sand. These pebble and cobble gravels are subrounded to rounded, moderately to poorly sorted, and clast-supported in a matrix of sand and silt. The unit contains foreset beds, and capping topset beds that are less well sorted. Personius (1990) mapped the foreset and topset beds separately (his units lpd and alp, respectively). This gravel and sand unit was deposited in a delta at the mouth of Box Elder Canyon during the Provo stillstand of Lake Bonneville. In the Brigham City quadrangle, almost all exposures of deltaic gravel have been extensively excavated for production of sand and gravel. Based on data in Smith and Jol (1992), and on observed high-wall heights and unit thicknesses in the large gravel pit that extends east into the Mount Pisgah quadrangle, King here estimates that the deltaic deposits are about 250 feet (75 m) thick. Smith and Jol (1992) implied these deposits are 400 feet (120 m) thick. Personius (1990) reported a thickness of about 80 feet (24 m) for topset and foreset beds exposed in the Mount Pisgah quadrangle.

Fan-Delta Deposits (Qad)

This unit of gravel, sand, silt, and clay was deposited at the mouth of Box Elder Canyon, and its upper surface is more than 50 feet (>15 m) lower than the top of the deltaic gravel (Qdg). The fan-delta deposits are grayish orange to pale yellowish orange, clast-supported, poorly bedded gravel with sand, and fine-grained matrix sediment. The deposits contain no calcareous cement, are locally cross-bedded, and locally contain equal proportions of gravel and sand. The clasts are subangular to well rounded, poorly to moderately sorted, and up to 8 inches (20 cm) in length. Deposits are coarser grained upslope toward deltaic gravels (Qdg) and finer grained downslope toward the distal fan delta (unit Qla). Personius (1990) noted that deposition was in a fan delta after the recession of Lake Bonneville from the Provo shoreline. A fan delta is built when an alluvial fan enters a lake or ocean, and includes both the fan and the delta. Here, the sediments probably include Provo-stillstand lacustrine-deltaic deposits, sub-Provo-stillstand alluvial-fan and lacustrine-deltaic deposits that contain abundant reworked materials from the Provo-shoreline delta, and locally overlying alluvial-fan deposits. A log of a Brigham City water well on the upper end of the fan delta (section 19, T. 9 N., R. 1 W.) (Bjorklund and McGreevy, 1973, p. 16) is here interpreted as showing that the fan-delta is 125 feet (38 m) thick, with 45 feet (14 m) of underlying fine-grained Lake Bonneville deposits, probably including prodelta deposits, and 240+ feet (73+ m) of pre-Lake Bonneville alluvial-fan gravel below the lacustrine deposits.

Mixed Lacustrine and Alluvial-Fan Deposits (Qla)

Mixed lacustrine and alluvial-fan deposits are located in the eastern part of the quadrangle. They consist of heterogenous sand, silt, clay, and some gravel. This mixed unit is characteristically gravel-bearing and generally becomes coarser upslope (finer downslope). The contact with finer grained lacustrine deposits (Qli), located downslope, is approximate and is based on the soil survey of Chadwick and others (1975). Upslope, alluvial-fan deposits (Qaf) are mapped where fan cover becomes continuous and gravel is more abundant. Upslope towards the mouth of Box Elder Canyon, a fan-delta (Qad) is mapped where gravel is more abundant. The mixed sediments are: (1) pre-Lake Bonneville alluvial-fan deposits that are slightly reworked by lacustrine processes; (2) the distal portion of the Box Elder Canyon alluvial fan and lacustrine delta, probably including prodelta deposits; and (3) lacustrine deposits with a thin, discontinuous cover of alluvium, located at the distal ends of most post-Lake Bonneville alluvial fans. A water well log (section 11, T. 9 N., R. 2 W.) (Bjorklund and McGreevy, 1973, p. 16) is here interpreted as showing that the gravelly distal portion of the Box Elder fan delta (Qla) is about 55 to 70 feet (16 to 21 m) thick and rests on fine-grained lacustrine deposits (Qli) that probably include some prodelta deposits.

In the Honeyville quadrangle, Oviatt (1986a) mapped most low-angle slopes below alluvial fans as sandy, lacustrine deposits (Qls), rather than gravel-bearing mixed deposits (Qla) as we have done. His unit labeled Qla is similar to our unit Qla.

Alluvial-Fan Deposits (Qaf)

This unit contains poorly sorted, angular boulders, cobbles, pebbles, sand, silt, and clay that were deposited in alluvial fans at the base of the mountain front in the eastern part of the quadrangle. On the fan-delta at Brigham City these deposits contain reworked, rounded material from the Provo-shoreline delta (Qdg, Qad). The

fans are graded approximately to modern stream levels and have distinct distributary channels and interchannel bars. This unit is mostly active alluvial fans, but probably includes some deposits in inactive older Holocene and possibly latest Pleistocene (post-Provo shoreline) alluvial fans. We were unable to consistently separate and map two ages of Holocene alluvial fans, as done by Personius (1990; his units af1 and af2). Personius (1990) apparently separated his two Holocene fan units on the basis of soil development and the fresher appearance of channels in his unit af1.

The maximum thickness of these Holocene alluvial-fan deposits probably exceeds 35 feet (18 m). The new Corinne water well near the middle of the alluvial fan at the mouth of Yates Canyon (plate 1) probably penetrated about 35 feet (18 m) of alluvial-fan gravel, and a log of the old Corinne water well (Case, 1985, well no. 141) shows about 27 feet (8.2 m) of probable alluvial-fan gravel. A log of a water well in the distal portion of the alluvial fan at the mouths of Cataract and Moss Rock Canyons (Bjorklund and McGreevy, 1973, p. 17) is here interpreted as showing that these distal fan deposits are 17 feet (5 m) thick.

We did not map debris-flow deposits separately from alluvial-fan deposits (Qaf), because some borders of debris-flow deposits are indistinct, such that contacts could not be completely mapped, and alluvial fans are typically debris-flow deposits. Debris-flow deposits were observed on fans from Precipice, Calls Fort, Donation, Yates, Baker, Dry, Antimony, Hansen, "two" Hansen (in W$^1/_2$ section 6, T. 9 N., R. 1 W.), and Kotter Canyons. Miller (1980) and Personius (1990) mapped some of these debris flows.

Older Alluvial-Fan Deposits (Qafo)

This unit contains deposits of poorly sorted, angular boulders, cobbles, pebbles, sand, silt, and clay that are remnants of older alluvial fans. These remnants are typically located near the heads of and are cut by the present generation of alluvial fans (Qaf). Fan remnants are present below the Provo shoreline near the mouths of Donation, Cataract, Moss Rock, Baker and Dry Canyons, and Miners Hollow, and downslope west of Hansen Canyon. Upper surfaces on the fan remnants are higher in elevation than those of the adjacent fans (Qaf). These older surfaces lack distinct channels and interchannel bars. The older fans are post-Provo stillstand in age, and may have formed during stillstands at the Gilbert shoreline or some Holocene lake level. This unit is not equivalent to the unit labeled Qaf_2 on the Honeyville quadrangle (Oviatt, 1986a; age - pre-Provo stillstand), or to the post-Lake Bonneville older alluvial fans (af2) of Personius (1990). The remnants we mapped as older alluvial fans were mapped as unit afp by Personius (1990; Provo-shoreline alluvial fans).

North of Baker Canyon, and more prominently near Donation Canyon and Miners Hollow, these older fan deposits look like they incompletely mantle fault and Lake Bonneville shoreline scarps. That is, these scarps are more prominent in adjacent lacustrine gravel deposits (Qlg) and show, though subdued, through the fan deposits.

Lacustrine and Alluvial Mud-Flat and Marsh Deposits (Qlam)

These deposits are near the center of, and next to deltaic-plain deposits on the southern margin of the quadrangle. This map unit is characterized by a high water table, marshes, slow-moving, low-gradient streams, and waters with high salt content. The deposits in the center of the quadrangle, around North Lake and the Cement Ponds, are yellowish gray to light-olive-gray to very dark-gray, organic-rich, mostly fine-grained sediment. They include: (1) thin Holocene lacustrine, marsh, and minor alluvial silt, clay and sand; and (2), where exposed, underlying lacustrine clay, silt, and some sand of Lake Bonneville. The marsh deposits on the southern margin of the quadrangle are the product of high water levels of Great Salt Lake during the 1980s and of previous Holocene flooding. These sediments are very dark gray, organic-rich, and muddy. The contacts with fine-grained lacustrine deposits (Qli) are approximate because the deposits are similar. They are based on the greater amount of marsh vegetation and organic matter in unit Qlam.

Deltaic Plain Deposits (Qdp)

This unit includes sand, silt, clay, and organic material deposited in the deltaic plain of Great Salt Lake by the Bear River south of Corinne. The deposits are in marshes, oxbow lakes, channels, point bars, and natural levees. The deltaic plain is subject to flooding from the Bear River and high water levels in Great Salt Lake.

Oxbow Lake Deposits (Qab)

This unit consists of fine-grained, organic-rich sediments that are being and were deposited in oxbow lakes in the cut-off meanders of the Bear River. The thickness of these deposits is not known because they are in uneroded depressions.

Stream Alluvium (Qal)

These deposits of sand, silt, clay, and gravel are lo-

cated along the Bear River, and other active and abandoned stream channels. The map unit includes terraces less than 20 feet (<6 m) above the present floodplain, and locally includes sediments deposited in marshes. Meandering stream channels that postdate the Gilbert shoreline have cut into lacustrine sediments along the Bear River. One alluvial channel cuts and reworks the Box Elder Canyon delta and fan-delta; these alluvial deposits are clast-supported, pebble and cobble gravels in a sand and silt matrix, and sand lenses. We included the stream alluvium mapped by Personius (1990; his unit al2) above this channel in our fan-delta deposits (Qad), because they appear indistinct except in their upper reaches, and these upper reaches are apparently parts of a distributary system.

Alluvial Terrace Deposits (Qat)

Terrace deposits overlie remnants of lacustrine sand and silt (Qls, Qli), on which the Bear River flowed after Lake Bonneville receded and before later incision. The terrace deposits consist of alluvial silt, very fine- to coarse-grained, sub-rounded to rounded sand, and gravel that are above the present floodplain of the river. The terrace surfaces are lower than nearby lacustrine deposits and the Gilbert shoreline (4,250 feet [1,295 m]). Terrace-surface elevations are at least 20 feet above river level and increase upstream from about 4,225 to 4,235 feet (1,288 to 1,291 m). This increase in elevation and their elevation below the Gilbert shoreline led us to conclude that these deposits are terraces rather than lacustrine deposits tied to a lake level (see following paragraph). The terrace deposits are at least 15 feet (4.5 m) thick.

Similar terrace-like features, caps of sand and silt deposits with flat-topped surfaces, have been reported upstream along the Malad and Bear Rivers. However, their age is uncertain along the Malad River, and their age and possible correlation is in question along the Bear River. Along the Malad River, Elder (1992) reported that cut-bank samples in terraces, taken at elevations of about 4,232 and 4,230 feet (1,290 and 1,289 m), were radiocarbon dated at about 2,400 and 7,700 years B.P., respectively. Miller (1980) depicted a radiocarbon date of about 4,000 years B.P. on terraces in the same area. On the northern edge of the Bear River City quadrangle, the uppermost terrace surfaces of the Malad River (tentatively correlated by Jensen with our Qat) are at an elevation of about 4,240 feet (1,292 m). Along the Bear River, Oviatt (1986a, 1986b) mapped flat-topped features (his Qls_1) upstream from the Gilbert shoreline and reported that their upper surfaces were at a nearly constant elevation of 4,245 to 4,250 feet (1,294 to 1,295 m). He therefore interpreted these capping sediments as deposits in a narrow estuary during the Gilbert inundation (highstand 4,250 feet [1,295 m] elevation) of Lake Bonneville. Our terrace deposits may or may not correlate with his unit Qls_1, because: 1) the setting is different; 2) a reported radiocarbon date of about 7,500 years B.P. (Oviatt, 1986a, 1986b) is on oxbow-lake deposits in cuts in the flat-topped features (C.G. Oviatt, written communication, 1995); and 3) the upper surfaces of the features are above an elevation of 4,240 feet (1,292 m).

Alluvial Gravel (Qag)

The lone exposure of this unit is located in the south bank of the Bear River southeast of Bear River City. The unit contains up to pebble-sized gravel and sand that, except for the upper 3 to 4 feet (0.9 to 1.2 m), are cemented with calcite or tufa. From the geomorphic expression, the sediments are apparently confined to a paleo-channel that formed after Lake Bonneville receded. Where exposed, this unit is less than 10 feet (3 m) thick.

Colluvium and Alluvium (Qac)

This unit is mapped in wider canyons in the Wellsville Mountains. It contains gravelly, rounded to angular, silt- to cobble-sized colluvium and alluvium, and locally some talus. In canyons with larger drainage basins, such as Moss Rock Canyon, present channels are incised 30 feet (9 m) into these deposits and the upper surfaces of the deposits slope away from the channels, giving the appearance of terraces or levees. So, these colluvial and alluvial deposits reach thicknesses of at least 30 feet (9 m). These terraces(?) may have formed during stillstands at the Provo or a lower level of Lake Bonneville, the Gilbert shoreline, or some Holocene lake level. This origin is similar to that proposed for the older alluvial fans (this study), and they possibly formed at the same time(s) as the older fans. Because it is impossible to show a fault and concealing deposits in the same ≤100-foot-wide (≤30 m) cleft in the mountains, colluvium and alluvium were not mapped in such clefts.

Colluvium and Fan Alluvium (Qacf)

This unit is mapped on some mountain front slopes between Miners Hollow and Cataract Canyon, and south of Dry Canyon. It contains gravelly, rounded to angular, silt- to cobble-sized colluvium and alluvium, and locally some talus. The deposits have a fan shape, head in clefts, and mantle lacustrine gravels. However, unlike alluvial fans, they are on steep slopes, lack a well-developed source drainage (head in clefts), and commonly head in undivided mass-movement deposits. They have

been mapped as mixed alluvium and colluvium because they were probably deposited by both processes. Alternatively, they are debris cones, which are similar to alluvial fans but are coarser grained and occur on steeper slopes. Their setting and shape is distinct from the canyon deposits of alluvium and colluvium (Qac), and alluvial-fan deposits (Qaf).

Mass-Movement Deposits, Undivided (Qm)

This unit encompasses various types of mass-movement deposits that can not be mapped separately at map scale, or that are so intimately intermixed that the types of mass movements can not be differentiated. The unit is generally present on the south sides of canyons, and includes talus and colluvium, and possibly minor debris flows and landslides. The contact with lacustrine gravels (Qlg) is based on the presence of gravel stripes in the mass-movement deposits. The stripes trend upslope-downslope, and contain more gravel and are less vegetated than inter-stripe areas. Many small exposures of this mass-movement unit are not shown on plate 1, because mapping them would obscure the fault that is located in the same ≤100-foot-wide (≤30 m) cleft in the mountains. Other unmappable slumps and slides are located along the Bear River north of Corinne; the scarps for these mass-movements are shown as hachured lines on plate 1, while the deposits are largely removed by the river.

Talus (Qmt)

Talus at the base of cliffs along the front of the Wellsville Mountains was mapped separately from other Quaternary deposits. Talus is angular, mostly gravel-sized rock debris. Talus contacts with undivided mass-movement deposits (Qm) were locally difficult to delineate due to the small size of talus sheets and the gradational nature of the deposits. Talus, as opposed to undivided mass-movement deposits, was mapped where scree slopes are large enough to show at map scale, and are not stabilized by vegetation.

