GEOLOGIC MAP OF THE RICHMOND QUADRANGLE, CACHE COUNTY, UTAH AND FRANKLIN COUNTY, IDAHO

by
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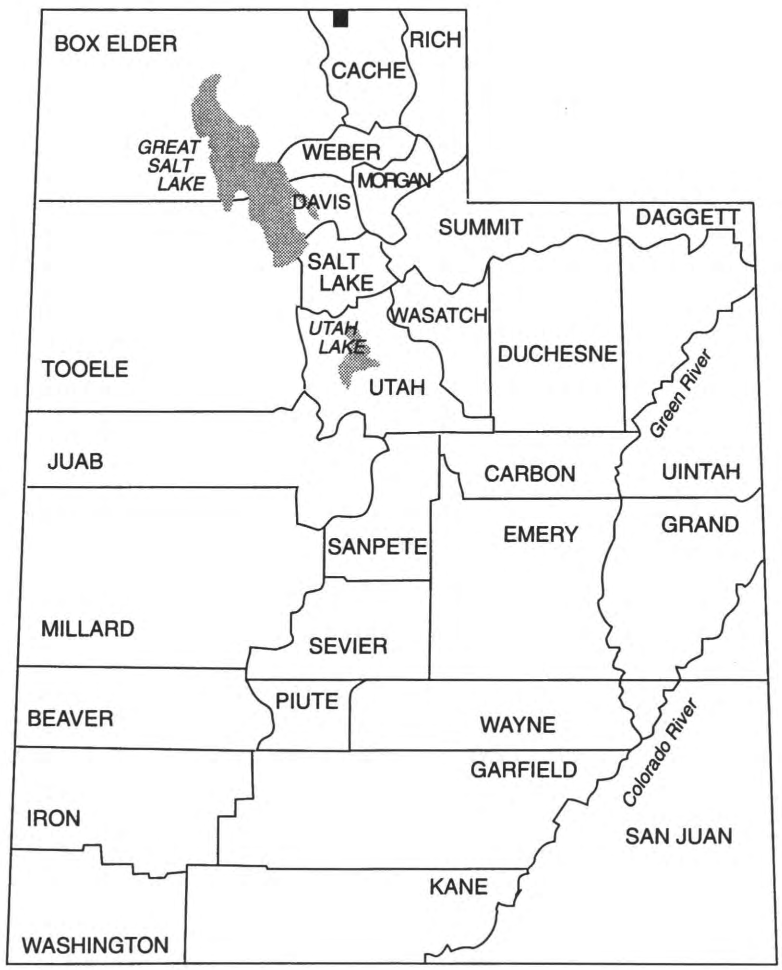

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GEOLOGIC MAP OF THE RICHMOND QUADRANGLE, CACHE COUNTY, UTAH AND FRANKLIN COUNTY, IDAHO

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ABSTRACT

The Richmond 7.5-minute quadrangle contains portions of the Bear River Range and Cache Valley, and was affected by the Jurassic to early Tertiary Sevier orogeny, and late Tertiary basin-and-range normal faulting. Normal faulting continues and is a significant hazard in the area, as shown by the August 1962 earthquake (M_S 5.7). Many allochthonous blocks of lower Paleozoic and Precambrian rocks have been mapped that are apparently the product of middle Tertiary low-angle normal faulting and large-scale late Tertiary mass movements. Surface and sub-surface data show that latest Pleistocene Lake Bonneville and at least one earlier Pleistocene lake occupied Cache Valley. Research for this project produced the first documentation of zeolites in the subsurface in the late Tertiary Salt Lake Formation, and a summary of oil and gas exploration in the area. This research also refined the locations and ages of high-angle normal faulting along the Miocene to Holocene East Cache fault zone.

INTRODUCTION

The Richmond quadrangle is in northern Cache County, Utah, on the western flank of the Bear River Range and the eastern edge of Cache Valley (figure 1). The area is on the eastern margin of the Basin and Range physiographic province and the western margin of the Middle Rocky Mountains physiographic province. Geologic structures in the area are related to

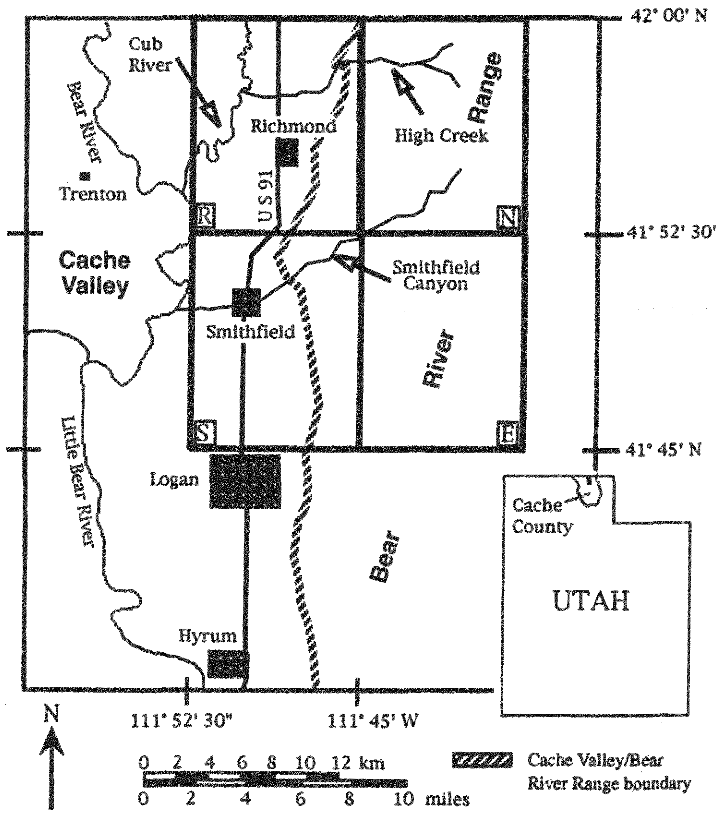


Figure 1. Index map of northern Utah, showing the Richmond (R), Naomi Peak (N), Smithfield (S), and Mt. Elmer (E) quadrangles.

[1] Presently at Santa Fe Pacific Mining Company, Elko, NV.
[2] Presently at GEO-HAZ Consultants, Estes Park, CO.

two regional events: (1) compression, folding, and thrust faulting associated with the Jurassic to the early Tertiary Sevier orogeny (Armstrong, 1968), and (2) extension and normal faulting, which may have started in the early Tertiary (Zoback and others, 1981; Stewart, 1983). Both low-angle and high-angle normal faults are present in the area (Brummer, 1991), and the east Cache fault zone, which crosses the quadrangle, has undergone Holocene normal faulting (McCalpin, 1989). Basin-and-range extension continues today in northern Utah (Westaway and Smith, 1989). Elevations in the quadrangle range from 4,440 feet (1,353 m) to over 7,480 feet (2,280 m). The greatest topographic relief is in the southernmost part of the quadrangle.

This map and the accompanying text were prepared under contract as part of the Utah Geological Survey mapping program, but are, in part, products of an assessment of earthquake hazards along the East Cache fault zone by McCalpin (1989), and an M.S. thesis on structural geology by Brummer (1991) at Utah State University. Therefore, this project combines detailed mapping of surficial sediments and bedrock units with new interpretations of the structural geology. Methods of data acquisition included field mapping on standard and low-sun-angle aerial photographs and topographic base maps, logging of well samples, and sampling of rock units. Surficial geology was mapped and compiled by James McCalpin in 1986 through 1988 (see also McCalpin, 1989). Except where noted, other mapping, interpretations, and descriptions are by Jon Brummer, from field work begun in May, 1988 and completed in October, 1989.

Previous geologic investigations in the Richmond area include work by Bailey (1927), Williams (1948, 1958, 1962), Dover (1985, 1987), McCalpin (1989), Brummer (1991), and Evans (1991) in Utah, and Oriel and Platt (1968, 1980) to the north in Idaho. Large-scale geologic mapping (>1:25,000 scale) has been done in the Smithfield 7.5-minute quadrangle to the south by Galloway (1970) and Lowe (1987), combined in Lowe and Galloway (1993). Mendenhall (1975) mapped parts of the Richmond and Naomi Peak quadrangles (1:12,000 scale) (figure 1). Zahn (1987) examined stratigraphy and mapped a portion of the western flank of the Bear River Range north of the Naomi Peak quadrangle in Idaho. Geophysical studies have been conducted by Peterson and Oriel (1970), Stanley (1972), Smith and Bruhn (1984), and Mabey (1985). Bedrock stratigraphy is documented in Peterson (1936), Maxey (1941, 1958), Williams (1948), Smith (1953), Adamson (1955), Adamson and others (1955), Galloway (1970), Mendenhall (1975), Buterbaugh (1982), Deputy (1984), and Morgan (1988).