Landslide and Slump Deposits (Qms)

Landslide deposits and associated scarps are present on the Manning Canyon Shale in Rattlesnake Canyon in the northeastern corner of the quadrangle. King (this study) believes a much larger slump, comprising all of Stoddard Hill, extends from the Mount Pisgah quadrangle west just into the Brigham City quadrangle (SE$^1/_2$ section 18, T. 10 N., R. 1 W.). King bases this interpretation on: (1) the rotated, block-like shape of Stoddard Hill; (2) the discontinuous, visible bedding with highly variable orientations in Stoddard Hill; (3) a location on strata that are susceptible to mass movement (Little Flat Formation); and (4) Dover's (1985) previous mapping of the deposits as a landslide or slump.

Eolian Sand (Qes)

This unit comprises a few small dunes less than 5 feet (≤1.6 m) high of very fine- to fine-grained sand on the mud flats near the Cement Ponds. Scattered vegetation is present on the dunes, indicating they are inactive or presently being eroded.

Fill Material and Disturbed Areas (Qhl, Qhs, Qhf, Qhd)

These deposits include: (1) the Brigham City sanitary landfill, located east of I-15 and south of Forest Street (Qhl); (2) sewage treatment ponds, located south of Corinne and east of the rest area on I-15 (Qhs); (3) scattered areas of fill (Qhf); and (4) other sites where human activities have obscured natural surficial deposits (Qhd). This material has been mapped because it could be prone to damaging ground movement during earthquake ground shaking.

Extensive fill (Qhf) was used in the construction of Interstate Highway I-15, several state secondary roads, railroad right-of-ways, and the Brigham City airport. Fill was also emplaced southeast of the I-15-Utah Highway 13/83 interchange prior to construction of the Vulcan plant. Levees and dikes have been constructed in the marshy area (Qlam) west of I-15 and along the Bear River. Fill has also been dumped into the oxbow lake east of Corinne.

From examinations of 1937, 1953, and 1966 aerial photographs, 1988 and 1993 field examinations, and the 1988 topographic map, it is evident that parts of a north-south elongate depression in Brigham City have been filled (Qhf), in some cases prior to 1937. North Pond is impounded by what looks like fairly recent fill (pimpled surface) on the 1937 photos. Some small, arcuate parts of the upslope margin of the depression look like small alluvial fans on the aerial photographs, so some fill could be natural. Parts of the alluvial channel of Box Elder Creek have also been filled. Only the two largest areas of alluvial-channel fill are shown on plate 1 (Qhf). Other natural contours in Brigham City have probably been modified.

From the same examinations, the natural surficial deposits at five other sites in the quadrangle have been obscured by human activities. These disturbances (Qhd) include: (1) cut-and-fill prior to warehouse construction west of the railroad tracks in Brigham City; (2) a gravel pit west of the tracks that might be filled with off-site

material; (3) sand and gravel operations in the floodplain of Box Elder Creek east of Brigham City; (4) a pile of off-site(?) material southeast of the Harper Ward cemetery, shown as a gravel pit on topographic maps; and (5) an abandoned gravel pit south of Bear River City that might be filled with off-site material.

STRUCTURAL GEOLOGY

The Brigham City quadrangle is located in northern Utah on the eastern margin of the Great Basin (figures 1 and 2). Consequently, Upper Proterozoic and Paleozoic rocks exposed in the Wellsville Mountains have been subjected to Mesozoic and early Cenozoic folding and thrust faulting, and later Cenozoic normal faulting. Bedding in these rocks dips about 30° to 50° northeast within a northeast-dipping homocline, in which lower Paleozoic strata are well exposed. The Wellsville Mountains are bounded by large-displacement, late Cenozoic, normal-fault zones, the Wasatch fault zone on the west and the West Cache fault zone of Cluff and others (1974) on the east. Cenozoic basin fill in the Bear River Valley is probably at most 7,000 feet (2,100 m) thick, and is late Cenozoic (Miocene and younger) in age (see Tertiary section, this report). As shown by Peterson (1974) and Zoback (1983), this basin is asymmetric with the steeper margin on the eastern side next to the Wellsville Mountains. Holocene surface ruptures on normal faults have been mapped in Quaternary surficial deposits along the mountain front north and east of Brigham City in this quadrangle and in the adjoining Honeyville, Mount Pisgah, Mantua, and Willard quadrangles (Oviatt, 1986a; Personius, 1988, 1990, 1991). These fault offsets demonstrate that the Wasatch fault zone has been active several times during the past 10,000 years in this area.

Several measured and calculated attitudes of each fault and associated features are reported in the following descriptions because faults in the Wellsville Mountains are poorly exposed and measured attitudes of fault-related features at a given site seldom indicate the actual fault-plane attitude (W.A. Yonkee, verbal communication, 1994).

Mesozoic and Early Cenozoic Folding and Thrust Faulting

The Upper Proterozoic and Paleozoic rocks in the quadrangle were folded, thrust-faulted and transported eastward during the Cretaceous and Paleocene Sevier and Laramide orogenies (for example Allmendinger and others, 1984; Miller, 1991; Yonkee, 1992). Strata exposed in the Wellsville Mountains are interpreted as being in the upper plate of the Willard thrust fault. To the west, Jensen (1994; after Allmendinger and others, 1984) placed the Samaria Mountain thrust (Hansel plate) west of Little Mountain. In contrast, W.A. Yonkee (unpublished cross section, 1990) placed it just east of Little Mountain, putting Little Mountain in the Hansel plate (see figure 1 for geographic locations). Well-exposed evidence for these orogenies in the Wellsville Mountains are the northeast-dipping homocline and the Box Elder thrust fault. The less-well exposed Wellsville Mountains transverse fault zone is probably also evidence for these orogenies. The homocline probably formed when post-Willard (Crawford and Absaroka) thrust faults ramped upward near the Wasatch Front and carried overlying rocks eastward (Yonkee, 1992). The dip on the homocline became steeper during Cenozoic extension (Miller, 1991).

The Box Elder thrust fault of Sorensen and Crittenden (1976) appears, from good exposures in the Mantua and Mount Pisgah quadrangles, to extend into the southeast margin of the Brigham City quadrangle. Projection of the thrust fault to the northwest from the Mount Pisgah quadrangle places the fault trace near the base of the Wellsville Mountains, east of Rees Spring and near the Wasatch fault zone, where it might be concealed by Quaternary deposits (plate 1). Our projected trace is east of the isolated outcrop near Kotter Canyon that we believe is Papoose Creek Formation and Caddy Canyon Quartzite. This interpretation requires a concealed low-angle thrust or normal fault between this isolated outcrop and exposures of Geertsen Canyon Quartzite farther upslope. Link and Smith (1992) implied that this low-angle fault is a late Cenozoic extensional feature, but it is offset by several northeast-trending faults that are probably Cenozoic in age.

Subsurface data don't refine the picture. No definitive evidence for a thrust fault was seen in the cuttings or geophysical logs from the deep (11,000 feet [3,353 m]) geothermal borehole in the Brigham City quadrangle; the previous interpretation by Campbell (in Doelling, 1980) was based on different formation picks (table 1). A thrust might be present in the borehole at a depth of 4,790 feet (1,460 m), if the West Canyon Limestone overlies the Great Blue Limestone without the intervening Manning Canyon Shale (table 1; text on Wellsville Mountains transverse fault zone).

Wellsville Mountains Transverse Fault Zone

In the Wellsville Mountains, a major transverse fault zone, here named the Wellsville Mountains transverse fault zone, cuts the homocline from near the mouth of

Moss Rock Canyon to the northeastern corner of the quadrangle (figure 2), and continues into the Honeyville quadrangle. The Wellsville Mountains transverse fault zone divides the Wellsville Mountains into two geologic domains, as first noted by Gelnett (1958). South of the Wellsville Mountains transverse fault zone, the Manning Canyon Shale is present, the Great Blue Limestone is much thicker (see Mississippian and Pennsylvanian stratigraphy), and smaller displacement transverse faults are more numerous and longer. See Davis (1985) for a synoptic map presentation of the Wellsville Mountains, and note the abrupt thinning of upper Mississippian rocks and the termination of the Wellsville Mountains transverse fault zone in the base of the Oquirrh Group.

Because portions of the fault zone are concealed, the nature of the structure is uncertain. The structure is either one fault zone cut into three segments by later faulting (our preferred interpretation), or three different faults. Apparent stratigraphic separation across the Wellsville Mountains transverse fault zone evidently decreases to the southwest and northeast along strike. As much as 5,800 feet (1,770 m) of apparent right-lateral strike-slip offset is present across the middle fault zone segment near Donation Canyon. Gelnett (1958) reported 3,700 and 4,500 feet (1,128 and 1,372 m; his plate 9 and text, respectively) of stratigraphic separation on a single large Wellsville Mountains transverse fault. From south to north, each segment or fault is described in separate paragraphs.

From near Moss Rock Canyon to the mouth of Cataract Canyon, the southern fault segment is inferred beneath surficial deposits between exposures of Geertsen Canyon Quartzite and Bloomington and Blacksmith Formations, and trends roughly north-south with apparent right-lateral, down-to-the-east movement (plate 1). This fault is inferred because: (1) the Blacksmith and Geertsen Canyon exposures are along strike of each other, and (2) inadequate space (<450 feet [<140 m]) is present between the Geertsen Canyon and Bloomington exposures to accommodate the normal stratal thicknesses (3,200 feet [970 m]) between these formations. S.F. Personius and J.P. Evans (written communications, 1995) suggested that these relationships might alternatively be the products of a concealed late Cenozoic normal fault related to the Wasatch fault zone. However, this concealed fault has down-to-the-east movement, not down-to-the-west, and is apparently offset by or terminates against an east-west-trending, Mesozoic and early Tertiary fault just south of and sub-parallel to Cataract Canyon.

Between Cataract and Donation Canyons, the middle fault segment trends roughly north-south, has a nearly straight surface trace, and thus apparently is a steeply dipping fault. However, we didn't find good exposures of the fault plane and other data support shallower dips, so the attitude of and displacement on the fault remain uncertain. The best-fit on intersecting cross sections yielded a dip of about 65° E (plate 2). The best constrained three-point solution yielded a dip of about 50° ESE; other three-point solutions yielded dips as low as about 35°, with dips to the southeast rather than east. Apparent stratigraphic separation just north of Cataract Canyon is about 4,200 feet (1,280 m), while it is about 5,200 feet (1,580 m) near Donation Canyon.

North of Donation Canyon, the northern fault segment is apparently concealed by shallow-dipping normal-fault blocks and then reappears in the Honeyville quadrangle (plate 1). Alternatively, it has the same trace as the northern shallow-dipping fault and low dip until it reaches the Honeyville quadrangle and reverts to a fault with steeper dip. About 7,000 feet (2,130 m) of our projected northeast-trending trace is concealed. The actual trace and attitude on this fault segment are uncertain. Using three-point solutions and the extent of the shallow-dipping fault block, the projected northeast-trending segment dips at an angle greater than 35° SE, if not offset by other concealed faulting. Intersecting cross sections show a dip of about 65° SE (plate 2). Apparent stratigraphic separation across the northern fault segment of the Wellsville Mountains transverse fault zone decreases from about 4,700 feet (1,430 m) at Donation Canyon to less than 3,700 feet (1,130 m) in the Honeyville quadrangle.

The age and origin of the Wellsville Mountains transverse fault zone is uncertain due to cover, segmentation, and differing characteristics. Gelnett (1958) first interpreted the fault zone as a single, unsegmented, southeast-dipping fault with normal, dip-slip, down-to-the-southeast movement. Oviatt (1986a) mapped the northern fault segment similarly, but also mapped and noted numerous tear faults (right-lateral strike-slip faults) related to thrusting. More recently, the middle segment was interpreted as an east-dipping fault with normal, dip-slip, down-to-the-east movement (Jensen, 1988). The roughly north-south trend (at a high angle to tear fault trends) and relatively steep apparent dip implies the Wellsville Mountains transverse fault zone is neither simply a tear nor a normal fault coeval with Mesozoic-early Tertiary thrust faulting. Further, parts of the Wellsville Mountains transverse fault zone are covered by shallow-dipping normal-fault blocks, and are cut by faults with apparent dip-slip, down-to-the-south movement. Therefore, the Wellsville Mountains transverse fault zone is older than late Cenozoic extension, and might be older than some Mesozoic-early Cenozoic

thrust faulting. The transverse fault zone may have formed during middle Tertiary extension. However, normal faulting during the middle Tertiary was typically at low angles to bedding (Zoback and others, 1981; Miller, 1991), and the transverse fault zone and the faults which cut the zone are at high angles to bedding. This leaves a thrust ramp or some complex fault interaction as the possible origin for the Wellsville Mountains transverse fault zone.

Using the above and following lines of reasoning, King interprets the Wellsville Mountains transverse fault zone as an oblique ramp down section to the south that has been offset (segmented) during later faulting. Because the Manning Canyon Shale is commonly a glide plane for and is locally entirely cut out by thrust faults in northwest Utah (Allmendinger and others, 1984), the missing Manning Canyon Shale and thinner Great Blue Limestone north of the Wellsville Mountains transverse fault zone (and in the geothermal borehole) implies the presence of a previously unrecognized Mesozoic-early Cenozoic thrust fault. This thrust fault would separate the Great Blue Limestone and West Canyon Limestone on the northern Wellsville Mountains (Honeyville quadrangle), and ramp up or down along the Wellsville Mountains transverse fault zone. We didn't find duplicated strata, and strata are not duplicated at Dry Lake, 5 miles (8 km) to the south in the Mount Pisgah quadrangle (see Mississippian and Pennsylvanian stratigraphy), so thrust duplication south of the Wellsville Mountains transverse fault zone was eliminated as a possible scenario. Because the Wellsville Mountains transverse fault zone has apparent right-lateral strike-slip movement, it does not seem to be an oblique or lateral ramp up into the Great Blue-Manning Canyon interval. The fault appears to ramp down from the Manning Canyon-Great Blue interval to lower Cambrian or Proterozoic strata, and might be a continuation of the Box Elder thrust fault of Sorensen and Crittenden (1976).

Some evidence supports the interpretation that the missing section north of the Wellsville Mountains transverse fault zone is due to an unconformity; this implies the Wellsville Mountains transverse fault zone is not a thrust ramp. First, very few faults with oblique or lateral ramps down section have been documented in fold and thrust terrains (W.A. Yonkee and J.C. Coogan, verbal communications, 1994). Also, the Middle and Upper Cambrian strata (Ute Formation through St. Charles Formation) are at least 10 percent thinner south of the Wellsville Mountains transverse fault zone. This is unlikely if the carbonate rocks south of the fault were transported from depositional sites farther to the west than the carbonates north of the fault. Carbonates typically become thicker to the west on the Cambrian, Utah-Nevada, continental shelf (Hintze, 1988, figure 17). However, the evidence for an unconformity is also ambiguous (see Mississippian and Pennsylvanian stratigraphy).

Other Faults

The Wellsville Mountains homocline is cut by numerous faults that have much smaller displacements than the Wellsville Mountains transverse fault zone (figure 2); these other faults have uncertain ages and senses of movement. Northeast- to east-southeast-trending faults, with mostly small apparent strike-slip offsets, can be simplistically interpreted as tear faults that formed during Mesozoic-early Cenozoic contraction. North- to east-trending faults, with mostly small normal offsets, may have formed during contraction, during later Cenozoic extension, or during both contraction and extension.

In the quadrangle, separating normal faults from strike-slip faults is not simple, because most slickensides demonstrate oblique slip. Also, few faults have orientations that conform with contraction or extension alone, and faults formed during contraction may have also undergone movement during extension. In attempts to decipher any pattern of faulting and to facilitate fault descriptions, the faults were classified by King. Based on trend, apparent dip, and other characteristics (figure 2; table 3), most faults fall into five sets, with some categorized as "unique" faults; other faults do not fit into any category (dashed on figure 2). Four of the fault sets trend east of north, including: (1) roughly east to east-northeast; (2) roughly northeast, with apparent steep dips; (3) roughly northeast, with shallow to moderate dips; and (4) roughly north-northeast. The fifth set has various trends with shallow to moderate dips, normal offset, and appear to cut or obscure other fault sets and unique faults. Therefore, the fifth set probably formed during late Cenozoic extension, and is discussed under the heading Late Cenozoic Normal Faulting. The other 4 fault sets, and unique and uncategorized faults may have formed during earlier contraction and/or late Cenozoic extension. The strange-looking bedding "cut-offs" shown on the cross sections (plate 2) may be the product of oblique slip on and/or "reuse" of faults.

Set-1 Faults

Set-1 faults (E to ENE trend) are the most numerous in the quadrangle. Observed attitudes and slickensides show oblique relative movement to the west, some down to the north and some down to the south, on vertical to nearly vertical faults (Antimony Canyon, Dry Lake mine,

Table 3.
Characteristics of fault sets in the Brigham City 7.5' quadrangle.

	Trend	Apparent Dip	Apparent Movement	Apparent Strike-Slip Offset	Length	Other
Set 1	E to ENE	near vertical >70°	down to west, oblique northwest and southwest	typically <100 feet; but three have 1000 feet	~1000 to 5000 feet; but three >5000 feet	some have reverse movement
Set 2	NE	steep >55°	right and left lateral, normal	<100 to 750 feet	~1000 to 5000 feet	may cut set-1 faults
Set 3	NE	moderate 30°to 60°	right lateral, normal down to south	100 to 500 feet	max. typically >3000 feet	apparent scissor faults
Set 4	NNE	near vertical? >70°	down to south, oblique southeast and southwest	typically <100 to 500 feet, but one has 1500 feet	~600 to 3000 feet	possible reverse movement on some; more abundant north of Wellsville Mountains transverse fault zone

upper Yates Canyon), and northwest reverse movement on the south-dipping Dry Lake mine fault. Reverse movement may have occurred on the Baker Canyon fault (south dipping) and the fault north of Cataract Canyon (north dipping?), but attitudes were measured on nearby fractures rather than on the fault planes. Dips of other faults could not be observed. Relative movement is assumed to be oblique to the northwest and southwest on these faults, except for a possible reverse fault north of Moss Rock Canyon. Apparent strike-slip offset on set-1 faults is typically less than 100 feet (30 m), but is about 1,000 feet (300 m) on the fault in Antimony Canyon, and the two faults near "two" Hansen Canyon (in NW1/2 section 6, T. 9 N., R. 1 W.) that bound a graben in the Mount Pisgah quadrangle. These large-displacement faults are in excess of 5,000 feet (1,525 m) long, while most set-1 faults are about 1,000 (300 m) to less than 5,000 feet (1,525 m) long.

The fault north of the ridge between Yates and Moss Rock Canyons has the trend of set-1 faults, but the relative movement is problematic. Different senses of movement on the fault (plate 1) suggest two episodes of faulting and reuse of only a part of the fault during the latter episode. The fault in lower Cataract Canyon might be a set-1 fault given the apparent 70° S to 70° N dip (three-point solutions) and sinuous trace like the set-1 fault in Antimony Canyon.

Set-2 Faults

Set-2 faults trend northeast, have steep dips, and are from about 1,000 feet (300 m) to 5,000 feet (1,525 m) long. Long set-2 faults include: (1) the pair between Cataract and Donation Canyons; (2) a pair of faults that might cross Moss Rock Canyon (concealed); and (3) possibly a fault between Cataract and Moss Rock Canyons. The northern fault of the Cataract-Donation pair has apparent normal and right-lateral relative movement, with apparent strike-slip offset up to 750 feet (230 m). The exact fault dip is uncertain. The measured dip was 65° SE, while three-point solutions yield dips of about 60° SE, and the best fit on the cross sections is about 55° SE (plate 2). Other faults in set-2 have apparent right- and left-lateral movement, with minimal to about 500 feet (150 m) of offset. As pointed out by J.P. Evans (written communication, 1995), some set-2 faults seem to cut some set-1 faults. Given trend and relative sense of movement, the fault in upper Donation Canyon in the shallow-dipping fault block might be a set-2 fault or a tear that developed during shallow-dipping normal faulting.

Two faults have characteristics of both set-2 and set-3 faults. A fault south of Calls Fort Canyon has a northeast trend, fractures that dip 90° to 75° N, and about 600 feet (180 m) of relative right-lateral, reverse movement. But three-point solutions indicate southeast dips of 35° to 40°, with down-to-the-south, normal movement, like set-3 faults. The fault between Cataract and Moss Rock Canyons might also be a set-3 fault, if the steep (70° SE) dip shown on plate 1 wasn't really measured on the fault plane. This fault has a shallow apparent dip (32° SE by three-point solution) and is concealed at the mountain front where it might bend to the southwest like set-3 faults.

Set-3 Faults

Set-3 faults are mostly over 3,000 feet (900 m) long, trend roughly northeast, dip moderately to the southeast, and have right-lateral, down-to-the-south relative movement. Measured dips were 30° to 57° SE, a 65° SE dip was reported, and three-point solutions yielded roughly 30° to 45° SE dips (plate 1; see also Gelnett, 1958; Perry in Doelling, 1980). Despite these low fault-plane dips, fractures dip as much as 75° and even 90° where fault planes are not visible. Set-3 faults are sub-parallel to ridges, and those that reach the mountain front then change trend to the southwest. Set-3 faults are located (1) between Yates and Baker Canyons (limited offset); (2) between Baker and Dry Canyons, including the Baker mine area; and (3) between Dry and Antimony Canyons; and are possibly located (1) northeast of the Baker mine; (2) between Cataract and Moss Rock Canyons (as noted in set-2 description); (3) south of Calls Fort Canyon (as noted in set-2 description); (4) between Precipice and Calls Fort Canyons (this fault might be a set-2 fault that meets a set-1 fault); and (5) just south of Precipice Canyon (these faults might be set-1 faults). Slickensides exposed in workings on the ridge between Baker and Dry Canyons indicate mostly dip-slip movement on faults that are placed in set 3 with certainty, although Gelnett (1958) reported horizontal movement at this location. South of Precipice Canyon, bedding attitudes above and below the fault(s) are different. Relative strike-slip offset on faults that are clearly set-3 faults is up to 500 feet (150 m) and is typically more than the offset on set-1 faults. Offset of most long set-3 faults decreases eastward, upsection into the mountains, indicating they are scissor faults. W.A. Yonkee and J.P. Evans (verbal communications, 1994) suggested that these longer faults are related to the development of the Wasatch fault zone, and hence are late Cenozoic in age.

Set-4 Faults

Set-4 faults are significant though limited in number. They trend north-northeast, have down-to-the-south movement, and are about 600 to 3,000 feet (180 to 900 m) long. The fault on the mountain front between Moss Rock and Yates Canyons has about 1,500 feet (450 m) of apparent right-lateral offset, down-to-the-east movement, and probably dips to the west (fractures 75° W; three-point solution 78° W). This indicates apparent reverse movement. The other faults in this set have less offset (<100 to about 500 feet [<30 m to 150 m]) and, in contrast to the general pattern, are more abundant north of the Wellsville Mountains transverse fault zone. Though it has the same trend, the north-northeast-trending fault between Cataract and Donation Canyons is the middle segment of the Wellsville Mountains transverse fault zone.

Unique Faults

Unique faults are discussed due to their length and uncommon characteristics. They trend both west and east of north. One north-northwest-trending fault (north of "two" Hansen Canyon, in NW 1/2 section 6, T. 9 N., R. 1 W.) is apparently a Cenozoic moderately dipping normal fault (69° W dip). Another fault trends west-northwest, dips about 85° (fractures indicate NNE and three-point solution indicates SSW) between Dry and Antimony Canyons, and has about 1,000 feet (300 m) of apparent left-lateral offset. This may be a tear fault; the sense of movement is opposite the set-4 reverse fault between Moss Rock and Yates Canyons. At least two other unique faults "snake" around ridges and canyons. In upper Cataract Canyon and across the Wellsville Mountains divide, one such fault changes trend from east-northeast to northeast; yet from a three-point solution at the divide, the fault dips about 75° SE. A fault with similar trend changes is probably present in the bottom of Moss Rock Canyon; but the apparent changes in trend might be due to interactions between several faults rather than to a change in trend of a single fault. Cover precluded a more accurate assessment.

Late Cenozoic Normal Faulting

Several moderately dipping, late Cenozoic normal faults are located in the area. These faults are termed moderately dipping, rather than steeply dipping, because late Cenozoic normal faults along the northern Wasatch and nearby East Cache fault zones dip about 20° to 60° (33° to 39° from best data) and 45° (Smith and Bruhn, 1984; Evans, 1991; respectively). Zoback (1983) reported dips of 40° to 80° on late Cenozoic normal faults in Utah, but these dips are not as well constrained. Exposed faults along the base of the Wellsville Mountains are part of the Brigham City and Collinston segments of the Wasatch fault zone (Personius, 1988, 1990, 1991). The Wasatch fault zone is the east and steepest side of a late Cenozoic, asymmetric graben in the Bear River Valley. This fault-bounded basin becomes shallower to the north; it is about 7,000 feet (2,100 m) deep on the southern margin and about 5,000 to 6,000 feet (1,525 to 1,830 m) deep on the northern margin of the quadrangle (after Peterson, 1974; Zoback, 1983). The western fault of the graben is located west of Brigham City in the Bear River City quadrangle near Little Mountain (Zoback, 1983) and is concealed (Jensen, 1994).

At least one large-displacement, moderately dipping,

late Cenozoic normal fault is partially exposed in the quadrangle. This fault is located along the mountain front in the Brigham City segment of the Wasatch fault zone and trends about N 25° W. To the east and west in the Wasatch fault zone, other faults might be concealed by surficial deposits in the Bear River Valley (plates 1 and 2). Together with shallow-dipping late Cenozoic normal faults, these faults are the fifth fault set introduced under the heading Other Faults.

In addition to the Wasatch fault zone, late Cenozoic, shallow-dipping normal faults are present in the Wellsville Mountains (Sprinkel, 1979; Oviatt, 1986a; this report) and the Mantua and Willard quadrangles (Crittenden and Sorensen, 1985). A low-angle normal fault might be concealed along the mountain front near Brigham City (Link and Smith, 1992)(see Box Elder thrust fault in section on Mesozoic and early Cenozoic folding and thrust faulting).

Shallow-Dipping Normal Faults

Several shallow-dipping normal faults are present in the northeastern corner of the Brigham City quadrangle (plate 1; figure 2). They seem to bound detached blocks in which strata dip moderately and at angles similar to nearby in-place strata. Shallow-dipping normal faults on the west flank of the Bear River Range also have these characteristics (Brummer, 1991). However, the faults in this quadrangle do not have the geologic characteristics of other shallow-dipping normal faults in northern Utah. Offset appears to decrease downslope on the shallow-dipping normal faults mapped in the Willard and Mantua quadrangles by Crittenden and Sorensen (1985), such that detached blocks are not present in these quadrangles. They also differ from shallow-dipping normal faults formed by reversal of movement along former thrust fault planes, as proposed by Sprinkel (1979), which have steep to overturned dips in adjacent strata.

One shallow-dipping normal fault extends from the Honeyville quadrangle (Oviatt, 1986a) into the northeast corner of the Brigham City quadrangle (plate 1). Two other blocks of displaced strata above shallow-dipping normal faults are present in the same corner of the Brigham City quadrangle; they have 8,474- and 8,657-foot summit elevations. The disparity of bedding dips within the larger block and apparent counter-clockwise rotation support transport along a shallow-dipping normal fault. Faults within the larger block may have formed before the shallow-dipping normal faults, in particular the northwest-trending fault that apparently dips 55° NE (three-point solution) and the northeast-trending, near-vertical fault in upper Donation Canyon. The north- to north-northeast-trending faults in the larger block might be tear faults that formed during transport of the block.

Moderately Dipping Normal Faults

Several moderately dipping, late Cenozoic normal faults are indicated by scarps or are inferred (concealed) in the quadrangle along the mountain front and on the west side of Brigham City (plates 1 and 2; figure 2). At least one of these faults has Quaternary offset (scarps), and all are probably part of the Brigham City segment of the Wasatch fault zone. One fault with major displacement has been diagrammatically shown along the mountain front as a concealed and approximately located projection of the Holocene fault scarp at Rees Spring (plates 1 and 2). Other fault scarps are present to the east and west, such that more than one fault with major offset may be present. Faults nearer to bedrock outcrops are shown on cross sections (plate 2). The 0.5-mile-long (0.8 km) normal fault with north-northwest trend and 69° W dip in bedrock (unit Ꞓgl) north of "two" Hansen Canyon (in NW1/2 section 6, T. 9 N., R. 1 W.) might also be part of the Wasatch fault zone.

Offset along this portion of the Wasatch fault zone has been estimated using several methods. Based on gravity data, Zoback (1983, figure 6) estimated about 11,200 feet (3.4 km) of vertical offset. Sorensen and Crittenden (1976) used a different type of offset measure, and suggested at least 15,000 feet (4.5 km) of stratigraphic offset. Using subsurface data from the #1 Davis geothermal borehole, King (this study) obtained a similar figure; about 15,500 feet (4,725 m) of strata (lowermost Caddy Canyon Quartzite to at least lower Lodgepole Limestone; table 1 and plate 2, lithologic column) are missing across a fault encountered at a depth of about 7,850 feet (2,390 m) in the borehole. Vertical offset on the Wasatch fault zone is probably more than 12,200 feet (3,720 m), based on subtracting the elevation of the Lodgepole Limestone in the borehole from the elevation of the Lodgepole in the Wellsville Mountains in the Honeyville quadrangle (perpendicular to dip).

The general location and existence of the concealed fault shown on plate 1 is constrained by borehole and outcrop data, and cross-section construction (plate 2). Because the #1 Davis geothermal borehole is about 1.5 miles (2.4 km) west of the mountain front, a fault projected between the borehole and the concealed trace shown on plate 1 would dip 35° to 40° W (cross section A-A′, plate 2). This dip is within the range of the best data for the northern Wasatch fault zone (33° to 39°). Exposed faults closer to bedrock exposures would be penetrated by the geothermal borehole unless they dip greater than 45° W (project below the bottom of the

borehole), or they dip about 35° W (to intersect the borehole at 7,850 feet [2,390 m]). If the exposed faults dip greater than 45° W, about 5,000 feet (1,525 m) of vertical offset has occurred across them; see offset of the Caddy Canyon-Papoose Creek contact (Zcc-Zpc) on cross section A-A´ (plate 2). Another fault with major offset is then required to get the total vertical offset on the fault zone up to 12,200 feet (3,720 m). A fault dip of 35° W (or less) is considered unlikely, because strata would be duplicated (see again Zcc-Zpc contact, plate 2), the Caddy Canyon-Papoose Creek contact would only be offset vertically about 4,300 feet (1,300 m) between the borehole and the homocline (versus the 12,200 feet [3,720 m] noted previously), and some fault or other structure would have to be present between the borehole and the homocline of the Wellsville Mountains. Therefore, the fault in the borehole is interpreted as the down-dip extension of a fault west of the exposed faults along the mountain front (plates 1 and 2). Alternatively, the fault in the geothermal borehole might be a buried fault, west of the concealed trace shown on plate 1, that dips about 60° W (not shown on plates 1 and 2), the dip of many normal faults in extensional terrains (Smith and Bruhn, 1984; Zoback, 1983).