STRATIGRAPHY

Introduction

Rocks from late Precambrian to early Paleozoic and Tertiary age, and Quaternary sediments are exposed in the quadrangle (plates 1 and 2). The Precambrian (upper Proterozoic) Mutual Formation and the Lower Cambrian Geertsen Canyon Quartzite are exposed on the western flank of the Bear River Range in the western limb of the Logan Peak syncline. Other Cambrian and Ordovician rocks exposed in the quadrangle are not in place, and formations are incompletely exposed; therefore, these stratigraphic thicknesses are not reported in this text. The Upper Cambrian St. Charles Formation and Lower Ordovician Garden City Formation are in low-angle fault contact with the Mutual and Geertsen Canyon Formations such that the intervening formations are missing. Figure 2 shows the usual stratigraphic section in the western Bear River Range, Utah. Isolated exposures of Mutual, Geertsen Canyon, St. Charles, and Garden City Formations, and probable Cambrian carbonates and shales (Middle Cambrian Ute? and Langston? Formations) have been mapped at lower elevations along the range front. Rocks in these isolated exposures were emplaced by low-angle faulting, and by landslides or rock falls from bedrock exposures farther to the east in the Bear River Range. Conglomerates and volcaniclastic rocks of the Tertiary Salt Lake Formation compose the rolling foothills along the range front. In the quadrangle, the contact between the Salt Lake Formation and older rocks is depositional, but to the northeast and south the contact has also been interpreted by Brummer (1991) as a high-angle and low-angle normal-fault contact, respectively. Various Quaternary deposits, mostly related to the late Pleistocene Bonneville lake cycle, cover the Cache Valley and mantle many bedrock units along the range front. Quaternary strata are best exposed in numerous gravel pits and stream drainages.

Precambrian

Mutual Formation (Zm)

The oldest rocks exposed in the quadrangle are quartzites with thin interbeds of conglomerate and argillite of the Precambrian (upper Proterozoic) Mutual Formation, named by Crittenden and others (1952). The Mutual Formation is mostly dark-red to purple to white and purple-and-white banded, medium- to coarse-grained quartzite with numerous, small cross-bed sets. The quartzite is composed of quartz sand that is locally micaceous. Conglomerate beds are composed of rounded granules and pebbles of white quartz and red chert in a quartzite matrix, and form 10 to 13 inch- (25 to 33 cm-) thick beds. Beds of green to dark-purple argillite, which are less than 1 foot (30 cm) thick, are scattered in the upper part of the formation; dark-purple argillite is micaceous. The lateral extent of conglomerate and argillite beds was not determined. Bedding throughout the formation is about 3 to 36 inches (8 - 91 cm) thick and generally strikes N. 15° E., and dips 41° SE. According to Mendenhall (1975), the exposed thickness of the Mutual Formation is approximately 3,000 feet (914 m) in the western Bear River Range, however, the base of the formation is not exposed in Utah. Crittenden and others (1971) reported and showed approximately 3,000 feet (914 m) of Mutual to the north near Pocatello, Idaho, and 1,200 feet (365 m) to the south near Huntsville, Utah. The age of the Mutual Formation is based on its position below the Browns Hole Formation near Huntsville, and a potassium-argon radiometric date of 570 Ma on volcanic rock from the Browns Hole (Crittenden and Wallace, 1973).

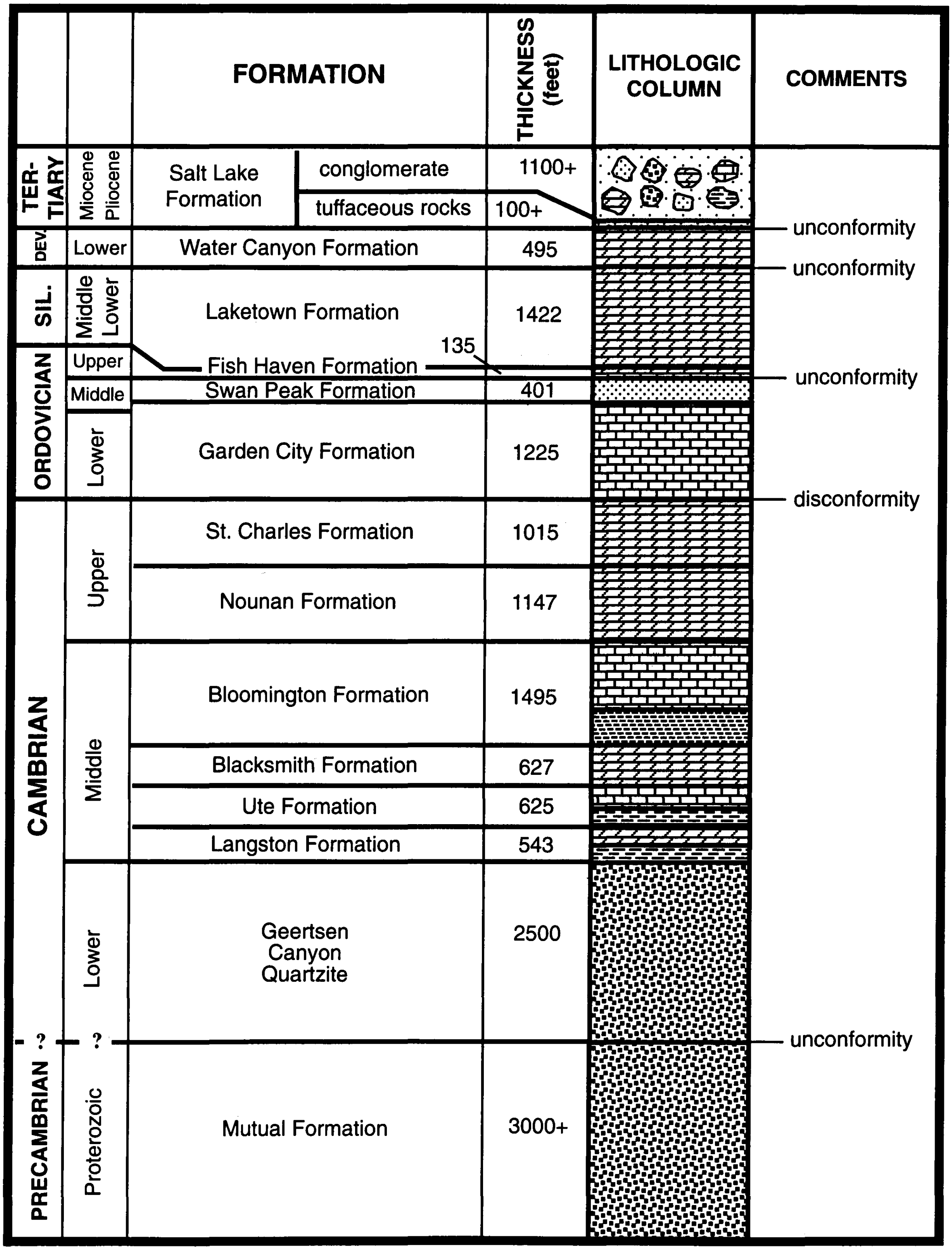


Figure 2. *Generalized stratigraphic section in the northwestern Bear River Range, Utah. Stratigraphy adapted from these reports: Salt Lake Formation - Mendenhall (1975); Water Canyon Formation - Taylor (1963); Laketown Formation - Budge (1966); Fish Haven Formation - Mecham (1973); Swan Peak Formation - Francis (1972) and Galloway (1970); Garden City Formation - Morgan (1988); St. Charles Formation - Maxey (1941); Nounan Formation - Gardiner (1974); Bloomington Formation - Maxey (1958); Blacksmith Formation - Hay (1982); Ute Formation - Deputy (1984); Langston Formation - Buterbaugh (1982); Geertsen Canyon Quartzite - Mendenhall (1975) and Galloway (1970); Mutual Formation - Mendenhall (1975) and Galloway (1970).*

The upper depositional contact of the Mutual Formation with the Geertsen Canyon Quartzite may not be conformable in the western Bear River Range. Near Pocatello, Idaho, the Mutual Formation is conformably overlain by a quartzite (Camelback Mountain Quartzite) similar to the Geertsen Canyon, whereas near Huntsville, Utah, about 500 feet (150 m) of Browns Hole Formation separates the Mutual from the Geertsen Canyon (Crittenden and others, 1971). The Browns Hole Formation was not recognized in the western Bear River Range by Brummer (1991) or Zahn (1987), although Dover (1985, 1987) tentatively mapped Browns Hole in this area. Dover (1985) included the red argillite near High Creek (noted by Mendenhall [1975] in the Mutual Formation in the Naomi Peak quadrangle), and the basalt flows in a Precambrian quartzite (noted by Galloway [1970] in the Smithfield quadrangle) in his Browns Hole(?) Formation. The missing Browns Hole, and strike and dip measurements near the Mutual-Geertsen Canyon contact, support an unconformable relationship in the western Bear River Range.