The shallow, north-south elongate depression in the western part of Brigham City might be the surface expression of a late Cenozoic, moderately dipping normal fault along a more westerly strand of the Wasatch fault zone (after Personius, 1990). The Cement Ponds flat and marsh (Qlam) might be evidence of tilting, an antithetic fault, or reverse drag along the Wasatch fault zone, given the depression and tilted surface shown by Personius (1990).

Personius (1990) showed numerous faults with Quaternary offset where changes in slope (scarps) occur along the mountain front in the Brigham City quadrangle. We mapped some of these scarps as faults, but we mapped others as Lake Bonneville shorelines, contacts of Quaternary map units, and combinations of contacts and shorelines. Some scarps might be the manifestations of buried, differentially eroded bedrock, because bedrock strikes at an acute angle to the mountain front. Two scarps, located northeast of Calls Fort and southeast of Rees Spring, were mostly destroyed by gravel extraction and are shown as concealed (dotted) on plate 1; plate 1 locations are from 1953 aerial photographs.

The length and number of fault scarps in Holocene deposits is greatest south of Hansen Canyon. In this area, Personius (1990) showed scarp heights of 13 and 26 feet (4 and 8 m) on different parts of the fault at Rees Spring. Trenching to the south-southeast in the Box Elder Canyon delta indicates that five Holocene faulting events have occurred along the delta portion of the Brigham City segment of the Wasatch fault zone. Details on offsets, dates and recurrence intervals are presented in Personius (1988, 1990, 1991), and McCalpin and Forman (1994).

Fault-scarp heights in lacustrine gravel (Qlg) below the Provo shoreline are similar to and greater than those in Holocene deposits. Personius (1990) showed scarp heights of 20 and 26 feet (6 and 8 m) on such fault scarps south of Miners Hollow. In this area, older alluvial fans (Qafo) appear to mantle rather than completely conceal the fault scarps, and the scarps do not cut these fans. Therefore the scarps are latest Pleistocene to Holocene in age. Scarp heights in Provo-shoreline deposits are greater on the fault southeast of Rees Spring (79 feet [24 m] high), but are only 26 feet (8 m) high in latest Pleistocene and Holocene deposits on the same(?) fault trace in the Mount Pisgah quadrangle (Personius, 1988, 1990, 1991). Personius (1990) showed a height of 62 feet (19 m) on a fault scarp between Baker and Dry Canyons in lacustrine gravel below the Provo shoreline. We mapped this scarp as a shoreline. The origin of this scarp could be determined by excavating the south end in an old (pre-1953), inactive gravel pit.

Other scarps we mapped as shorelines might also be fault scarps. Personius (1990) noted remnants of a fault zone (two wedges of fault-scarp colluvium) in the gravel pit about 2,700 feet (825 m) northeast of Calls Fort. He interpreted three surface-rupturing fault events of post-Provo shoreline (latest Pleistocene to Holocene) age from his observations. On 1953 aerial photographs, a fault scarp was visible on half of a Holocene alluvial fan and the scarp extended north to the alluvial fan at the mouth of Precipice Canyon. The scarp is now mostly obscured (dotted trace on plate 1) by sand and gravel operations in the north/larger pit. We mapped two scarps east of the pits as shorelines, or they might be manifestations of differentially eroded bedrock (note outcrops upslope), because we didn't see faults in either Calls Fort gravel pit. However, because recontouring and sloughing have degraded pit exposures, the fault scarp colluvium Personius saw could now be destroyed or concealed. The shorelines we mapped between Miners Hollow and Donation Canyon might be fault scarps, since they align with faults to the north and south.

The north-south elongate, shallow depression in Brigham City is similar to others located just to the south (Personius, 1990, and written communication, 1995), and is roughly colinear with a fault mapped by Personius (1990) in the Wasatch fault zone south of the quadrangle. This depression could have formed due to lateral-spread failure (see seismic hazards) or might be a small graben

above a normal fault. A graben is shown on plate 1, because the relief and roughly colinear trend are consistent with the graben interpretation. From comparisons of 1937 and 1966 aerial photographs, 1969 and 1988 topographic maps, and field observations, this depression is now mostly obscured by fill and recontouring. Where not disturbed, the depression has surface relief of about 3 to 10 feet (1 to 3 m). The estimated original scarp locations of the graben are shown on plate 1.

MINERAL RESOURCES

Gravel and Sand

Abundant gravel and sand were deposited near the mountains in the Brigham City quadrangle through wave action and deltaic processes in Lake Bonneville, and in alluvial fans. Sand and gravel pit outlines are shown as short, dashed, hachured lines on plate 1. The largest deposits of extractable material are in remnants of the Provo-shoreline delta at the mouth of Box Elder Canyon (Qdg; some Qad); most of this material is in the adjacent Mount Pisgah and Mantua quadrangles. These deltaic deposits contain more gravel than sand, and small amounts of finer grained material. This delta has been and, in 1994, was still being extensively excavated, reducing its size. The next largest pits are located northeast of Brigham City and Calls Fort in lacustrine gravels (Qlg) and in lacustrine sediments under alluvial fans (Qaf). These pits typically contain more angular and finer grained material than the deltaic deposits. The southern Calls Fort pit was being used in 1992, while the northern Calls Fort pit and the pit northeast of Brigham City had been recontoured. Well-sorted lacustrine beach(?) sand (Qls) is present below lacustrine and alluvial gravel in the Calls Fort pits. Such clean sands might be concealed by gravel elsewhere along the mountain front. Other smaller sand and gravel deposits are present along the mountain front in lacustrine gravels and alluvial fans between the largest pits; these deposits contain more silt and clay than deposits in the larger pits. The sand and gravel deposits in the quadrangle have been used for base and surface gravel, and for borrow in highway construction. Additional data on some of these deposits is contained in a materials inventory by the Utah State Department of Highways (1965).

Cement Raw Materials

Marl and an underlying clay (Qlam) from the Cement Ponds at Baker Spur were excavated by the Ogden Portland Cement Company in the early 1900s to produce portland cement at a plant about 5.5 miles (9 km) northwest of Brigham City (Burchard, 1911, p. 525-526; Eckel, 1913). The plant ruins are located between Interstate Highway 15 and the Cement Ponds in section 33, T. 10 N., R. 2 W., and were shown on the 1969 Brigham City 7.5-minute quadrangle topographic map. Figure 4 shows the excavation equipment, deposits, and ponds, probably during Burchard's field investigation (after McGregor and Abston, 1994). Salty water now

Figure 4. *Excavation equipment, marl and clay deposits, and resulting pond at Ogden Portland Cement Company operation on Baker Spur, north-northwest of Brigham City in about 1910. Photograph from McGregor and Abston (1994); they attributed the photograph to Burchard. This photograph of the Cement Ponds was probably taken during examinations for Burchard's (1911) report.*

fills these excavations in the mud flats. Eckel (1913) provided other details on the operations, though he didn't mention the source for gypsum, commonly used to slow hardening of cement.

Limestone, Dolomite, and Quartzite

Numerous limestone- and dolomite-bearing units that are exposed in the quadrangle have been used for lime production and aggregate elsewhere in northern Utah (Williams, 1958; Doelling, 1980; Tripp, 1991). Historically, the major consumer of lime in the area was the sugar beet processing industry, but all Utah plants were closed by 1993 (B.T. Tripp, verbal communication, 1993). The end use of these rocks determines the required qualities and no data are available on the qualities of these rocks in the quadrangle.

The utility of the Geertsen Canyon Quartzite for silica is unknown because no data are available on the qualities of this unit in the quadrangle.

Limestone, dolomite, and quartzite from the quadrangle might be used for decorative stone because stone with a wide variety of colors and various hardnesses is available in outcrops and alluvial fans along the mountain front. As examples, stones from alluvial fans were used to construct the Calls Fort monument and a building just east of State Highway 69 about 1.5 miles (2.4 km) south of the Calls Fort monument (shown as a church in the SW1/4 NW1/4 section 23, T. 10 N., R. 2 W. on the 1988 topographic map).

Salt

In the past, water was diverted from Salt Creek into evaporation ponds in the center of the north half of section 17, T. 10 N., R. 2 W. to recover sodium chloride (NaCl). The source of Salt Creek is Crystal Hot Spring in the Honeyville quadrangle. Bjorklund and McGreevy (1974, table 8) reported that water from the spring contained 39,700 milligrams per liter (mg/l) total dissolved solids, with 23,000 mg/l chloride, 14,000 mg/l sodium, 810 mg/l calcium and 670 mg/l potassium. Doelling (1980, table 10) reported a similar analysis. A rough idea of the salt content is indicated by the fact that lower, cool reaches of Salt Creek do not freeze in the winter. Bjorklund and McGreevy (1974) reported additional information on the spring, and on the salt load the creek introduces into the Bear River.

Metallic Minerals

Several mines and numerous exploration workings for metallic minerals were excavated in the Box Elder mining district in the quadrangle. Major workings are in Cambrian limestones in close proximity to transverse faults in and near Baker and Antimony Canyons (map numbers 1, 2, and 3 on table 4 and plate 1). Minor production of copper, gold, silver and antimony was reported from the district, and most workings contained oxidized, highly limonitic (gossans?), lead-, zinc- and silver-bearing mineralization, with minor copper showings. Stibnite was mined from a quartz vein in Cambrian limestone (map number 3); the vein also contained calcite, limestone fragments, clay, and a small amount of malachite. Butler and others (1920), Perry (in Doelling, 1980, p. 184, 186-187, 203-206), Perry and McCarthy (1977), Utah Geological Survey Utah Mineral Occurrence System (UMOS) files, and table 4 contain more specific information on the district, production, workings, and mineralization.

Other small adits and prospect pits are in carbonate and quartzite strata in the Wellsville Mountains, where abundant limonite, hematite and calcite, and minor copper carbonates (malachite and azurite) are present. The largest of these workings in the quadrangle are listed in table 4. This type of mineralization, with small amounts of lead, zinc and silver, is typically located along and near major and minor faults. Mineralization along faults also includes dolomitization of limestone and dolomite fracture fillings.

Oil and Gas

No productive oil or gas wells have been documented in the Brigham City quadrangle (table 5), but natural gas was produced for local use from several wells in Box Elder County south of the quadrangle (Campbell in Doelling, 1980) and possibly within the quadrangle (Kaliser, 1976). Sources of the gas are probably bacterially attacked peat deposits in Quaternary sediments (Campbell in Doelling, 1980; Clem and Brown, 1985). Older boreholes were apparently designed to explore for the shallow biogenic (marsh) gas that had been reported in water wells, springs, and seeps along the eastern shore of Great Salt Lake. The wells drilled in 1981 may have been attempts to find hydrocarbons that were thermally generated from Tertiary lacustrine deposits, like the oil and gas reported in Great Salt Lake by Patton and Lent (1980), and Bortz (1984). For additional details see table 5, Kaliser (1976), Campbell in Doelling (1980), Clem and Brown (1985), and Kerns (1987).

WATER RESOURCES

In the quadrangle, surface water, mostly from the Bear River, is the primary source for irrigation and stock

Table 4.
List of mine and exploration workings in the Brigham City 7.5-minute quadrangle.

Map No.	Name-Workings	Location	Mineralization and Description	Host Formation/Unit (see plate 1)	Ref./ Loc. Ref.
1	**Baker mine** (production) multiple workings	upper Baker Canyon	Pb-Zn-Ag, with minor Cu & Au values in limonitic fault zone; no sulfides seen; large dump, though production trammed away; fluorite on dump of adit above main adit	Garden City	A, D A, B
2	**Dry Lake Antimony mine** (production) multiple workings	Antimony Canyon (mislabeled Copper Blossom Mine on topographic map)	3-10 ft. wide stibnite (Sb) bearing quartz vein that contains calcite and carbonate fragments; in fault zone; large dump at lower adit not indicative of mineralization	uppermost Blacksmith	A, B A
3	**Copper Blossom mine** multiple workings	ridge south of Baker Canyon (label at wrong site on topographic map)	limonite gossan along brecciated fault zone, with Pb-Zn-Cu values; moderate sized dump though transport on nearby Baker mine tram was possible	upper and lower Nounan	A, B A, B
4	adit (caved)	Cataract Canyon	in limestone along fault; small to moderate sized dump	uncertain Cambrian carbonate	A, B A, B
5	adits (caved) & prospect	ridge north of Cataract Canyon	fault zone in limestone; limonite-stained breccia zone; tiny dumps	Hodges Shale(?)	A, B A, B
6	adit	near mouth of Calls Fort Canyon	crush zone with calcite fracture fillings; quartz on dump; about 50 ft. long; tiny dump	upper Blacksmith	B C
7	adit	upper Miners Hollow	dump contains calcite, malachite, azurite, limonite, hematite; rock is fractured and brecciated; along fault; about 80+ ft. long; tiny dump	upper middle Bloomington	B B, C
8	adit (north)	ridge north of Cataract Canyon	limonite along fractured zone along fault; about 30 ft. long and up to 6 ft. wide; hematite-stained small dump	lower Laketown	B C, B
9	adit & prospect	ridge north of Yates Canyon	limonite-stained fault zone	lower Nounan	B B, C
10	adit	south of Precipice Canyon	tiny dump	Blacksmith	B B
11	prospect	north of Calls Fort Canyon		Blacksmith - Hodges Shale contact	B B
12	adit	north of Calls Fort Canyon	brecciated zone with calcite matrix and milky quartz; about 50 ft. long; tiny dump	Blacksmith	B B
13	prospects	south of Calls Fort Canyon	limonite gossan with hematite and dolomite	upper Blacksmith	B B
14	adit	mouth of Miners Hollow		upper Geertsen Canyon	B B
15	prospect	south of Miners Hollow	limonite gossan on fault	upper Langston	B B
16	prospect(s)	ridge south of Miners Hollow	limonitic zone over 4 ft. wide, irregular; fault zone; friable yellow brown sandy siltstone = (?)alteration	upper Blacksmith	B B
17	prospect	ridge north of Miners Hollow	fault zone	lower-upper Nounan contact	B B

Table 4 (continued)

Map No.	Name-Workings	Location	Mineralization and Description	Host Formation/Unit (see plate 1)	Ref./ Loc. Ref.
18	prospect	ridge north of Miners Hollow	hematite, malachite, calcite and limonite in dolomitized fault zone with dolomite fracture fillings	middle Bloomington	B B
19	prospect	upper Miners Hollow		Calls Fort Shale	B B
20	adit & prospect	north of mouth of Cataract Canyon	some limonite at 40 ft. adit in Naomi Peak Limestone; limonite in prospect in Spence Shale	lower Langston	B B
21	adit	south of mouth of Cataract Canyon	no mineralization; 8 ft. long; near fault	basal Nounan	B B
22	prospect	south of Moss Rock Canyon	iron oxides along fault zone	uppermost Garden City	B B
23	adits (3), 2 caved	south of Moss Rock Canyon	limonite, calcite and rare hematite on dump at fault intersection	Hodges Shale	B B
24	prospect	Yates Canyon		upper Blacksmith	B B
25	adits (caved) & prospect	mouth of Baker Canyon	azurite, malachite, calcite, quartz and limonite on dump and pit; small to moderate-sized dump that might be partly from Baker and Copper Blossom workings	upper Blacksmith	B B
26	adit	north of Baker mine	limonite and hematite staining; tiny to small dump	upper St. Charles or Garden City	B B
27	adit (caved)	above Baker mine	calcite vein along small fault limonite and quartz on dump; tiny to small dump	lower Laketown	B B
28	prospect	upper Baker Canyon	limonite near fault	lower Laketown	B B
29	adit	mouth of Dry Canyon	fault zone	Blacksmith(?)	B B
30	adit	"two" Hansen Canyon	75+ ft. long; tiny to small dump	lower Geertsen Canyon	B B
31	adit	south of "two" Hansen Canyon	30 ft. long, iron oxide staining in quartzite; malachite on dump; small dump, yet too big for length	lower Geertsen Canyon	B B

References (ref.)
A Perry in Doelling (1980)
B This report
C 1988 Brigham City 7.5 minute topographic map
D Perry and McCarthy (1977)

Table 5.
Significant boreholes in the Brigham City area (data from Clem and Brown, 1985; Kerns, 1987; Campbell in Doelling, 1980; Utah Geological Survey files; Utah Division of Oil, Gas and Mining files). See also table 1 and plate 1.