Joints, fractures, and slickensides are present in the Mutual Formation. A conjugate set of joints, found throughout the formation, is oriented generally N. 83° E., 75° NW., and N. 55° W., 85° SW. Spacing of joints and fractures ranges from about one inch (3 cm) near fault contacts to as much as 24 inches (61 cm) elsewhere. The fractured quartzite and slickensides in the southeast corner of the quadrangle indicate a northward continuation of a thrust fault mapped by Galloway (1970) in the Smithfield quadrangle (see Structure section).

Cambrian System

Cambrian rocks within the quadrangle are assigned to the Geertsen Canyon Quartzite, St. Charles Formation, and units that resemble the Langston and Ute Formations. Special units of out-of-place Cambrian(?) limestone, and jumbled outcrops of Proterozoic and Cambrian quartzite are also discussed here.

Geertsen Canyon Quartzite (Ꞓgc)

The Geertsen Canyon Quartzite, named by Crittenden and others (1971), consists mostly of olive, tan, white, orange-pink, and pink, coarse-grained quartzite, with some conglomerate. Conglomerate in the quartzite is composed of well-rounded pebbles of red chert, and white, gray, and pink quartz. Conglomerate beds have sharp basal boundaries and grade upward into quartzites. Bedding in the quartzite is difficult to discern in most places. Where recognizable, bedding is up to 3 feet (1 m) thick. The average strike and dip of bedding is N. 25° E., 41° SE. The Geertsen Canyon Quartzite and underlying Mutual Formation form steep slopes and cliffs on the western flank of the Logan Peak syncline. The Geertsen Canyon Quartzite is Early Cambrian in age, based on its position above the Browns Hole Formation at Huntsville, Utah, and a potassium-argon radiometric date of 570 Ma on the Browns Hole (Crittenden and Wallace, 1973).

In the Bear River Range in Utah, the Geertsen Canyon Quartzite has been referred to as the Brigham Formation (Galloway, 1970; Mendenhall, 1975); and together with the Mutual Formation as the Brigham Quartzite (Williams, 1948, 1958) and Brigham Group (Crittenden and others, 1971). The same lithologies are present just to the north in the Bear River Range in Idaho, but are given different names within the Brigham Group (Link and others, 1987). In addition, the contact between the Mutual and the overlying quartzite has been placed at different horizons (compare Mendenhall, 1975; Dover, 1987; and Zahn, 1987).

The depositional contact of the Geertsen Canyon with the overlying Langston Formation is exposed to the east in the adjacent Naomi Peak quadrangle. Near the top of the Geertsen Canyon, where it intertongues with the overlying Langston, the quartzite contains shale interbeds. The thickness of the Geertsen Canyon on the western flank of the Bear River Range is approximately 2,500 feet (762 m) (Galloway, 1970; Mendenhall, 1975).

Proterozoic and Cambrian Quartzite, Undifferentiated (ꞒZq)

Isolated, stratigraphically out-of-place, jumbled outcrops of Precambrian and Cambrian quartzite are present in the Cache Valley southeast of Richmond, and near the central southern margin of the map (plate 1). These outcrops are composed of large, angular boulders, blocks, and slabs of Mutual Formation quartzite and Geertsen Canyon Quartzite. Outcrops are up to about 1,500 feet (450 m) long and 660 feet (200 m) across, and are surrounded by Quaternary sediments. The chaotic nature and the location of the outcrops suggest that they have fallen or slid into the valley from bedrock exposures farther to the east. The outcrops are interpreted to be the exposures of unrooted blocks sitting in Tertiary rocks, and covered by Tertiary rocks and Quaternary deposits. The exposures are surrounded by dotted hachured lines (plate 1) that indicate gravity-slide blocks; the exact extent of the blocks is uncertain, so the dotted lines are diagrammatic (plates 1 and 2).

A few less disrupted exposures of quartzite were mapped as the Mutual Formation (Zm) and Geertsen Canyon Quartzite (Ꞓgc) in the hanging wall of a low-angle normal fault southeast of Richmond (plates 1 and 2). Because exposures are limited and the extent of the fault sheet is not known, the buried trace of the low-angle normal fault has not been portrayed on plate 1.

Langston(?) Formation (Ꞓl?)

A small, isolated outcrop at the mouth of the large drainage just north of City Creek (section 36, T. 14 N., R. 1 E., plate 1) has dimensions of about 500 by 1,000 feet (150 by 300 m), and contains an olive-tan, very fissile clay shale with minor dark-gray, finely crystalline to micritic limestone. The rocks are obviously out of stratigraphic position (plate 1) and, based on lithologic similarities (see Buterbaugh, 1982), are interpreted as a block derived from the Langston Formation. The nearest in-place outcrops of the Langston are approximately 3 miles (5 km) to the east in the Naomi Peak quadrangle (see Dover, 1987). This isolated exposure is interpreted as an unrooted gravity-slide block that is sitting in Tertiary rocks (labeled Ꞓl? and surrounded by dotted hachured lines on plate 1).

Ute(?) Formation (Єu?)

This small, isolated outcrop, near that of the Langston(?) Formation (section 36, T. 14 N., R. 1 E., plate 1), is less than 500 feet (150 m) across, and is a medium- to light-gray, oolitic limestone. The limestone is out of stratigraphic position (plate 1), and based on lithologic similarities (see Deputy, 1984), is interpreted as a block derived from the Ute Formation. From this Ute(?) outcrop near the mouth of the large drainage just north of City Creek, the nearest in-place outcrops of the Ute are approximately 3 miles (5 km) to the east in the Naomi Peak quadrangle (see Dover, 1987). Like the Langston(?) outcrop, this isolated Ute(?) exposure is interpreted as an unrooted gravity-slide block that is sitting in Tertiary rocks (labeled Єu? and surrounded by a dotted hachured line on plate 1).

Cambrian(?) Limestone (Єls?)

A stratigraphically out-of-place, small, isolated outcrop of Cambrian(?) limestone is located west of Richmond (section 27, T. 14 N., R. 1 E.). The outcrop is about 300 by 100 feet (90 by 30 m), and is surrounded by Quaternary deposits. Like similar isolated outcrops in the quadrangle, this outcrop is interpreted as an unrooted gravity-slide block that is sitting in Tertiary rocks, and is covered by Tertiary rocks and Quaternary deposits. Hence, the outcrop is surrounded by a dotted hachured line on plate 1.

St. Charles Formation (Єsc)

Exposures of the St. Charles Formation (Upper Cambrian) in the quadrangle consist of an upper, gray to dark-gray, brecciated, fine- to medium-crystalline dolostone and a lower, poorly exposed, thin, white to tan, calcareous quartz arenite that is probably the Worm Creek Quartzite Member named by Richardson (1913). The upper dolostone has a sucrosic texture on weathered surfaces and a fetid smell when freshly broken. The quartz arenite is sporadically and incompletely exposed at the base of the mountain front where Tertiary rocks unconformably overlie the St. Charles. Good exposures of the dolostone are visible on the ridges north and south of Nebo Creek, in the hanging wall of the low-angle normal fault, and at the base of Crow Mountain (section 11, T. 13N., R. 1E.). Although the formation appears conformably overlain by the Ordovician Garden City Formation in the quadrangle, Morgan (1988) reported the contact as disconformable in the Bear River Range. In the hanging-wall block of the low-angle normal fault (plate 1), brecciation disrupts bedding in most outcrops; strike and dip measurements of intact bedding range from N. 11° W., 12° NE. to N. 31° E., 32° SE. Bedding orientations on Crow Mountain are not as uniform as those at Nebo Creek, and appear to wrap around the north end of the mountain. This contributes to the overall impression of greater disruption at Crow Mountain than at Nebo Creek, hence longer transport distance. The Crow Mountain exposures are probably part of a late Tertiary gravity-slide (see Structure section). North of Crow Mountain are two small outcrops of brecciated dolostone, surrounded by dotted hachured lines (gravity-slide). These outcrops are believed to be blocks that slid or tumbled downslope from outcrops in the hanging wall of the low-angle normal fault (plate 1).

Ordovician System

Garden City Formation (Ogc)

The Garden City Formation (Lower Ordovician) is the only Ordovician unit exposed in the quadrangle (plates 1 and 2). The formation is a medium- to dark-gray, micritic to medium-crystalline limestone that is moderately vuggy. The basal portion of the exposed unit is siltier than the upper part and contains intraclasts of micritic limestone. Black chert and tan stringers of silt are scattered throughout the unit. Bedding is thin (2 to 8 inches [5-20 cm]) and has a general strike and dip of N. 32° E., 44° SE. Brecciation in the Garden City Formation is confined to specific horizons. Locally, the brecciated beds are in sharp contact with undeformed beds of limestone. The contact between the Garden City Formation and the underlying St. Charles Formation was found north and south of Nebo Creek in the hanging wall of the low-angle normal fault, and at the northern end of Crow Mountain. On Crow Mountain, Garden City exposures are more broken up and bedding is commonly warped in contrast to less disrupted exposures near Nebo Creek. The Crow Mountain exposures are probably part of a Tertiary gravity-slide block (see Structure section). The upper portion of the Garden City Formation is not present in the quadrangle due to faulting, erosion, and/or burial. North of Crow Mountain and near the brecciated blocks of St. Charles Formation dolostone are two blocks of brecciated Garden City limestone (surrounded by dotted hachured lines on plate 1). The blocks are probably from bedrock outcrops farther east and have tumbled or slid downslope.