Name/Company	Location (sec-T-R) (ft from sec. line)	Completion Date/Status	Tests	TD (feet)	Unit Tops (feet)
PLOTTED ON PLATE 1					
#1 Nichols P.S. Stacey et al.	CNENW sec. 21, T. 9 N., R. 2 W.	8-15-55 D&A (capped)	gas shows	1220 1035?	surface Quaternary TD Salt Lake(?)
#1 Davis (Joint Steam Venture) Geothermal Kinetics	SWSWNW sec. 16, T. 10 N., R. 2 W.	7-28-74 water well	geothermal; no oil or gas shows	10986 11005	See table 1.
#1-9 Christensen Burnett Oil	NESE sec. 24 T. 9 N., R. 3 W. (1980fsl, 820fel)	8-4-81 plugged back to 895 ft., water well	Tertiary(?) gas	6000	<1010 Salt Lake 3550 Laketown 3940 Fish Haven (4850 Fish Haven) 5140 Swan Peak 5410 Garden City TD Garden City
NOT PLOTTED ON PLATE 1, EXACT LOCATION NOT KNOWN (last 3 may be in Willard quadrangle)					
#1 Corinne Oil and Gas	sec. 31, T. 10 N., R. 2 W.	?-10-18 D&A open 1920	Quaternary & Tertiary gas	976	surface Quaternary TD Salt Lake(?)
#1 Corrinne[sic] unknown	sec. 8, T. 9 N., R. 2 W.	pre-1961 open?	surface gas shows	?	?
#1 Brigham City Cristion & Davis	sec. 22, T. 9 N., R. 2 W.	1944 spud open?	gas shows	1250	TD Salt Lake?
#2 Brigham City Cristion & Davis	sec. 22, T. 9 N., R. 2 W.	pre-1961 open?	gas shows	?	?
#1 Brigham City unknown	sec. 23, T. 9 N., R. 2 W.	pre-1937? open?	surface gas shows	?	?
NOT IN BRIGHAM CITY QUADRANGLE					
#1 Stanley Admantia Corp.	CNENE sec. 31, T. 10 N., R. 3 W. (660fnl, 660fel)	2-8-56 D&A		80 to 100	surface Quaternary
#1 Knudson Rhine Petroleum	NESW sec. 30, T. 9 N., R. 2 W. (3476fnl, 1523fwl)	4-3-58 D&A	gas show	2308	surface Quaternary TD quartzite
#1 Chesapeake Energy Burnett Oil	NWNWSW sec. 27 T. 9 N., R. 3 W. (1995fsl, 655fwl)	5-18-81 junked	not tested	273	
#1-A Chesapeake Energy/Burnett Oil	NENWSW sec. 27 T. 9 N., R. 3 W. (1995fsl, 555fwl)	9-2-81 D&A	tested no shows	4610	surface Quaternary 815 Salt Lake? 1650 Laketown 2770 Fish Haven 3048 Swan Peak 3260 Garden City 4436 St. Charles

Abbreviations:
sec - section, T - Township, R - Range, N - North, W - West; NE - NE¼, NW - NW¼, SE - SE¼, SW - SW¼, C - center, fsl - feet from south line, fnl - feet from north line, fwl - feet from west line, fel - feet from east line; D&A - drilled and abandoned; TD - total depth

watering. Minor amounts of ground water are used for municipal and domestic supplies, irrigation and stock watering. Most irrigated land is underlain by several hundred feet of silty Lake Bonneville and other older Quaternary deposits that are poor sources of ground water. The major ground-water sources are the sand and gravel deposits in alluvial fans (Qaf, Qafo, Qla), along shorelines of Lake Bonneville (Qlg, Qls, Qla), and in the Box Elder Canyon delta and fan delta (Qdg, Qad, Qla). These deposits constitute the Brigham City-Perry ground water area of Bjorklund and McGreevy (1974). They stated that the greatest ground-water potential in the lower Bear River drainage is in the fan delta. The ground-water potential of bedrock aquifers in the quadrangle has not been evaluated. For details see Bjorklund and McGreevy (1973, 1974), and Price and Jensen (1982). Data on more recent wells are available from the Utah Division of Water Rights, Utah Department of Natural Resources.

Data on municipal water supplies obtained in the Brigham City quadrangle are reported in table 6. Part of the Brigham City water supply comes from wells in the fan delta (Qad) on the eastern side of town, but most of their water comes from springs and wells in Mantua Valley (Jensen, this report). Most of the Corinne municipal water supply comes from well(s) in the alluvial fan (Qaf) at the mouth of Yates Canyon. Some water for Corinne and all the water for West Corinne comes from springs in Yates and Baker Canyons, respectively. These springs are along faults in the canyon bottoms, so the relative contribution of water from bedrock versus water from near-surface flow in the fractured canyon floors is not known.

GEOTHERMAL RESOURCES

Several hot and warm springs and wells are present near Brigham City, and the potential exists for low-temperature hydrothermal energy in the area (Goode, 1978; Klauk and Budding, 1984; Oviatt, 1986a). Because the #1 Davis geothermal exploration borehole (11,005 feet [3,354.3 m] deep)(table 5) had a bottom-hole temperature of only 232° F (111° C) and thermal logging showed lower borehole temperatures even at the bottom of the hole (>220° F [104° C]) (UGS well-log files), a high-temperature (>300° F [150° C]) geothermal resource is unlikely. The water in this borehole was a brine (85,000 mg/l total dissolved solids), and the borehole was reportedly plugged and abandoned (Goode, 1978, p. 104). However, an uncapped 12-inch (30 cm) casing was observed at the site in 1994, with a water level about 1 foot (30 cm) down from the top of the casing, and unconfirmed reports indicate that the #1 Davis borehole is a monitor well for Crystal Hot Spring, located in the Honeyville quadrangle.

GEOLOGIC HAZARDS

Seismic hazards, mass movements, shallow ground-water, floods, flammable gas, and expansive soils have been reported in the quadrangle. The radon hazard has only been depicted in a general way (Kaliser, 1976; Black, 1993), and should not be used in place of site-specific studies. No evidence of karst or collapsible soils was found in the quadrangle. General information on soil and rock characteristics in Utah that can present engineering problems is available in Mulvey (1992).

Seismic Hazards

Seismic hazards within the quadrangle include ground shaking, and surface fault rupture and related deformation, with resulting effects such as liquefaction, slope failure, and flooding. Historically, large earthquakes (≥Modified Mercalli intensity V) were reported at Brigham City in 1920 (Williams and Tapper, 1953; Richins, 1979). But, the actual epicenters are unknown, and may not have been in the lower Bear River Valley. Because the small depression in the western part of Brigham City is apparently a faulted graben that cuts Holocene materials (see Structural Geology section), it warrants further examination with respect to seismic hazards.

Because the Wasatch fault zone passes through the Brigham City quadrangle, the area is in the highest Uniform Building Code seismic zone (3) in the state of Utah (International Conference of Building Officials, 1991, p. 194). However, potential peak ground accelerations are reportedly lower than those in the Ogden and Salt Lake City areas (Youngs and others, 1987). The extensive Quaternary units that contain fine-grained sediments (map units Qal, Qdp, Qli, Qla, Qls and Qlam) and have shallow ground-water levels (see Bjorklund and McGreevy, 1974, plate 3) are those most prone to damage from ground shaking. Given the same earthquake, ground shaking will be more severe on this unconsolidated valley fill than on bedrock or gravelly sediments (Qaf, Qad, Qdg, Qlg) along the mountain front.

The damage to structures from surface rupture and related deformation during large-magnitude earthquakes is greatest along and adjacent to faults. Fault-scarp analyses and trenching along the Brigham City segment of the Wasatch fault zone indicated that six surface-rupturing earthquakes have occurred on this segment during

Table 6.
Municipal water supplies in the Brigham City quadrangle
(after Utah Department of Environmental Quality, Division of Drinking Water)

Water System	Source Name	Source Type	Flow (gpm)	Latitude (N) d	m	s	Longitude (W) d	m	s	Source Unit
Brigham City	Cooley well	well	1160	41	30	51.0	112	00	08.0	fan delta
Brigham City	Cemetery #1	well	1000	41	30	11.5	112	00	18.3	fan delta
Brigham City	Cemetery #2	well	1000	41	30	11.5	112	00	18.5	fan delta
Corinne	Batty spring, aka Yates Canyon Spring	spring	65	41	34	55.0	112 112	01 01	19.0[?] 14.0*	fault
Corinne	#1 well	well	—	41	34	48.0	112	01	38.0	lake or alluvial gravel
Corinne	Cutler well, aka new (1989) well	well	245	41	34	48.5	112 112	01 01	33.5[?] 35.0*	unknown
West Corinne	lowest spring	spring	50	41 41	31 34	37.0[?] 37.0*	112	01	10.0	fault
West Corinne	second lowest	spring	50	41	34	41.0	112	00	56.0	fault
West Corinne	third lowest	spring	50	41	34	42.0	112	00	53.0	fault
West Corinne	main spring, aka Baker Spring	spring	235	41 41	34 34	41.0[?] 42.0*	112	00	50.0	fault

Abbreviations:
N - north; W - west, gpm - gallons per minute; d m s - degrees, minutes, seconds; [?]--reported location uncertain; aka - also known as; * - data from this report

the past 13,000 years. Surface displacements of about 3 to at least 8 feet (1.0 to >2.5 m) have occurred about every 1,150 to 2,070 years in the past 10,000 years, and were probably associated with earthquakes of about magnitude 7 (after Personius, 1988, 1990, 1991; McCalpin and Forman, 1994).

Liquefaction occurs when ground shaking takes place in sandy, water-saturated sediments. These materials loose strength due to increased pore-water pressure, causing buildings and other construction to settle and tilt due to loss of support. Liquefaction features were observed in the Bear River Valley following the 1962 Cache Valley earthquake (Lander and Cloud, 1964). Note that Interstate Highway I-15, state secondary roads, the Brigham City airport, and railroads in the Bear River Valley are built on fill placed on sandy fine-grained deposits that are likely saturated with water, making them susceptible to damage from ground shaking and liquefaction.

Details of potential liquefaction hazards in the quadrangle, including a map, are presented in Bay (1987). Moderate to high liquefaction potential is present in the Bear River Valley due to saturated granular soils. In contrast, a very low potential is mapped in the Wellsville Mountains, and on the alluvial fans and lacustrine delta along the mountain front where ground water is deeper. Most of Brigham City is located on the Box Elder Canyon fan delta such that most of the city has a very low liquefaction potential; downslope, the fan delta in the western part of Brigham City (Qad and Qaf next to Qla) has low to moderate potential (Bay, 1987, plate 3).

Various kinds of earthquake-induced slope failures are a potential hazard in sloping areas. Liquefaction can lead to lateral spread of material on slopes as low as 0.5 percent (0.3°) and flow landslides on slopes steeper than 5 percent (>3°)(Youd, 1978; National Research Council, 1985). This frequently leads to the failure of stream banks and dikes; dikes and banks along the Bear River (plate 1) are therefore susceptible. Other slope-failure hazards in the quadrangle are earthquake-induced rock

falls and landslides in the mountains and along the mountain front.

Earthquake-related flooding can result from dam or dike failure, canal failure, landslides damming drainages, diversion of streams, lowering and tilting of ground surfaces, Great Salt Lake seiches, and rupturing of water lines. In this quadrangle, flooding due to tilting is well displayed in the marshy area north-northwest of Brigham City, which includes North Lake and the Cement Ponds (after Personius, 1990).

Mass Movements

The potential exists for landslides, rock falls, and debris flows in the quadrangle. Except for Brigham City, most habitation is presently distant from the steep slopes and canyons in the Wellsville Mountains, where mass movements are most likely. On the east side of Brigham City, extending into the Mount Pisgah quadrangle, homes have been built on alluvial fans and at the base of other steep slopes. The fans are potential sites of debris flows as well as flash flooding. Homes at the base of steep slopes, regardless of the surficial or bedrock map unit, could be damaged by rock falls. Cutbanks along the Bear River north of Corinne, where numerous landslide and slump scarps are present (plate 1), also have a high potential for mass movement. The landslide and slump mapped on the east side of the Wellsville Mountains (Qms, plate 1) might pose some threat in the Mount Pisgah quadrangle. Late Holocene debris flows were mapped by Miller (1980) and Personius (1990) at the mouths of Calls Fort, Donation, Baker, Hansen and "two" Hansen (in NW$^1/_2$ section 6, T. 9 N., R. 1 W.) Canyons, and an unnamed canyon two canyons north of Hansen Canyon. We observed similar debris-flow deposits on fans from Precipice, Yates, Dry, Antimony, and Kotter Canyons. Most of the young alluvial fans (Qaf) we mapped in the Brigham City quadrangle probably include a debris-flow component (Personius, written communication, 1995), and are therefore hazard areas (see also section on floods).

Shallow Ground Water

Shallow ground water is a potential hazard in the western two-thirds of the quadrangle. Bjorklund and McGreevy (1974, plate 3) portray the potentiometric surface as being at or above ground level for all the deposits in the Bear River Valley (Qli, Qls, Qal, Qlam, Qla, Qdp, Qat) that are lower in elevation than alluvial fans. In contrast, most of Brigham City and the alluvial fans along the mountain front do not have shallow ground water; these sites are shown as having depths to ground water of about 10 to 100+ feet (3 to 30+ m) by Bjorklund and McGreevy (1974, plate 3). However, Personius (written communication, 1995) noted local perched water tables and resultant springs along the Wasatch fault zone. Shallow ground water hampers any excavation and foundation construction, and can preclude installation of septic tanks and subsurface structures. Shallow ground water also increases the possibility of liquefaction during an earthquake. Placing underground storage tanks, landfills, and solid and hazardous waste sites in areas of shallow ground water is ill-advised.