Tertiary System

Wasatch Formation and Salt Lake Formation are common terms for Tertiary strata in northern Utah. Wasatch rocks are usually described as red conglomerates and sandstones, whereas Salt Lake rocks are mostly described as light-brown to white conglomerate, sandstone, limestone, and tuff (Williams, 1948, 1962, 1964; Smith, 1953; Adamson, 1955; Adamson and others, 1955). However, Oviatt (1986a, 1986b) pointed out the correlation and stratigraphic nomenclature problems with the two formations as they had been described and applied. These problems are the product of great lateral and vertical variance in facies. Oviatt (1986a, 1986b) avoided the formal terms Wasatch Formation and Salt Lake Formation, and used genetic or descriptive nomenclature for Tertiary rocks in northern Utah. For this report, the formation names are retained, but the member designations of Adamson and others (1955) are abandoned. In place of formal member names, lithologic terms are used to designate the mappable units of the Salt Lake Formation, following the approach of Williams (1962).

Wasatch Formation (not exposed)

The Wasatch Formation is not exposed in the Richmond quadrangle, but is probably present at depth in the Cache Valley beneath the Salt Lake Formation and Quaternary sediments. The Wasatch Formation is about 360 feet (110 m) thick in a drill hole near the Logan airport (#1 Lynn Reese, table 1), and unconformably overlies a purple quartzite. This Wasatch contains red-tinged clasts of quartz sandstone, quartzite and chert, and gray carbonate and sandstone, with about 50 feet (15 m) of overlying carbonate and quartz sandstone that is neither red nor tuffaceous (Brummer, 1991, appendix). Patton and Lent (1980) showed 470 feet (222 m) of early Tertiary rocks in the #1 Lynn Reese well. In a drill hole about 7 miles (11 km) southwest of Richmond (#7-10 Hauser Farms, table 1), Wasatch Formation cuttings were not observed, even though the hole apparently bottomed in white quartzite (Brummer, 1991, appendix; Evans, 1991). About 1,200 feet (365 m) of Wasatch Formation was reported in a nearby drill hole (#1-10 Hauser Farms, table 1). From these data, the Wasatch may be irregularly distributed in subsurface; it is shown diagrammatically as several hundred to 800 feet (244 m) thick on cross-sections (plate 2). The Wasatch Formation is exposed east of the quadrangle in the Bear River Range (Dover, 1985, 1987; Oaks and Runnells, 1992).

Salt Lake Formation

Two units within the Salt Lake Formation are mapped in the quadrangle: conglomerate and tuffaceous rocks. Both units underlie the rolling foothills of the Bear River Range. The conglomerate unit is also present upslope, on Cambrian and Ordovician rocks that were transported along a low-angle normal fault. The foothills of Salt Lake Formation are apparently bounded on the west by a concealed high-angle normal fault, and on the east are in depositional contact with older rocks. The eastern (foothill) contact is mostly with the Mutual Formation and dips about 35 degrees west. However, a concealed high-angle normal fault is probably present just west of this contact (Brummer, 1991). The Salt Lake Formation is covered by large areas of colluvium, landslide deposits, and pediment-mantle gravel. The generally poor exposures make bedding and stratigraphic markers difficult to find. Poor exposures of similar, bouldery bedrock (Salt Lake Formation and Precambrian-Cambrian quartzites) and Quaternary deposits (colluvium, pediment mantle, boulder, and landslide) allow different geologic interpretations, such that contacts for these units on the Richmond quadrangle do not match those on the Smithfield quadrangle (compare to Lowe and Galloway, 1993). At the base of the foothills in the Richmond quadrangle, the conglomerate overlies the tuffaceous rocks, which are very poorly exposed. Exposed thickness of the two members combined is approximately 1,200 feet (366 m) (Mendenhall, 1975). This thickness represents only a small part of the Salt Lake Formation because the lower portion of the section is not exposed in the Cache Valley. Williams (1964) used potassium-argon radiometric dates and paleontologic evidence to infer a Miocene to Pliocene age for the Salt Lake Formation in Cache Valley. For additional paleontologic data see Yen (1947), Brown (1949), and McClellan (1977).

A more accurate estimate of thickness and stratigraphic relationships of the Salt Lake Formation was gained from well and seismic-reflection data. Drill cuttings from the Utah Geological Survey sample library were logged for two wells in the Cache Valley outside the quadrangle. A total of about 6,200 feet (1,890 m) and 4,030 feet (1,230 m) of Salt Lake Formation conglomerate and tuffaceous claystone was logged in the #1 Lynn Reese and #7-10 Hauser Farms cuttings, respectively (Brummer, 1991, appendix). From seismic data, Salt Lake Formation dips are near horizontal and Tertiary strata become thicker to the south (Evans, 1991); therefore, the thicknesses logged are probably near actual thicknesses. These data mean that the Salt Lake Formation is probably less than 6,200 feet (1,890 m) thick in the Richmond quadrangle. The #7-10 Hauser Farms well is apparently on a structural high in the central Cache Valley (Dover, 1985; Evans, 1991, plate 4c), so using a thickness of 4,030 feet (1,230 m) in the Richmond quadrangle is not ap- propriate.

In contrast with the singular stratigraphic relationship in surface exposures in the quadrangle (conglomerate on tuffaceous rocks), drill cuttings show that the Salt Lake Formation in the Cache Valley is probably a sequence of interbedded conglomerates and tuffaceous rocks (Brummer, 1991). The geologic cross sections show this as an intertonguing relationship, with the conglomerate thickening eastward toward the Bear River Range (plate 2). These dashed and queried subsurface contacts between the two Salt Lake lithologic units are diagrammatic due to the lack of well control in the quadrangle.

Salt Lake Formation conglomerate (Tslc): This unit is a thick, clast-supported conglomerate consisting of subrounded to well-rounded, coarse-grained sand to pebbles and boulders in a finer grained, tuffaceous, white to gray, sandy matrix. Conglomerate clasts are green argillite; purple, white, red, and pink quartzite; brown to white sandstone; crystalline, weathered dolostone; black chert; oolitic and fossiliferous micritic limestone; and crystalline limestone. Clast composition varies from south to north; gray carbonate clasts are dominant in the southern part of the quadrangle, and quartzite clasts become more abundant northward. This gradational change reflects, in part, the change in bedrock parent material from south to north along the range front (refer to plate 1). The quartzite clasts appear to be from the Geertsen Canyon and Mutual Formations and the argillite is probably from the Mutual. The carbonate clasts could be from any of several lower Paleozoic formations. The Salt Lake conglomerates also probably contain reworked clasts from the Wasatch Formation. The depositional environment of the Salt Lake Formation is interpreted as alluvial fans that formed from material shed from the Bear River Range into the developing Cache Valley. Where measurable, bedding planes strike generally N. 30° W. to N. 60° W., and dip 6° to 12° to either the east or the west. Imbricated cobbles in the conglomerate in Dry Canyon in the Smithfield quadrangle indicate a transport direction to the southwest. Good exposures of the conglomerate can be found along the north side of High Creek (SW¼ section 5, T. 14 N., R. 2 E. and NE¼ section 7, T. 14 N., R. 2 E.), on the slopes of Richmond Knoll (section 13, T. 14 N., R. 1 E.), on ridge tops north and south of City Creek (section 31, T. 14 N., R. 2 E. and section 6, T. 13 N., R. 2 E.), and at the mouth of Oxkiller Hollow (NE¼ section 24, T. 14 N., R. 1 E.).

Table 1. *Summary of oil- and gas-related drilling activity in the Cache Valley, Utah, near the Richmond quadrangle. Data from Utah Geological Survey files, Division of Oil, Gas and Mining files, Peterson (1946), McGreevy and Bjorklund (1970), Ritzma (1975), and Clem and Brown (1985).*

Name / Company	Location (T&R) (ft. to sec. line)	Completion Date/Status	Tests	Total Depth (feet)	Unit Tops (feet)
#1 Lynn Reese **Amoco**	NWSW 17 - T12N-R1E 1980 fs1 760 fw1	2-3-77 D&A	none	8159	Wasatch 7395 Swan Pk (?) 7750
Cache Valley Oil #1 (Toombs)	NWNENW 25 - T13N-R1W ~100 fn1 ~1400 fw1	1925 (1917?) water well	Quat. & Tert. gas shows	1650 (1475?)	Salt Lake 0 Madison(?) btm
#1 Ed Gossner **Utah-Idaho Explor.** (Cache Valley Dairy)	SWNESW 19 - T13N - R1E (1980fs1 - 1452fw1 ?)	5-1-57 water well	Quat. & Salt Lake gas shows	5500	Salt Lake 1485 "Penn." 5203
#5 Fee **Lynn Erickson**	SWSW 14 - T13N - R1W 1200 fs1 - 1200 fw1	9-10-61 uncertain	none reported	136	not reported
#2 Fee **Lynn Erickson**	SWNW 14 - T13 N - R1W 2760 fs1 180 fw1	1-8-60 (?) uncertain	gas well	200 (?)	not reported
#7-10 Hauser Farms **North Am. Res.**	NWSWNE 10 - T13N - R1W 1533 fn1 2415 fe1	12-31-84 D&A	none	5329	Salt Lake 3700 (?) Precambrian 4650
#1-10 Hauser Farms **North Am. Res.**	SWNENE 10 - T13N - R1W 700 fn1 1100 fe1	10-26-84 D&A	none	7200	Salt Lake 3700 (?) Wasatch 4970 Precambrian 6130
#1 C.A. Brown **Karmis Oil & Gas** (N. Brown)	NWNW 10 - T13 N - R1W 660 fn1 250 fw1	6-10-57 water well	none (Miss. water & gas)	5210	Salt Lake 1424 Penn. rocks 4031 Miss. rocks 5106
#1 Lower **Drilco Investment**	NWSENE 27 - T14N - R1W 1822 fn1 831 fe1	9-20-82 D&A	none	1677	Salt Lake <1400
#1 Steven Szot **Delta Petroleum**	SESW 19 - T14N - R1E 660 fs1 1980 fw1	1-10-83 (?) uncertain	shut in (?)	8930	not reported
#2 Stephen Szot **Delta Petroleum**	NWSE 19 - T14N - R1E 1980 fs1 1980 fe1	8-4-81 D&A	none (?)	500 (?)	not reported
none-water well **R. Jacobs Drilling**	NESW 19 - T14N - R1E	3 (?) - 75 uncertain	gas & mud blowout	186	uncertain
#4 William Harris **Warner Valley Oil**	SENE 27 - T14N - R1E 3300 fs1 750 fe1	5-6-76 D&A	none	3157	not reported
No. 1 **Eureka Oil Co.**	NWNW 9 - T14N - R1W	7-?-52 DSI (water well?)	not reported	729	not reported
#1 Glover **Delta Petroleum**	19 (?) - T14N - R1E (?) (NENE 24 - T14N - R1W ?)	3-3-81 D&A	not reported	510 (?)	not reported
Szot #3 **Delta Petroleum**	19 - T14N - R1E (?) (NESW 19 - T14N - R1W ?)	4-27-81 (?) D&A	not reported	511	not reported

Abbreviations: fs1 = from south line, fw1 = from west line, fn1 = from north line, fe1 = from east line, D&A = drilled and abandoned, DSI = drilling suspended.

A small travertine deposit, covering an area of about 6 to 9 ft^2 (3 m^2), is located on the side of a depression in the Salt Lake conglomerate near an elevation of 6,180 feet (1,945 m) along an east-west-trending ridge just north of City Creek (section 31, T. 14 N., R. 2 E.; plate 1). The travertine is compact, laminated to thinly layered, yellow-brown to white sparry calcite that contains pebbles of conglomerate. The overall appearance leaves the impression of deposition on the banks of a pool of water. This deposit, interpreted as a hot-spring deposit, may indicate proximity to a fracture system or fault zone. The deposit is late Tertiary or Quaternary in age.

Salt Lake Formation tuffaceous rocks (Tslt): This map unit is composed of nearly white to light-tan to olive-gray, calcareous, tuffaceous claystone with beds and lenses of gray volcanic ash. The tuffaceous unit is interpreted as lithified, fluvial and lacustrine, devitrified and vitric, volcaniclastic sediments that were deposited in a basin that developed during normal-faulting. The claystone is blocky when fresh, but becomes weakly fissile when weathered. The unit is poorly to moderately consolidated and is horizontally bedded. Exposures of the claystone are very poor, but several better exposures were examined and sampled at the mouths of High Creek, Oxkiller Hollow, and Cherry Creek, and at three other sites (see locality symbols in Tslt and labeled Tslt on plate 1). At the locality northeast of Richmond Knoll (NW¼ section 7, T. 14 N., R. 2 E.), an exposure of claystone contains gray ash in small pods (about 2 to 10 inches [6 to 26 cm] in diameter) that resemble rip-up clasts. Ash is also present in the small isolated exposure (Tslt) on Crow Mountain. In an exposure of the contact between Salt Lake conglomerate and the claystone along an irrigation canal north of High Creek (NW¼ NE¼ section 7, T. 14 N., R. 2 E.), the overlying conglomerate truncates horizontal beds of tuffaceous claystone and ash in what appears to be a cut-and-fill structure. Because exposures are poor, the claystone-conglomerate contact is usually mapped with a queried line (plate 1).

The non-clay constituents of the tuffaceous claystone were determined from outcrop samples, and drill cuttings from two wells in the Cache Valley (#1 Lynn Reese and #7-10 Hauser Farms; both outside the quadrangle). The various constituents of surface samples were determined by binocular-microscopic examination of processed material. Processing included removal of clay-sized particles followed by magnetic separation. The dominant non-clay components were glass shards with stretched vesicles, which confirmed the tuffaceous nature of the claystone observed in the field. Lesser amounts of biotite, hornblende, magnetite, and muscovite were present. Binocular-microscopic examination of the claystone from the drill cuttings showed that marcasite, calcite, bitumen, quartz, and fossil ostracodes, gastropods and pelecypods (pyritized) are scattered throughout the tuffaceous unit. A bed of clinoptilolite-bearing tuff that may be up to 130 feet (40 m) thick exists beginning at a depth of about 3,460 feet (1,055 m) below the valley floor in the #1 Lynn Reese well. The actual thickness of this unit may be less because of possible down-hole contamination of the drill cuttings.

Quaternary System

Pleistocene and Holocene sediments in the quadrangle consist of alluvial, lacustrine, deltaic, and mass-movement deposits. About 1,100 feet (335 m) of Quaternary deposits were logged from cuttings in the #1 Lynn Reese well. Sediments were fine-grained to conglomeratic, and coarser grained sediment included quartz, carbonate, quartzite, and chert (Brummer, 1991, appendix). About 1,400 feet (400 m) of Quaternary sediments were reported from other wells in the area (table 1). Most of the exposed Pleistocene sediments were deposited during the late Pleistocene Bonneville lake cycle, about 30,000 to 10,000 years ago (for details see Scott and others, 1983; Currey and Oviatt, 1985; McCalpin, 1989; Oviatt and others, 1990, 1992). The major events of the Bonneville lake cycle are summarized in figure 3. The Cache Valley was probably inundated by at least one older Pleistocene lake (pre-Lake Bonneville) (Scott and others, 1983; Oviatt and Curry, 1987; Oviatt and others, 1987), and older Pleistocene (pre-Lake Bonneville) sediments are present in the subsurface (Lowe, 1987). Holocene deposits in the quadrangle are mainly the product of alluvial processes operating over the past 10,000 years.

As determined from drill cuttings (in part #1 Lynn Reese and #7-10 Hauser Farms wells), the older Pleistocene sediments, which underlie the fine-grained Bonneville lake-cycle deposits in the Cache Valley, are fine-grained to gravelly. About 920 feet (280 m) of these sediments were encountered in the #1 Lynn Reese well (Lowe, 1987; Brummer, 1991, appendix). Although not exposed in the Cache Valley, these sediments were described by Lowe (1987) as Little Valley lacustrine and pre-Bonneville-lake-cycle alluvial-fan deposits. These mostly gravelly deposits are shown on the geologic cross sections as Quaternary gravels (plate 2), and the thicknesses and contacts are very approximate.

Lake Bonneville occupied the Cache Valley basin during the latest Pleistocene (figure 3) and formed several geomorphic features that can be seen today in the quadrangle. The most prominent feature is the Bonneville shoreline, about 5,100 feet (1,554 m) elevation on the eastern side of the quadrangle. The Provo shoreline is only visible on the northern end of Crow Mountain at an elevation of about 4,800 feet (1,463 m)(plate 1). Other prominent features include the ancient lake bottom and several deltas.