Floods

In the Brigham City quadrangle, the Bear River delta below 4,212 feet (1,284 m) elevation was flooded by Great Salt Lake during the historic high level in 1986. Because thresholds between Great Salt Lake and the adjacent Great Salt Lake Desert are at elevations of 4,213 to 4,217 feet (1,285 m), 4,217 feet (1,285 m) is considered the maximum height of significant flood hazard from Great Salt Lake in the quadrangle. This level was attained during the "Little Ice Age" several hundred years ago (Currey, Atwood, and Mabey, 1984; Harty and Christensen, 1988). A water-level rise to 4,217 feet (1,285 m) would inundate the southwestern corner of the quadrangle, and further raise the level of shallow ground water.

Canyons in the quadrangle are susceptible to flash flooding during heavy rainfall and rapid snowmelt, like flooding that struck the Ogden area in 1983 (see Wieczorek and others, 1983, 1989). Snowmelt flooding occurred on Box Elder Creek in Brigham City in February, 1911 (James and others, 1980). Both types of flooding can be accompanied by debris flows (see Mass Movements section). The younger alluvial fans (Qaf) are sites of potential flash flooding and debris-flow outrun. Note in particular the residential areas on the mountain-front fans, as well as the fan along Box Elder Creek in Brigham City. See James and others (1980) for details on the flood hazard on the fan of Box Elder Creek.

Cloudburst flooding was reported on August 18, 1881 at Brigham City, and an October 17, 1937 cloudburst caused a landslide in Box Elder Canyon, which blocked the highway (Woolley, 1946). Cloudburst flooding was also reported in Brigham City on June 3, 1963 and June 24, 1969 (Butler and Marsell, 1972), and other cloudbursts have been reported in the area (Woolley, 1946; Butler and Marsell, 1972).

Flow in the Bear River is regulated by numerous upstream impoundments, so the flows reported here are mostly evidence for wet years. In roughly the last 40

years, reported maximum flows of the Bear River north of Corinne were 14,770 (May 19, 1984), 12,000 (February 20, 1986), 9,770 (June 4, 1983) and 9,400 (April 8, 1985) cubic feet per second (418.3, 339.8, 276.7 and 266.2 m^3/s) compared to a mean flow of 1,780 cubic feet per second (50.2 m^3/s) (U.S. Geological Survey Water Yearbooks for Utah).

A flood hazard exists along the lower Bear River in the unlikely event that Cutler Dam fails. Assuming a worst-case scenario (complete and instantaneous failure like that caused by an earthquake), Case (1984) calculated that the flood-wave-crest elevation would be about 4,257 feet (1,297.5 m) at Bear River City and about 4,232 feet (1,290 m) at Corinne. This worst-possible flood would inundate part of eastern Bear River City and all of Corinne; for details see Case (1984).

Federal Emergency Management Agency (FEMA) flood insurance rate maps can be consulted for information on the flooding potential along the Bear River, Malad River, Box Elder Creek, and in the marshy area northwest of Brigham City (Cement Ponds-North Lake). However, these maps do not address hazards due to flash flooding. Data on historic flash-flooding and flooding potential along Box Elder Creek in Brigham City is presented in James and others (1980).

Flammable Gas

Flammable methane(?) gas from Cenozoic deposits is a potential problem in the Bear River Valley. Such gas has been reported in several wells, and in springs or seeps along the southern margin of the quadrangle (Kaliser, 1976; this report, Oil and Gas section). The gas could cause explosions and fire. This phenomena has not been adequately documented.

Expansive Soils

Expansive soils of Chadwick and others (1975) do not correlate well with any of our Quaternary map units, but most wet areas in the quadrangle (units Qal, Qdp, Qlam) contain soils with high shrink-swell potential, including the area from Brigham City west to Black Slough. Site-specific geotechnical soils/foundation studies are recommended prior to construction in the Bear River Valley at elevations lower than deltas and alluvial fans.

ACKNOWLEDGMENTS

Reviews by and consultations with C.G. "Jack" Oviatt (Kansas State University), James P. Evans (Utah State University), S.F. Personius (U.S. Geological Survey), Doug Sprinkel, Mike Hylland, Bob Blackett, Grant Willis, and Hellmut Doelling (all UGS) greatly improved the quality of this report and plates. We also thank D.R. Currey (University of Utah), Mike Lowe, F.D. Davis, L.F. Hintze, and M.L. Ross (all UGS) for their discussions, suggestions, and assistance on various aspects of the project. Additional paleontological identifications not listed in table 2 were provided by Lloyd Gunther and W.J. Sando. Any misconceptions that remain are the authors.

REFERENCES

Allmendinger, R.W., Miller, D.M., and Jordan, T.E., 1984, Known and inferred Mesozoic deformation in the hinterland of the Sevier belt, northwest Utah, *in* Kerns, G.J., and Kerns, R.L., Jr., editors, Geology of northwest Utah, southern Idaho and northeast Nevada: Utah Geological Association Publication 13, p. 21-34.

Arnow, Ted, and Stephens, Doyle, 1990, Hydrologic characteristics of the Great Salt Lake, 1847-1986: U.S. Geological Survey Water Supply Paper 2332, 32 p.

Babcock, L.E., and Robison, R.A., 1988, Taxonomy and paleobiology of some Middle Cambrian *Scenella* (Cnidaria) and hyolithids (Mollusca) from western North America: University of Kansas Paleontological Contributions Paper 121, 22 p.

Bay, J.A., 1987, Liquefaction potential mapping of Weber, Box Elder and Cache Counties, Utah: Logan, Department of Civil and Environmental Engineering, Utah State University, M.S. thesis, 140 p., 6 plates, scale 1:48,000 (published as Utah Geological Survey Contract Report 94-6).

Beus, S.S., 1958, Geology of the northern part of Wellsville Mountain, northern Wasatch Range, Utah: Logan, Utah State University, M.S. thesis, 84 p., scale 1:24,000.

Bjorklund, L.J., and McGreevy, L.J., 1973, Selected hydrologic data, lower Bear River drainage basin, Box Elder County, Utah: Utah Department of Natural Resources, Division of Water Rights Basic Data Release no. 23, 22 p.

Bjorklund, L.J., and McGreevy, L.J., 1974, Ground-water resources of the lower Bear River drainage basin, Box Elder County, Utah: Utah Department of Natural Resources, Division of Water Rights Technical Publication no. 44, 58 p.

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

Bortz, L.C., 1984, Heavy-oil deposit, Great Salt Lake, Utah, *in* Meyer, R.F., editor, Exploration for heavy crude oil and natural bitumen: American Association of Petroleum Geologists Studies in Geology, no. 25, p. 555-563.

Brummer, J.E., 1991, Origin of low-angle normal faults along the west side of the Bear River Range in northern Utah: Logan, Utah State University, M.S. thesis, 103 p., 2 plates, scale 1:100,000.

Bryant, Bruce, Naeser, C.W., Marvin, R.F., and Mehnert, H.H., 1989, Ages of Late Paleogene and Neogene tuffs and the beginning of rapid regional extension, eastern boundary of the Basin and Range Province near Salt Lake City, Utah: U.S. Geological Survey Bulletin 1787-K, 12 p.

Budge, D.R., 1966, Stratigraphy of the Laketown Dolostone, north-central Utah: Logan, Utah State University, M.S. thesis, 86 p.

Budge, D.R., and Sheehan, P.M., 1980, The Upper Ordovician through Middle Silurian of the eastern Great Basin, Part 1, Introduction - Historical perspective and stratigraphic synthesis: Milwaukee Public Museum Contributions in Biology and Geology 28, 26 p.

Burchard, E.F., 1911, Cement, *in* Mineral resources of the United States, 1910: U.S. Geological Survey, Part 2, Nonmetallic minerals, p. 469-535.

Buterbaugh, G.J., 1982, Petrology of the lower Middle Cambrian Langston Formation, north-central Utah and southeastern Idaho: Logan, Utah State University, M.S. thesis, 166 p.

Butler, B.S., Loughlin, G.F., Heikes, V.C., and others, 1920, The ore deposits of Utah: U.S. Geological Survey Professional Paper 111, p. 221-222.

Butler, Elmer, and Marsell, R.E., 1972, Developing a state water plan - Cloudburst floods in Utah, 1939-1969: U.S. Geological Survey and Utah Division of Water Resources Cooperative Investigations Report no. 11, 103 p.

Case, W.F., 1984, Cutler Dam inundation study: Utah Geological and Mineral Survey unpublished report, 1 p.

Case, W.F., 1985, Significant drill holes of the Wasatch Front valleys including Cache Valley and Tooele Valley: Utah Geological and Mineral Survey Open-File Report 82, 235 p.

Chadwick, R.S., and others, 1975, Soil survey of Box Elder County, Utah, eastern part: U.S. Department of Agriculture, Soil Conservation Service, 223 p.

Clem, Keith, and Brown, K.W., 1985, Summary of oil and gas activity in northeastern Utah and southeastern Idaho, *in* Kerns, G.J., and Kerns, R.L., Jr., editors, Orogenic patterns and stratigraphy of north-central Utah and southeastern Idaho: Utah Geological Association Publication 14, p. 157-166.

Cluff, L.S., Glass, C.E., and Brogan, G.E., 1974, Investigation and evaluation of the Wasatch fault north of Brigham City and Cache Valley faults, Utah and Idaho; a guide to land-use planning with recommendations for seismic safety: Oakland, California, Woodward-Lundgren and Associates, unpublished report for U.S. Geological Survey, contract no. 14-08-001-13665, 193 p., 35 plates, scale 1:24,000.

Conway-Morris, Simon, and Robison, R.A., 1988, More soft-bodied animals and algae from the Middle Cambrian of Utah and British Columbia: University of Kansas Paleontological Contributions Paper 122, 48 p.

Crittenden, M.D., Jr., Schaeffer, F.E., Trimble, D.E., and Woodward, L.A., 1971, Nomenclature and correlation of some upper Precambrian and basal Cambrian sequences in western Utah and southeastern Idaho: Geological Society of America Bulletin, v. 82, p. 581-602.

Crittenden, M.D., Jr., and Sorensen, M.L., 1985, Geologic map of the Mantua quadrangle and part of the Willard quadrangle, Box Elder, Weber, and Cache Counties, Utah: U.S. Geological Survey Miscellaneous Investigations Map I-1605, scale 1:24,000.

Currey, D.R., Atwood, Genevieve, and Mabey, D.R., 1984, Major levels of Great Salt Lake and Lake Bonneville: Utah Geological and Mineral Survey Map 73, scale 1:750,000.

Currey, D.R., and Oviatt, C.G., 1985, Durations, average rates, and probable causes of Lake Bonneville expansions, stillstands and contractions during the last deep-lake cycle, 32,000 to 10,000 years ago, *in* Kay, P.A. and Diaz, H.F., editors, Problems of and prospects for predicting Great Salt Lake levels: Papers from a conference held in Salt Lake City, March 26-28, 1985, Center for Public Affairs and Administration, University of Utah, p. 9-24.

Currey, D.R., Oviatt, C.G., and Czarnomski, J.E., 1984, Late Quaternary geology of Lake Bonneville and Lake Waring, *in* Kerns, G.J., and Kerns, R.L., Jr., editors, Geology of northwest Utah, southern Idaho and northeast Nevada: Utah Geological Association Publication 13, p. 227-237.

Davis, F.D., compiler, 1985, Geology of the northern Wasatch Front: Utah Geological and Mineral Survey Map 53-A, scale 1:100,000.

Deputy, E.J., 1984, Petrology of the Middle Cambrian Ute Formation, north-central Utah and southeastern Idaho: Logan, Utah State University, M.S. thesis, 124 p.

Doelling, H.H., 1980, Geology and mineral resources of Box Elder County, Utah: Utah Geological and Mineral Survey Bulletin 115, 251 p., scale 1:125,000.

Dover, J.H., 1985, Geologic map and structure sections of the Logan 30' x 60' quadrangle, Utah and Wyoming: U.S. Geological Survey Open-File Report 85-216, 31 p., scale 1:100,000.

Dutro, J.T., Jr., and Sando, W.J., 1963, New Mississippian formations and faunal zones in Chesterfield Range, Portneuf quadrangle, southeast Idaho: American Association of Petroleum Geologists Bulletin, v. 47, no. 11, p. 1963-1986.

Eardley, A.J., and Hatch, R.A., 1940, Proterozoic (?) rocks in Utah: Geological Society of America Bulletin, v. 51, p. 795-844.

Eckel, E.C., 1913, Portland cement materials and industry in the United States, Part III - Portland cement resources of the United States, Utah: U.S. Geological Survey Bulletin 522, p. 348-349.

Elder, A.S., 1992, The paleoecology and geomorphology of Holocene deposits of the southern Malad River, Box Elder County, Utah: Logan, Utah State University, M.S. thesis, 57 p.

Eliason, J.F., 1969, The Hyrum and Beirdneau Formations of north-central Utah and southeastern Idaho: Logan, Utah State University, M.S. thesis, 86 p.

Evans, J.P., 1991, Structural setting of seismicity in northern Utah: Utah Geological Survey Contract Report 91-15, 37 p., 3 plates, scale 1:100,000.

Francis, G.G., 1972, Stratigraphy and environmental analysis of the Swan Peak Formation and Eureka Quartzite, northern Utah: Logan, Utah State University, M.S. thesis, 125 p.

Gardiner, L.L., 1974, Environmental analysis of the Upper Cambrian Nounan Formation, Bear River Range and Wellsville Mountain, north-central Utah: Logan, Utah State University, M.S. thesis, 121 p.

Gelnett, R.H., 1958, Geology of the southern part of Wellsville Mountain, Wasatch Range, Utah: Logan, Utah State University, M.S. thesis, 73 p.

Goode, H.D., 1978, Thermal waters of Utah: Utah Geological and Mineral Survey Report of Investigation no. 129, 183 p.

Gunther, L.F., and Gunther, V.G., 1981, Some Middle Cambrian fossils of Utah: Brigham Young University Geology Studies, v. 28, part 1, 87 p.

Harty, K.M., and Christensen, G.E., 1988, Flood hazard from lakes and failure of dams in Utah: Utah Geological and Mineral Survey Map 111, 8 p., scale 1:750,000.

Hay, H.W., Jr., 1982, Petrology of the Middle Cambrian Blacksmith Formation, north-central Utah: Logan, Utah State University, M.S. thesis, 157 p.

Hintze, L.F., 1988, Geologic history of Utah: Provo, Brigham Young University Geology Studies, Special Publication 7, 202 p.

International Conference of Building Officials, 1991, Uniform building code: International Conference of Building Officials, Whittier, California, 1,050 p.

James, L.D., Larson, D.T., Hoggan, D.H., and Glover, T.L., 1980, Flood damage mitigation in Utah: Logan, Utah State University, Utah Water Research Laboratory Publication P-80101, 106 p.

Jensen, M.E., 1988, Stratigraphy and structure of the central Wellsville Mountains, Utah (abstract): Geological Society of America Abstracts with Programs, v. 20, p. 422-423.

Jensen, M.E., 1994, Geologic map of the Bear River City quadrangle, Box Elder County, Utah: Utah Geological Survey Map 151, 12 p., scale 1:24,000.

Kaliser, B.N., 1976, Final report to the U.S. Geological Survey, Earthquake hazard reduction program, U.S. Geological Survey Grant no. 14-08-0001-G-166: Utah Geological and Mineral Survey Report of Investigation no. 108, 231 p.