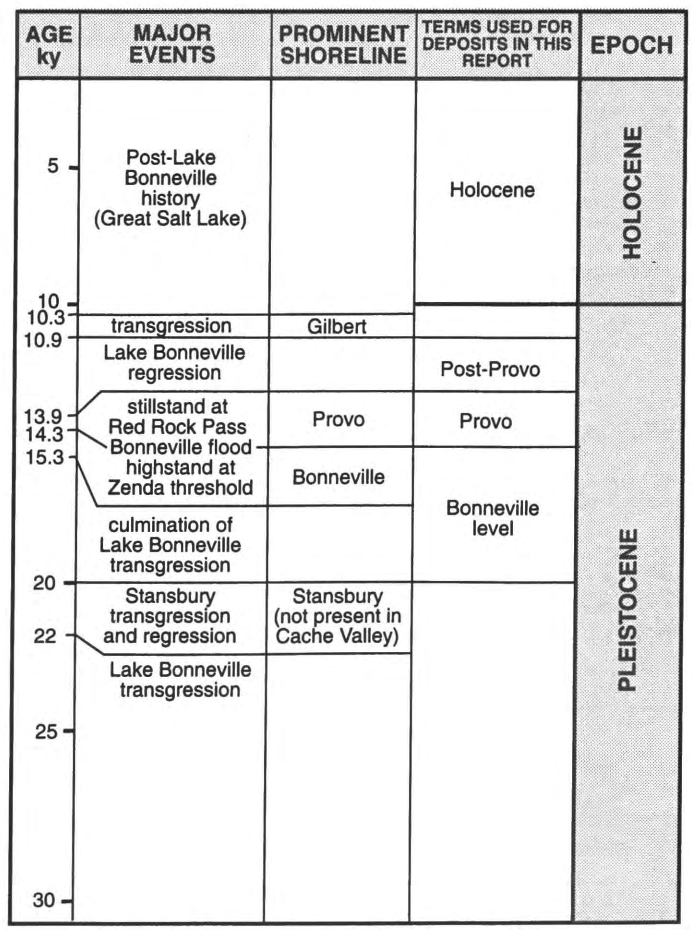


Figure 3. Summary of Lake Bonneville history 30,000 to 10,000 years ago (from Oviatt and others, 1992).

Lacustrine and Deltaic Deposits (Qlg_4, Qls_4, Qd_3, Qdg, Qlg_3, Qls_3, Qds, Qlf)

Quaternary lacustrine deposits in the Richmond quadrangle are associated with the various levels of the Bonneville lake cycle (see plate 2 - Unit Correlations, and figure 3). Deposits consist of gravel, sand, silt, and clay, and are divided into three groups: (1) deposits associated with the Bonneville highstand and the transgression of Lake Bonneville (Bonneville-level deposits; 20,000 to 14,300 years ago); (2) deposits associated with the rapid drop of the lake (Zenda threshold failure), the Provo stillstand, and the regression of Lake Bonneville (Provo-level deposits; 14,300 to about 11,000 years ago); and (3) undivided Bonneville lake-cycle sediments. Generally, lacustrine sediments deposited near the mountain front are gravel and sand. Silt and clay were deposited in quieter water farther from shore on the lake bottom or in sheltered embayments.

Two lacustrine/deltaic map units exposed in the quadrangle are associated specifically with the Bonneville-level highstand. Gravels and sands (Qlg_4) were deposited in beaches, bars, spits, and small deltas. These deposits contain clast-supported, pebble and cobble gravel in a matrix of sand and silt, with interbedded sand lenses. The clasts are usually subrounded to rounded. The deposits (Qlg_4) form a narrow band of gravel that parallels the mountain front (plate 1) with an exposed thickness of less than 35 feet (10 m). Coarse to fine sand, silt, and minor amounts of clay form another unit (Qls_4). These fine-grained, typically rhythmically bedded sediments were deposited offshore in deeper water or as embayment fill, such as that mapped northeast of Crow Mountain. Unit Qls_4 is less than 17 feet (5 m) thick, and in many places is only a thin veneer, less than 3 to 6 feet (1-2 m) thick, over the Salt Lake Formation tuffaceous rocks (Tslt).

Three deltaic and two lacustrine map units are associated with the Zenda threshold failure, Provo-level stillstand, and regression of Lake Bonneville. Provo-level deltas (Qd_3) are mapped topographically below the Bonneville shoreline deposits along City Creek, Cherry Creek, and High Creek; they have exposed thicknesses of less than 85 feet (25 m). These Provo-level deltaic deposits are clast-supported, subrounded to rounded, pebble and cobble gravels in a matrix of sand and minor silt. Much of the material was derived from the erosion of older Bonneville shoreline deposits (Qlg_4, Qls_4), when Lake Bonneville dropped rapidly from its highstand, that is, when the Zenda threshold failed and the Bonneville flood occurred. Younger deltas (Qdg) developed as the lake receded below the Provo-level stillstand (less than about 13,900 years ago). Sediments in these younger deltas (Qdg) are similar to those in Provo-level deltas (Qd_3); thicknesses are uncertain, but are probably less than 17 feet (5 m). Along High Creek, one of the younger deltas (Qdg) has been bisected by later downcutting of the creek. Small post-Provo-level deltas (Qdg) were also developed along, and are cut by, City Creek and Cherry Creek. Longshore currents swept gravel, sand, and silt southward from Provo-level deltas to form beaches, bars, and spits (unit Qlg_3) on the east side of the valley. These deposits are clast supported, subrounded to rounded pebble and cobble gravel in a sparse matrix of sand and silt, with some thin sand beds intermingled. The exposed thickness is less than 17 feet (5 m). Downslope from the Provo-level gravels, the valley floor is composed of coarse to fine sand, silt, and minor clay (unit Qls_3) that are typically rhythmically bedded. These sediments settled in quieter, deeper water than did deltaic and shoreline gravels, and have exposed thicknesses of less than 17 feet (5 m). In the northwestern corner of the quadrangle, a large area is composed primarily of silt and fine sand (unit Qds) that is probably less than 17 feet (5 m) thick. This unit is either a portion of the distal Bear River delta in Lake Bonneville (McCalpin, 1989), or is reworked material from the incision of the Bear River into its Provo-level delta in Idaho (Williams, 1962). Therefore, the silt and sand (Qds) were deposited during the Provo stillstand and regression from the Provo level, or during regression only. This delta was deposited on and might be interbedded with some lake-bottom clay and silt (Qlf)(Williams, 1962).

Lake-bottom clay, silt, and minor fine sand were deposited, usually in thick beds, throughout the Bonneville lake cycle and are not associated with any specific lake level, transgression or regression. Therefore, they are mapped as undivided, fine-grained, deep- or quiet-water sediments (Qlf). The thickness of these lake-bottom deposits in the Smithfield quadrangle is 40 to 50 feet (12 - 15 m). Contacts of this unit (Qlf) with slightly coarser grained deposits (Qls_3, Qal_1, Qan, Qds, Qaly) often were inferred with the aid of the soil-survey maps of Erickson and Mortensen (1974).

Deposits mapped as lacustrine gravel (Qlg_4, Qlg_3) and sand (Qls_4, Qls_3) in this report were labeled differently in the adjacent Smithfield quadrangle (see Lowe and Galloway, 1993). Our Qlg_4 equals their Qlc_4; our Qlg_3 equals their Qlc_3; our Qls_4 equals their Qlc_4 and Qlf_4; and our Qls_3 equals their Qlc_3.

Alluvial Deposits (Qal_5, Qal_4, Qal_3, Qal_2, Qal_1, Qaly, Qan, Qap, Qaf_2, Qaf_1, Qac)

Stream alluvium of various ages is mapped in most of the small canyons of the Bear River Range as well as along the Bear River and Cub River on the floor of Cache Valley. The stream alluvium is clast-supported, pebble to cobble gravel in a matrix of sand, silt, and minor clay. These stream-alluvium units have exposed thicknesses of less than 17 feet (5 m) unless otherwise stated. Deposits are moderately sorted and clasts are subangular to rounded. The oldest stream alluvium (Qal_5) is mapped in a paleodrainage between City Creek and Nebo Creek. The age of this alluvium is inferred to be early to middle Pleistocene because the drainage appears truncated by alluvium (Qal_4) graded to the Bonneville-highstand shoreline. Stream alluvium (Qal_4) graded to the Bonneville-highstand shoreline (late Pleistocene; about 15,300 to 14,300 years ago) was found at Nebo Creek, City Creek, Cherry Creek, Oxkiller Hollow, and Praters Hollow. Brummer notes that at Praters Hollow these deposits have a fan morphology that is apparent on aerial photographs, contain debris-flow deposits, and extend below the Bonneville shoreline (plate 1). This means the Praters Hollow exposure might be an alluvial fan of slightly different age (Qaf_3, pre-Holocene). The interpretation of McCalpin (Qal_4) is shown on plate 1. Alluvium in terraces on the north side of the unnamed creek between City and Cherry Creeks (Qal_3) was deposited when the creek was graded to the Provo-level shoreline (approximately 14,300 to 13,900 years ago). Alluvium found along the Cub River and High Creek in terraces more than 16 feet (5 m) above the modern stream level is younger still (unit Qal_2). Along High Creek, these terraces (Qal_2) are inset into Bonneville lake-cycle gravels. The youngest alluvium (Qal_1) was deposited by the Cub River, Bear River, Spring Creek, and High Creek on modern floodplains and in terraces less than 16 feet (5 m) above the modern stream level. Along the Bear River, this unit is predominantly sand and silt rather than mostly gravel. Areas of undivided Holocene alluvium (Qaly) including floodplain and terrace gravel, sand and silt containing small patches of colluvium and alluvial-fan deposits, were mapped in many of the smaller intermittent drainages. This unit (Qaly) is probably less than 35 feet (10 m) thick. A thin veneer of Qaly was deposited over lake-bottom sediments (Qlf) between Richmond and High Creek.

A natural levee deposit is mapped along the Bear River in the southwest corner of the quadrangle. Contacts of this levee deposit (Qan) were inferred from the soil-survey maps of Erickson and Mortensen (1974). This unit is composed of fine sand and silt and is probably less than 17 feet (5 m) thick. These deposits were mapped as unit Qdn in the Smithfield quadrangle (see Lowe and Galloway, 1993).

A gravel-capped pediment surface is preserved on the conglomerate member of the Salt Lake Formation at elevations from 5,160 to 6,400 feet (1,573 to 1,951 m). Well-rounded cobbles and boulders of Mutual Formation quartzite and Geertsen Canyon Quartzite are scattered about the surface. Williams (1948) named this pediment surface the McKenzie Flat surface and assigned a post-Pliocene age to it. McCalpin (1989) described the pediment-mantle deposits (Qap) as 100,000 to 200,000 years old, clast-supported pebble, cobble and boulder gravels in a matrix of sand, silt, and minor clay, with poor sorting and angular to rounded clasts. The pediment-mantle deposits are commonly a thin discontinuous veneer, and exposed thicknesses are less than 35 feet (10 m).

Alluvial-fan deposits of two ages are mapped in the quadrangle. These deposits are clast-supported, angular to subrounded, pebble and cobble gravels in a matrix of sand, silt, and clay. Deposits are poorly sorted, locally bouldery, contain recycled Bonneville lake-cycle gravels, and have exposed thicknesses of less than 17 feet (5 m). The older fan deposits (Qaf_2) are early to middle Holocene and are distinguished from the younger (late Holocene) fan deposits (Qaf_1) by having less apparent, subdued debris-flow levees.

Undivided Holocene alluvium and colluvium (Qac), deposited as stream and fan alluvium, hillslope colluvium, and small landslide deposits, are mapped in the upper reaches of the smaller drainages in the Bear River Range. These deposits are mostly moderately to poorly sorted with clast sizes that range from sand to boulders. The degree of rounding of the clasts is also quite variable from poorly to well rounded.

Mass-Movement Deposits (Qmc, Qms)

Large areas of hillslope colluvium (Qmc) cover the Salt Lake Formation (Tslc and Tslt). These colluvial deposits are pebble, cobble, and boulder gravels that are mostly supported by a matrix of sand, silt, and clay. Deposits are primarily unsorted and unstratified, with exposed thicknesses of less than 17 feet (5 m). On slopes below pediment surfaces, the colluvial sediments (Qmc) were derived from pediment-mantle deposits (Qap). Other mass-wasting deposits are slides, slumps, and flows (Qms) that occur on the Salt Lake Formation. These deposits are unsorted, unstratified sand and silt to boulder-rich gravel and bedrock blocks. Thicknesses are highly variable. Shallow debris slides are common on north-facing slopes underlain by Tertiary bedrock.

STRUCTURAL GEOLOGY

The predominant structural features in the quadrangle are related to two major tectonic events: thrust faulting and folding associated with the Jurassic to early Tertiary Sevier orogeny (Armstrong, 1968; Wiltschko and Dorr, 1983; Yonkee, 1992), and later Tertiary normal faulting, which may have started 36 million years ago in the Great Basin (Stewart, 1978, 1983; Zoback and others, 1981). During the Sevier orogeny, Precambrian and Paleozoic rocks now exposed in the Bear River Range were thrust eastward approximately 65 miles (104 km) from their original site of deposition (Levy and Christie-Blick, 1989), and were folded into a broad syncline named the Logan Peak syncline by Williams (1948). These rocks are in the hanging wall of the Paris-Willard thrust sheet (Dover, 1987; Coogan, 1992). Some of these rocks were further displaced by at least three episodes of younger Tertiary normal faulting and gravity sliding, referred to as normal faulting and mass movement in Brummer (1991). Basin-and-range style extensional tectonism continues today in northern Utah (Westaway and Smith, 1989).

Visible structures in the quadrangle include all or parts of: (1) the Logan Peak syncline, (2) at least one thrust fault, (3) at least one low-angle normal fault, (4) several high-angle normal faults, and (5) gravity-slide blocks. These structures are described according to their geometries, orientations, map patterns, and field relationships. The descriptions are followed by a history of the structural relationships.

Logan Peak Syncline

The Logan Peak syncline is the most obvious feature in the Bear River Range that is related to the Sevier orogeny. In the quadrangle, the Mutual Formation and the Geertsen Canyon Quartzite strike north to northeast and dip moderately to the east (average N. 19° E., 40° SE.) forming the west limb of the syncline (see Brummer, 1991 for details). The axis of the syncline, which lies to the east in the Naomi Peak quadrangle, plunges gently to the south and southwest (Williams, 1948; Dover, 1985, 1987). Due to the orientation of the syncline relative to the range-front normal faults, progressively older rocks are exposed from south to north on the west flank of the Bear River Range.

Thrust Fault(s)

Slickensides and fractured quartzite of the Mutual Formation and Geertsen Canyon Quartzite are evidence for the thrust fault mapped in the southeast corner of the quadrangle (closed sawteeth on plate 1). The fracturing is so widespread that the eastern thrust fault mapped by Galloway (1970) in the northeast corner of the Smithfield quadrangle, is probably part of the same thrust fault; more than one thrust slice might be present or the different traces might be differences in mapping a wide zone. In the Richmond quadrangle, the fault is the contact between the Geertsen Canyon Quartzite and the underlying Mutual Formation. As shown on plate 1, the fault strikes roughly north and dips approximately 45 degrees to the west. An undulating slickenside surface in the Mutual Formation, at an elevation of 5,400 feet (1,700 m) in the Smithfield quadrangle (about 850 feet [260 m] from east line and 1,700 feet [520 m] from north line, section 18, T. 13 N., R. 2 E.), strikes approximately N. 28° W. and dips from 0° to 47° SW. Other slickenside surfaces in Mutual quartzite in the Smithfield quadrangle strike approximately north and dip west at moderate angles (30° to 35°). This thrust fault is not traceable north of, and may be truncated by, a low-angle normal fault (Brummer, 1991). Galloway (1970) estimated maximum displacement on this fault to be approximately 800 feet (244 m) in the Smithfield quadrangle.

Mendenhall (1975) mapped two bedding-plane thrust faults in the Mutual Formation in the Richmond quadrangle. He also described and mapped similar thrust faults in the Geertsen Canyon Quartzite, particularly near its contact with the Langston Formation, to the east in the Naomi Peak quadrangle. None of these faults were recognized during mapping for this project. Where documented in the Bear River Range, this style of fault dips east in orientations similar to the bedding in the west limb of the syncline (Galloway, 1970; Mendenhall, 1975).

Low-Angle Normal Faults

In the Richmond quadrangle, low-angle normal faults have dips much less than 45 degrees, the division between low-angle and high-angle normal faults. A low-angle normal fault was mapped north and south of Nebo Creek on the southeast margin of the quadrangle (shown with open sawteeth on the hanging wall on plate 1). The fault places east-dipping carbonate and quartz arenite of the St. Charles Formation, and carbonate of the Garden City Formation in the hanging wall, above east-dipping Mutual Formation and Geertsen Canyon Quartzite. The fault is recognized by missing rock units (compare figure 2 to plate 2), and by breccia and yellowish-gray carbonate gouge along the fault. On south-facing slopes, contrasting vegetation further delineates the fault trace (figure 4). Where exposed, the fault strikes north to northeast (up to N. 30° E.), and dips approximately 20° to 22° NW. In the hanging wall, the St. Charles is brecciated in most outcrops. Brecciation in the Garden City is less extensive and appears to be confined to specific layers or beds, such that undeformed beds are in sharp contact with intensely brecciated beds. Footwall deformation consists of slickenside surfaces on loose blocks of quartzite, and fractured and brecciated quartzite near the fault. Salt Lake Formation conglomerate (Tslc) covers the fault trace to the north and to the south of fault exposures, and remnants of the conglomerate are present on the hanging-wall block (plate 1). On the basis of the displacement of the contact between the St. Charles Formation and the Garden City Formation, from the Naomi Peak quadrangle to the Richmond quadrangle, the dip slip on this low-angle normal fault is approximately 2.1 miles (3.4 km).