Kerns, R.L., Jr., 1987, Review of the petroleum activity of the Utah portion of the Great Basin, *in* Kopp, R.S. and Cohenour, R.E., editors, Cenozoic geology of western Utah - Sites for precious metal and hydrocarbon accumulations: Utah Geological Association Publication 16, p. 487-526.

Klauk, R.H., and Budding, K.E., 1984, Geothermal assessment of the lower Bear River drainage and northern East Shore ground-water areas, Box Elder County, Utah: Utah Geological and Mineral Survey Report of Investigation 186, 64 p.

Lander, J.F., and Cloud, W.K., 1964, United States earthquakes, 1962: U.S. Department of Commerce, Coast and Geodetic Survey, p. 15-21.

Leatham, W.B., 1985, Ages of the Fish Haven and lowermost Laketown Dolomites in the Bear River Range, Utah, *in* Kerns, G.J., and Kerns, R.L., Jr., editors, Orogenic patterns and stratigraphy of north-central Utah and southeastern Idaho: Utah Geological Association Publication 14, p. 29-38.

Lindsay, R.F., 1977, Petrology and petrography of the Great Blue Formation at Wellsville Mountain, Utah: Brigham Young University Geology Studies, v. 24, part 1, p. 115-136.

Link, P.K., and Smith, L.H., 1992, Late Proterozoic and Early Cambrian stratigraphy, paleobiology and tectonics - Northern Utah and southeastern Idaho, *in* Wilson, J.R., editor, Field guide to geologic excursions in Utah and adjacent areas of Nevada, Idaho, and Wyoming: Utah Geological Survey Miscellaneous Publication 92-3, p. 461-481.

Lowe, M.V., 1987, Surficial geology of the Smithfield quadrangle, Cache County, Utah: Logan, Utah State University, M.S. thesis, 143 p., scale 1:24,000.

Maxey, G.B., 1941, Cambrian stratigraphy in the northern Wasatch region: Logan, Utah State Agricultural College, M.S. thesis, 64 p.

Maxey, G.B., 1958, Lower and Middle Cambrian stratigraphy in northern Utah and southeastern Idaho: Geological Society of America Bulletin, v. 69, p. 647-688.

McCalpin, James, and Forman, S.L., 1994, Assessing the paleoseismic activity of the Brigham City segment, Wasatch fault zone, Utah; Site of the next major earthquake on the Wasatch Front?: U.S. Geological Survey Final Technical Report, Contract no. 1434-92-G-2205, 19 p.

McGregor, J.K., and Abston, Carl, 1994, Photographs of historical mining operations in Colorado and Utah from the U.S. Geological Survey Library: U.S. Geological Survey Digital Data Series DDS-12.

Miller, D.M., 1991, Mesozoic and Cenozoic tectonic evolution of the northeastern Great Basin, *in* Buffa, R.H., and Coyner, A.R., editors, Geology and ore deposits of the Great Basin, Field trip guidebook compendium: Reno, Nevada,

Geological Society of Nevada, v. 1, p. 202-228.

Miller, D.M., Crittenden, M.D., and Jordan, T.E., 1991, Geologic map of the Lampo Junction quadrangle, Box Elder County, Utah: Utah Geological Survey Map 136, 16 p., scale 1:24,000.

Miller, D.M., and Schneyer, J.D., 1994, Geologic map of the Sunset Pass quadrangle, Box Elder County, Utah: Utah Geological Survey Map 154, 14 p., scale 1:24,000.

Miller, R.D., 1980, Surficial geologic map along part of the Wasatch Front, Salt Lake Valley, Utah: U.S. Geological Survey Miscellan-eous Field Studies Map MF-1198, 13 p., scale 1:100,000.

Morgan, S.K., 1988, Petrology of passive margin epeiric sea sediments - The Garden City Formation, north-central Utah: Logan, Utah State University, M.S. thesis, 156 p.

Mulvey, W.E., 1992, Soil and rock causing engineering geologic problems in Utah: Utah Geological Survey Special Study 80, 23 p., scale 1:500,000.

Murchison, S.B., 1989, Fluctuation history of Great Salt Lake, Utah during the last 13,000 years: Salt Lake City, University of Utah, Ph.D. dissertation, 137 p.

National Research Council, 1985, Liquefaction of soils during earthquakes: Washington, D.C., National Academy Press, 240 p.

Oaks, R.Q., Jr., James, W.C., Francis, G.G., and Schulingkamp, W.J., II, 1977, Summary of Middle Ordovician stratigraphy and tectonics, northern Utah, southern and central Idaho, *in* Heisey, E.L., Lawson, D.E., Norwood, E.R., Wach, P.H., and Hale, L.A., editors, Rocky Mountain thrust belt geology and resources: Wyoming Geological Association, Twenty-ninth Annual Field Conference Guidebook, p. 101-118.

Oviatt, C.G., 1986a, Geologic map of the Honeyville quadrangle, Box Elder and Cache Counties, Utah: Utah Geological and Mineral Survey Map 88, 13 p., scale 1:24,000.

Oviatt, C.G., 1986b, Geologic map of the Cutler Dam quadrangle, Box Elder and Cache Counties, Utah: Utah Geological and Mineral Survey Map 91, 7 p., scale 1:24,000.

Oviatt, C.G., and Currey, D.R., 1987, Pre-Bonneville Quaternary lakes in the Bonneville Basin, Utah, *in* Kopp, R.S., and Cohenour, R.E., editors, Cenozoic geology of western Utah - Sites for precious metal and hydrocarbon accumulations: Utah Geological Association Publication 16, p. 257-263.

Oviatt, C.G., Currey, D.R., and Miller, D.M., 1990, Age and paleoclimatic significance of the Stansbury shoreline of Lake Bonneville, northeastern Great Basin: Quaternary Research, v. 33, p. 291-305.

Oviatt, C.G., Currey, D.R., and Sack, Dorothy, 1992, Radiocarbon chronology of Lake Bonneville, eastern Great Basin, USA: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 99, p. 225-241.

Oviatt, C.G., McCoy, W.D., and Reider, R.G., 1987, Evidence for a shallow early or middle Wisconsin-age lake in the Bonneville Basin, Utah: Quaternary Research, v. 27, p. 248-262.

Patton, T.L., and Lent, R.L., 1980, Current hydrocarbon exploration activity in the Great Salt Lake, *in* Gwynn, J.W., editor, Great Salt Lake - A scientific, historical and economic overview: Utah Geological and Mineral Survey Bulletin 116, p. 115-124.

Perry, L.I., and McCarthy, B.M., 1977, Lead and zinc in Utah, 1976: Utah Geological and Mineral Survey Open-File Report 22, 525 p.

Personius, S.F., 1988, A brief summary of the surficial geology along the Brigham City segment of the Wasatch fault zone, Utah, *in* Machette, M.N., editor, In the footsteps of G.K. Gilbert - Lake Bonneville and neotectonics of the eastern Basin and Range Province, Guidebook for field trip twelve, Geological Society of America, 100th Annual Meeting, Denver, Colorado, 1988: Utah Geological and Mineral Survey Miscellaneous Publication 88-1, p. 27-32.

Personius, S.F., 1990, Surficial geologic map of the Brigham City segment and adjacent parts of the Weber and Collinston segments, Wasatch fault zone, Box Elder and Weber Counties, Utah: U.S. Geological Survey Miscellaneous Investigations Map I-1979, scale 1:50,000.

Personius, S.F., 1991, Paleoseismic analysis of the Wasatch fault zone at Brigham City trench site, Brigham City, Utah, and Pole Patch trench site, Pleasant View, Utah: Utah Geological and Mineral Survey Special Studies 76, 39 p.

Peterson, D.L., 1974, Bouguer gravity map of part of the northern Lake Bonneville basin, Utah and Idaho: U.S. Geological Survey Miscellaneous Field Studies Map MF-627, scale 1:250,000.

Price, Don and Jensen, L.J., 1982, Surface-water resources of the northern Wasatch Front, Utah: Utah Geological and Mineral Survey Map 53-B, scale 1:100,000.

Richins, W.D., 1979, Earthquake data for the Utah region, 1850-1978, *in* Arabasz, W.J., Smith, R.B., and Richins, W.D., editors, Earthquake studies in Utah, 1850 to 1978: University of Utah Seismograph Stations, p. 57-251.

Ross, R.J., Jr., 1951, Stratigraphy of the Garden City Formation in northeastern Utah and its trilobite faunas: New Haven, Connecticut, Yale University, Peabody Museum Bulletin 6, 161 p.

Sadlick, Walter, 1955, The Mississippian-Pennsylvanian boundary in northeastern Utah: Salt Lake City, University of Utah, M.S. thesis, 77 p.

Sandberg, C.A., and Gutschick, R.C., 1979, Guide to conodont biostratigraphy of Upper Devonian and Mississippian rocks along the Wasatch Front and Cordilleran hingeline, Utah: Brigham Young University Geology Studies, v. 26, part 3, p. 107-134.

Sandberg, C.A., and Gutschick, R.C., 1984, Distribution, microfauna, and source-rock potential of Mississippian Delle Phosphatic Member of Woodman Formation and equivalents, Utah and adjacent states, *in* Woodward, Jane, Meissner, F.F., and Clayton, J.L., editors, Hydrocarbon source rocks of the greater Rocky Mountains region: Rocky Mountain Association of Geologists, Denver, Colorado, p. 135-178.

Sando, W.J., and Bamber, E.W., 1985, Coral zonation of the Mississippian System in the Western Interior Province of North America: U.S. Geological Survey Professional Paper 1334, 61 p.

Scott, W.E., McCoy, W.D., Shroba, R.R., and Rubin, Max, 1983, Reinterpretation of the exposed record of the last two cycles of Lake Bonneville, western United States: Quaternary Research, v. 20, p. 261-285.

Smith, D.G., and Jol, H.M., 1992, Ground-penetrating radar investigation of Lake Bonneville delta, Provo level, Brigham City, Utah: Geology, v. 20, p. 1083-1086.

Smith, R.B., and Bruhn, R.L., 1984, Intraplate extension tectonics of the eastern Basin and Range - Inferences on structural style from seismic reflection data, regional tectonics and thermal-mechanical models of brittle-ductile deformation: Journal of Geophysical Research, v. 89, p. 5733-5762.

Sorensen, M.L., and Crittenden, M.D., Jr., 1976, Type locality of Walcott's Brigham Formation, Box Elder County, Utah: Utah Geology, v. 3, p. 117-121.

Sorensen, M.L., and Crittenden, M.D., Jr., 1979, Geologic map of the Huntsville quadrangle, Weber and Cache Counties, Utah: U.S. Geological Survey Geologic Quadrangle Map GQ-1503, scale 1:24,000.

Sprinkel, D.A., 1979, Apparent reverse movement on previous thrust faults along the eastern margin of the Basin and Range Province, north-central Utah, *in* Newman, G.W., and Goode, H.D., editors, Basin and Range symposium and Great Basin field conference: Rocky Mountain Association of Geologists, p. 135-144.

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

Sweide, A.P., 1977, Synecology and faunal succession of the Upper Mississippian Great Blue Limestone, Bear River Range and Wellsville Mountain, north-central Utah: Logan, Utah State University, M.S. thesis, 152 p.

Taylor, M.E., 1963, The Lower Devonian Water Canyon Formation of northeastern Utah: Logan, Utah State University, M.S. thesis, 63 p.

Taylor, M.E., Landing, Ed, and Gillett, S.L., 1981, The Cambrian-Ordovician transition in the Bear River Range, Utah-Idaho - A preliminary evaluation, *in* Taylor, M.E., editor, Short papers for the second international symposium on the Cambrian System: U.S. Geological Survey Open-File Report 81-743, p. 222-227.

Tripp, B.T., 1991, The industrial rock and mineral industry in Utah, 1990: Utah Geological and Mineral Survey Circular 82, 31 p.

Utah State Department of Highways, 1965, Materials inventory - Box Elder County: Utah State Department of Highways, 17 p., 7 maps, scale approximately 1:200,000.

Walcott, C.D., 1908, Cambrian geology and paleontology, No. 1 - Nomenclature of some Cambrian Cordilleran formations: Smithsonian Miscellaneous Collections, v. 53, p. 1-12.

Welsh, J.E., 1983, Differences in the Oquirrh Group and the Granger Mountain Group between the Oquirrh Mountains and Wallsburg Ridge, Wasatch Mountains, Utah (abstract): Geological Society of America Abstracts with Programs, v. 15, no. 5, p. 290.

Wieczorek, G.F., Ellen, S.D., Kips, E.W., Cannon, S.H., and Short, D.N., 1983, Potential for debris flow and debris flood along the Wasatch Front between Salt Lake City and Willard, Utah, and measures for their mitigation: U.S. Geological Survey Open-File Report 83-635, 45 p.

Wieczorek, G.F., Lips, E.W., and Ellen, S.D., 1989, Debris flows and hyperconcentrated floods along the Wasatch Front, 1983 and 1984: Bulletin of the Association of Engineering Geologists, v. 26, no. 2, p. 191-208.

Williams, J.S., 1943, Carboniferous formations on the Uinta and northern Wasatch Mountains, Utah: Geological Society of America Bulletin, v. 54, no. 4, p. 591-624.

Williams, J.S., 1948, Geology of the Paleozoic rocks, Logan quadrangle, Utah: Geological Society of America Bulletin, v. 59, no. 11, p. 1121-1164, scale 1:125,000.

Williams, J.S., 1958, Geologic atlas of Utah, Cache County: Utah Geological and Mineral Survey Bulletin 64, 98 p., scale 1:125,000.

Williams, J.S., 1962, Lake Bonneville - Geology of southern Cache Valley, Utah: U.S. Geological Survey Professional Paper 257-C, p.133-135.

Williams, J.S., 1964, The age of the Salt Lake Group in Cache Valley, Utah-Idaho: Utah Academy of Sciences, Arts and Letters Proceedings, v. 41, p. 269-277.

Williams, J.S., 1971, The Beirdneau and Hyrum Formations of north-central Utah: Smithsonian Contributions to Paleobiology no. 3, p. 219-229.

Williams, J.S., and Tapper, M.C., 1953, Earthquake history of Utah, 1850-1949: Bulletin of the Seismological Society of America, v. 43, no. 3, p. 191-218.

Williams, J.S., and Taylor, M.E., 1964, The Lower Devonian Water Canyon Formation of northern Utah: Laramie, Contributions to Geology, University of Wyoming, v. 3, no. 2, p. 38-53.

Williams, J.S., and Yolton, J.S., 1945, Brazer (Mississippian) and lower Wells (Pennsylvanian) section at Dry Lake, Logan quadrangle, Utah: American Association of Petroleum Geologists Bulletin, v. 29, no. 8, p. 1143-1155.

Woolley, R.R., 1946, Cloudburst floods in Utah, 1850-1938: U.S. Geological Survey Water Supply Paper 994, 128 p.

Youd, T.L., 1978, Major cause of earthquake damage is ground failure: Civil Engineering, v. 48, no. 4, p. 47-51.

Youngs, R.R., Swan, E.H., Power, M.S., Schwartz, D.P., and Green, R.K., 1987, Probabalistic analysis of earthquake ground shaking hazard along Wasatch Front, Utah, *in* Gori, P.L., and Hayes, W.H., editors, Assessment of regional earthquake hazards and risk along the Wasatch Front, Utah, volume 2: U.S. Geological Survey Open-File Report 87-585, p. M-1 to M-110.

Yonkee, W.A., 1992, Basement-cover relations, Sevier orogenic belt, northern Utah: Geological Society of America Bulletin, v. 104, p. 280-302.

Zoback, M.L., 1983, Structure and Cenozoic tectonism along the Wasatch fault zone, Utah, *in* Miller, D.M., Todd, V.R., and Howard, K.A., editors, Tectonic and stratigraphic studies of the eastern Great Basin: Geological Society of America Memoir 157, p. 3-26.

Zoback, M.L., Anderson, R.E., and Thompson, G.B., 1981, Cainozoic evolution of the state of stress and style of tectonism of the Basin and Range Province of the western United States: Philosophical Transactions of the Royal Society of London, v. A300, p. 407-434.

APPENDIX

Measured section BC1

Starting location approximately 0.4 mile southeast of mouth of Antimony Canyon. Section was measured up the north side of Chimney Rock (center SE1/4 section 36, T. 10 N., R. 2 W.). Measured by Mark E. Jensen on May 13, 14, and 19, 1986 using a Jacobs staff.

Ute Formation

Interbedded shale and limestone.

Langston Formation
Upper map unit

9. Dolostone - medium light gray to yellowish gray fresh; pale grayish orange, medium dark gray, and medium light gray weathered; medium to very coarsely crystalline, very thick bedded, blocky splitting, forms ledges, good exposure, contains fossil fragments and cross-bedding, weathers to a sandy surface. Crossed fault with uncertain offset and measured 23 feet to the top of this unit. Part of section may be duplicated.
   118 feet

8. Limestone - medium gray fresh and weathered, fine to medium crystalline, thin bedded, slabby splitting, forms a cliff, good exposure, contains small shell fragments, contains coarse- and fine-crystalline layers, local calcite-filled or replaced vugs, sharp contact with underlying unit.
   80 feet

7. Dolostone - similar to unit 9, except medium dark gray and medium light gray are not present as weathered colors.
   64 feet

262 feet Total thickness of upper map unit

Spence Shale Member

6. Shale and limestone, interbedded.
   Shale - dark gray and light gray fresh, medium dark gray and moderate yellowish brown weathered, non-calcareous, laminated to very thin bedded, platy to flaggy splitting, forms ledgy slopes, fair exposure, locally silty, contains horizontal burrows.
   Limestone - silty, medium dark gray fresh, medium light gray and moderate orange weathered, very fine to finely crystalline, laminated to very thin bedded, shaly to flaggy splitting, locally fossiliferous. Fossil samples BC-1 and BC-2a to g are from 140 and 148 feet above the base of Spence Shale Member, respectively. See Table 2 for fossil identifications.

225 feet Total thickness of Spence Shale Member

Naomi Peak Member

5. Limestone - medium gray fresh and weathered, medium grained, medium to very thick bedded, slabby splitting, forms a ledge, good exposure, contains layers of light-brown weathering sandstone.
   21 feet

4. Sandstone - medium light gray fresh, moderate to dark yellowish brown weathered, fine grained, dolomite cemented, thick to very thick bedded.
   15 feet

36 feet Total thickness of Naomi Peak Member

523 feet Total thickness of the Langston Formation

Crossed to north side of fault to measure Langston Formation. Rocks probably not duplicated or omitted in section.

Geertsen Canyon Quartzite
Upper map unit

3. Quartzite - dark gray fresh, moderate brown (5YR 3/4) weathered (weathers darker than unit 1), medium to coarse grained, subrounded to rounded, moderately to well sorted, clear quartz grains, thick to very thick bedded, blocky to massive splitting, forms a cliff, good exposure, sharp contact with underlying unit, contains cross-bedding, contains *Skolithos* in upper part of unit, also contains horizontal burrows along bedding planes. Crossed a small fault with approximately 5 feet of displacement.
   328 feet

2. Quartzite with bedding due to argillite - medium gray to medium light gray fresh, light brown (5YR 5/6) to moderate brown (5YR 3/4) to medium light gray weathered, medium grained, well sorted, quartz grains, laminated to thin bedded, medium bedded near base, platy to slabby splitting, forms slight recess in cliff, good exposure, thinner beds are micaceous, ripple marked, and contain 10% moderate brown earthy grains.
   28 feet

356 feet Total thickness of upper map unit

Lower map unit (exposed portion)

1. Quartzite - grayish orange pink, pale reddish orange (10R 7/6), and medium dark gray fresh, grayish orange pink, pale reddish orange, and light olive gray (10G 6/2) weathered, medium to coarse grained, rounded, moderately sorted, medium to very thick bedded, slabby to massive

splitting, forms light-colored blocky cliffs, good exposure, contains pebble conglomerate layers up to 1 foot thick, locally contains pebbles along bedding planes, contains iron staining and cross-bedding, cross-bed surfaces contain sand and granules, contains argillaceous partings and lenses up to 0.5 feet thick. Lower contact not exposed, concealed by lacustrine gravel. Scattered outcrops of quartzite are exposed farther down the slope below the bottom of the measured section, and are surrounded by lacustrine gravel.
1,561 feet

1,917 feet Measured thickness of the Geertsen Canyon Quartzite

Estimated thicknesses of lower map unit and Geertsen Canyon Quartzite are greater than 3,500 and greater than 3,860 feet, respectively. These estimates are based on exposures in Mount Pisgah and Brigham City quadrangles (using outcrop width, dip and topography), and the probable presence of a concealed fault at the base of these exposures (plate 1).

Measured Section BC2

Reconnaissance section located on ridge on north side of Cataract Canyon, approximately 0.6 mile northeast of mouth of Cataract Canyon (SE1/4 NW1/4 SW1/4 section 13, T. 10 N., R. 2 W.). Measured on August 14, 1986 by Mark E. Jensen using a Jacobs staff.

Laketown Dolomite

3. Dolostone--medium light gray (N6) fresh, medium gray (N5) weathered, very finely crystalline, very thick bedded, forms cliffs, bioturbated, contains chert nodules.
thickness not measured

2. Dolostone, banded light and dark gray. At 117 feet from base of unit is the first appearance of what appears to be Thalassinnoides trace fossils. Light bands - dark gray (N3) fresh, medium light gray to light gray (N6-N7) weathered, very finely crystalline, medium to very thick bedded, contains white to dark gray chert blebs. Top of the last light-colored band contains chert nodules.
Dark bands - dark gray (N3) weathered, very finely crystalline, medium to very thick bedded, forms banded cliffs and ledges, contains chert stringers.
243 feet

Total thickness of Laketown Dolomite not measured.

Fish Haven Dolomite

1. Dolostone - medium dark gray (N4) and dark gray (N3) fresh and weathered, finely crystalline, very thick bedded, slabby splitting, forms cliffs, locally contains blobs of light chert, contains rugose corals and small tabulate corals (i.e. small *Favosites* sp. and *Halysites* sp.). Lower contact is covered, but upper surface of quartzite appears to have only a few inches of relief.
178.2 feet

178 feet Total thickness of the Fish Haven Dolomite

Swan Peak Quartzite

Quartzite, white to moderate reddish orange.

Measured Section BC3

Section is located on the south bank of Bear River (SE1/4 NW1/4 NW1/4 section 7, T. 10 N., R. 2 W.). This section was first measured by C.G. "Jack" Oviatt (his section H9, unpublished notes) on October 28, 1983 during field work on the adjoining Honeyville quadrangle, and was remeasured by Mark E. Jensen on April 23, 1987 using a Jacobs staff.

Lacustrine sand deposits (Bonneville Lake cycle)

3. Sand - medium gray (N5) mottled with light brown (5YR 5/6), very fine grained, moderately sorted, laminated to medium bedded, contains cross-bedding. This unit continues to top of bluff.
25 feet

25 feet Measured thickness of lacustrine sand deposits

Lacustrine silt deposits (Bonneville Lake cycle)

2. Clay - silty, medium dark gray (N4) fresh, pale olive (10Y 6/2) and dark yellowish brown (10YR 4/2) oxidized, laminated to thin bedded, blocky splitting, silt content varies vertically through unit, contains sand in laminated to very thin beds, and ostracods. Unoxidized, medium gray (N5) to black, laminated algal material from near the base of this unit (C.G. Oviatt, written communication, 1985) yielded a radiocarbon age of about 21,000 years, indicating deposition during the Stansbury stillstand (Oviatt and others, 1990).
19.0 feet

1. Sand - medium gray (N5) and grayish orange (10YR 7/4), very fine to fine grained, moderately sorted, laminated in part but mostly poorly bedded, upper 1.0 foot contains interbedded sand, silt, and clay.
4.6 feet

Covered, alluvial and colluvial material. Bear River at a low stage when measured.

23.6 feet Measured thickness of lacustrine silt deposits

Measured Section BC4

Section measured on the west bank of Bear River on Holmgren farm, south of the Gilbert shoreline near confluence of the Bear and Malad Rivers (NW1/4 SW1/4 section 19, T. 10 N., R. 2 W.). Measured by Mark E. Jensen on April 23, 1987 using a Jacobs staff.

Lacustrine silt deposits (Bonneville Lake cycle)

5. Silt, with very fine-grained sand--pale yellowish brown (10YR 6/4), laminated to very thin bedded. This unit extends to top of river bank.
   14.4 feet

4. Clay - silty, dark yellowish gray (5Y 6/2) with thin bands of dark yellowish orange (10YR 6/6), contains dark-colored laminations and stringers, laminated to very thin bedded.
   1.6 feet

3. Sand, with silt - pale yellowish brown (10YR 6/2) fresh, very fine grained, contains low-angle cross-bedding, laminated to very thin bedded, blocky splitting.
   1.0 feet

2. Clay - silty, fresh color light olive gray (5Y 6/1) with laminations of light brown (5YR 5/6), oxidized colors same as fresh colors, laminated bedding, upper 1.2 feet contain interbedded sand which is very fine grained and very thin bedded.
   2.8 feet

1. Clay - silty, mostly covered, grayish black (N2) and medium dark gray (N4) fresh, light olive gray (5Y 5/2) and dark yellowish brown (10YR 4/2) oxidized, laminated bedding, contains lighter and darker colored laminations.
   4.5 feet

Bear River at low stage.

24.3 feet Measured thickness of deposits

Measured Section BC5

Starting location on the north side of Cataract Canyon and extended up over a ridge with elevation label of 8657 feet (NW1/4 NW1/4 NE1/4 section 13, T. 10 N., R. 2 W.). Measured by Mark E. Jensen on August 27, and September 1, 1987, using a Jacobs staff.

Manning Canyon Shale (incomplete)

17. Covered. Measured to approximate position of fault.
    70 feet

16. Limestone - platy splitting, mostly covered.
    10 feet

15. Shale - black fresh, dark gray weathered, laminated bedding, noncalcareous.
    18 feet

14. Limestone - medium light gray weathered, laminated to thin bedded, upper 1 foot is bleached, poor exposure.
    37 feet

13. Shale - pale yellowish brown fresh, laminated to very thin bedded, covered.
    18 feet

12. Limestone - medium light gray to medium gray weathered, becomes medium dark gray weathered upsection, very fine grained, very thin to thin bedded, contains beds of black chert up to 6 inches thick, contains brachiopods, contains crinoid stems near top of unit, good exposure.
    87 feet

11. Shale - light olive gray (5Y 6/1) fresh, pale grayish orange weathered, noncalcareous, laminated bedding, forms a depression between limestone units, poor to fair exposure. Basal 2 feet of this unit weathers dark gray and has iron staining, appears to have a higher iron content than the rest of this unit.
    30 feet

10. Limestone - medium gray weathered, fine grained, contains black chert, very thin bedded, upper part is medium bedded, forms small ledges and slopes, fossiliferous, fair exposure, upper 2 feet of unit is bleached.
    118 feet

9. Shale - light olive gray (5Y 6/1) fresh, pale grayish orange weathered, noncalcareous, laminated bedding, forms a depression between limestone units, poor to fair exposure.
    30 feet

418 feet Measured thickness of Manning Canyon Shale

Great Blue Limestone
Upper map unit

8. Limestone - dark gray fresh, medium dark gray weathered, fine to medium grained, medium bedded, blocky splitting, contains less chert than unit 6, chert occurs as nodules and beds up to 1 foot thick, fossiliferous, contains horn coral, fair exposure, forms slopes and ledges, upper 2 feet of unit appears bleached.
   437 feet

7. Limestone - interbedded very thin and thicker bedded limestone, poor exposure.
   102 feet

6. Limestone - dark gray fresh, medium dark gray weathered (weathers darker than underlying unit), fine to medium grained, medium bedded, blocky splitting, contains very thin to thin bedded chert (which locally makes up 5-10% of the rock), fossiliferous, forms slopes and ledges, fair to good exposure.
   203 feet

   742 feet Total thickness of upper map unit

Middle map unit

5. Interbedded limestone, siltstone, mudstone, and shale; forms slopes and ledges below steeper slopes of upper member, upper contact is covered.
   Limestone - medium gray weathered, very fine grained, medium to thick bedded, blocky splitting, contains crinoid stems, brachiopods, horn coral, and dark chert nodules, some beds contain pisolite-like structures up to approximately 3 inches in diameter, one bed contains brecciation along the top.
   Siltstone ("shale") - dark gray fresh, grayish orange and light olive gray (5Y 5/2) weathered, very fine sand and silt, very thin to medium bedded, flaggy splitting, variable calcareous cement, contains rough "nodules" of limestone (up to about 6 inches long).
   Mudstone - minor, greenish gray (5GY 6/1) weathered, thin bedded.
   Shale - black shale in some covered slopes between ledges.
   355 feet

4. Mudstone ("shale") - greenish gray (5GY 6/1) fresh and weathered, also dark yellowish brown weathered, contains limestone "nodules" (more abundant near top), grades to limestone at top of ledge, contains laminations but is thick bedded, contains brachiopods, forms a ledge, good exposure.
   26 feet

3. Interbedded limestone, mudstone, and shale.
   Limestone - medium dark gray fresh, very fine grained, thick bedded, forms ledges and slopes, fair to good exposure, some beds contain abundant fossil fragments.
   Mudstone - grayish orange, dark yellowish gray, and yellowish gray weathered, with "nodules" of limestone up to 5 inches in length set in the mudstone matrix and limestone as very thin to thin beds, "nodules" weather medium gray, contains brachiopods; mudstone is thin to medium bedded, and forms ledges and slopes.
   Shale (mudstone) - medium light gray to dark gray fresh, light olive gray weathered, slightly calcareous, very thin to medium bedded.
   64 feet

2. Covered slope, probably same as unit 1.
   65 feet

1. Interbedded mudstone, shale, and limestone. Unit grades upward from shale to mudstone with limestone "nodules" to limestone, then a sharp boundary and a shale begins again. Abundant brachiopods at top of this unit.
   Mudstone - grayish orange, dark yellowish gray, and yellowish gray weathered, with "nodules" of limestone up to 5 inches in length set in the mudstone matrix and limestone as very thin to thin beds, "nodules" weather medium gray, contains brachiopods; mudstone is thin to medium bedded, and forms ledges and slopes.
   Shale (mudstone?) - medium light gray to dark gray fresh, light olive gray weathered, slightly calcareous, very thin to medium bedded.
   Limestone - medium gray weathered, very fine grained, medium bedded.
   90 feet

   600 feet Total thickness of middle map unit

   1,342 feet Total thickness of upper and middle map units

Lower map unit

Limestone, medium dark gray weathered, very fine to fine grained, medium bedded, forms ledges.