Various interpretations exist concerning the formation of low-angle normal faults in the Richmond and Smithfield quadrangles. Mendenhall (1975) attributed the low-angle normal fault described above to landsliding. Galloway (1970) and Sprinkel (1979) believed the low-angle normal faults formed by reversal of movement on preexisting thrust fault(s). The low-angle, west-dipping surface described by Galloway (1970) is the same structure that Bailey (1927) described as a normal fault. Brummer (1991) concluded that the low-angle structures are low-angle normal faults that formed without a preexisting thrust fault, under a different stress state than high-angle normal faults.

High-Angle Normal Faults

In the quadrangle, four high-angle normal faults form a zone that is approximately four miles (6.4 km) wide; the zone extends from the mountain front of the Bear River Range west into the valley floor (plate 1, faults labeled A, B, C and D, east to west).

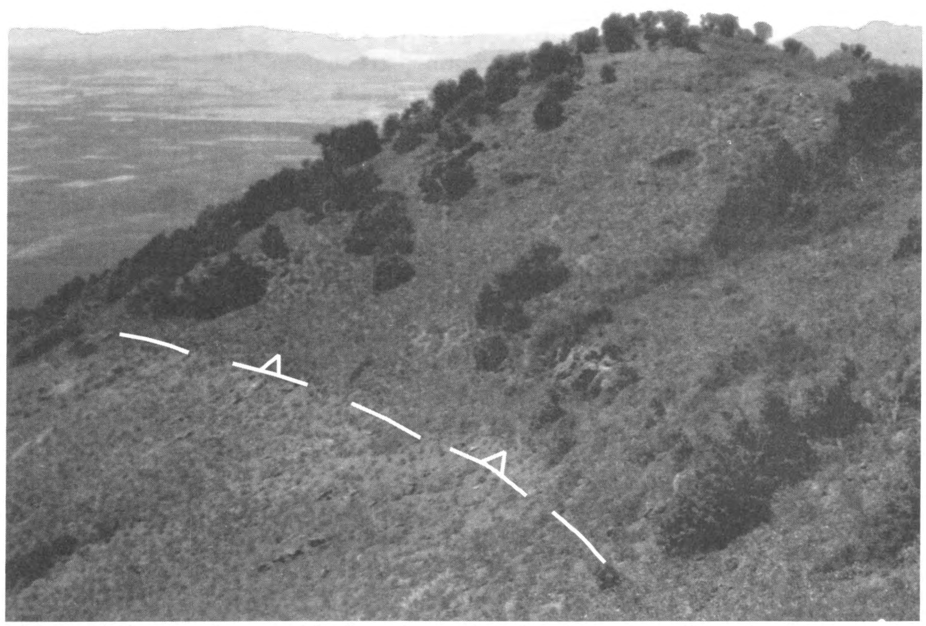


Figure 4. *Low-angle normal fault on the south-facing slope above Nebo Creek (view is to the northwest). Fault trace is visible due to change in vegetation.*

These sub-parallel faults strike north to northeast, and comprise the northern segment of the East Cache fault zone of McCalpin (1989). The eastern two faults (A and B) are manifested by bedrock escarpments in Precambrian and Tertiary rocks, respectively, and bound rolling foothills of Tertiary Salt Lake Formation. The western two faults are mostly (fault C) to completely (fault D) concealed by Bonneville lake-cycle and younger sediments. Along all four faults, bedrock units have been displaced down to the west. Many of the faults appear to have had more than one episode of movement. Another fault might be present west of the labeled faults.

These characteristics are in contrast to those of the central segment of the East Cache fault zone (Logan area), where: (1) only one major north-striking fault is present, (2) the deformation zone is less than one-half mile (1 km) wide, (3) the valley floor abuts the range front, (4) Tertiary rocks are not exposed, and (5) Holocene (post-Lake Bonneville) movement has taken place (McCalpin, 1989).

Previous investigations (Smith and Bruhn, 1984, figure 7; Evans, 1991) using seismic-reflection profiles define fault geometry and movement in the East Cache fault zone. South of the quadrangle, faults dip about 50 to 70 degrees west with some listric flattening at depth. Dips of about 70 degrees are reported in the Richmond area. From outcrops in the Bear River Range, formation tops in the #1 Lynn Reese well, and seismic data, net slip across the East Cache fault zone was estimated at 11,800 and 8,900 feet (3,600 and 2,700 m) near Richmond and the north border of the quadrangle, respectively. Note that net slip and the thickness of Cenozoic basin fill decreases northward (Evans, 1991). Slip on any particular fault in the Richmond quadrangle is uncertain due to limited well control. Estimates of throw (vertical displacement) for individual faults (A through D) in the following text are from the limited well data and kinematic reconstructions in Brummer (1991).

Fault A

Fault A is concealed by thin Salt Lake Formation conglomerate (Tslc) along most of its trace. In the Richmond quadrangle, fault A is best observed on the ridge between Oxkiller and Praters Hollows (plate 1), where it strikes approximately N. 25° E. and dips about 70° NW. in Mutual Formation quartzite. A small scarp less than three feet high (<1 m), altered and brecciated quartzite, and slickensides in loose blocks of quartzite are evidence for the fault. The fault is very near the contact of the Salt Lake Formation conglomerate (Tslc) and the Mutual Formation. To the northeast in the Naomi Peak quadrangle, the Salt Lake Formation is on the west side of the fault against the Mutual Formation on the east side; this interpretation is based on a sharp break in slope from steep slopes on Mutual outcrops to gentle slopes on the Salt Lake Formation. South of Oxkiller Hollow, fault A is not easily traceable because of cover by the Salt Lake Formation. Interpreted extension south of Oxkiller Hollow is based on: (1) the slight break in slope near the contact of the Salt Lake Formation and older rocks south of City Creek, (2) the fault-contact relationship between the Salt Lake and Mutual Formations to the north, and (3) the rough parallelism in strike between the Salt Lake-older rock contact and fault B on the west side of the Salt Lake exposures (plate 1; see also Brummer, 1991). Throw associated with the latest phase of movement on this fault is thought to be less than 650 feet (200 m) based on kinematic reconstructions (Brummer, 1991, plate 3). From the described relationships, the latest movement on fault A is broadly coeval with the deposition of the Salt Lake Formation, hence Miocene to Pliocene in age.

Fault B

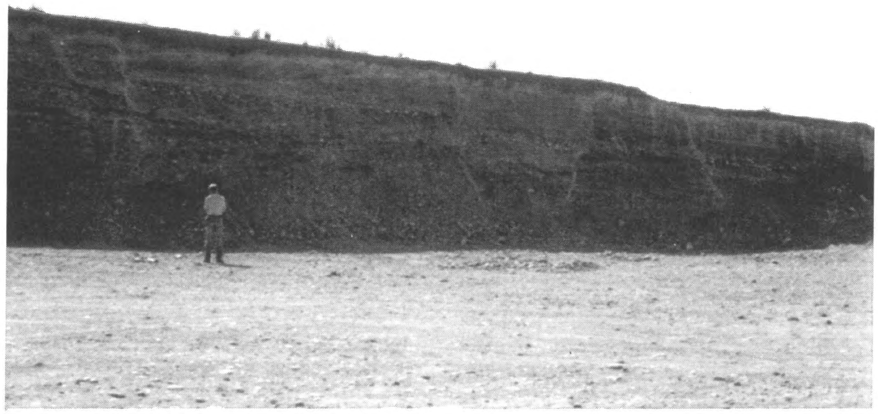
Fault B is manifested by an escarpment in the Salt Lake Formation against which Bonneville lake-cycle sediments were deposited. This fault is entirely concealed by Bonneville-level shoreline sediments (Qls_4, Qlg_4). The escarpment which defines the southern portion of fault B disappears northeast of Richmond Knoll, and apparently steps westward as another similar escarpment is visible to the west across High Creek (also labeled B on plate 1). This westward step-out of the escarpment is interpreted as minor segmentation of fault B. The dip of this fault was nowhere measurable, but is inferred to be 60° to 70° west (Brummer, 1991). Throw associated with the latest phase of movement on this fault is estimated to be less than 1,640 feet (500 m) based on kinematic reconstructions (Brummer, 1991, plate 3) and on water-well logs that indicate shallow depths (<150 feet [46 m]) to Salt Lake Formation sediments on the west side of the fault (McCalpin, 1989; Brummer, 1991). Earlier phases of displacement on this fault might have resulted in up to 1.62 miles (2.6 km) of total throw (Brummer, 1991, plate 3). Because no scarps or other visible signs of displacement were seen in the Bonneville-level silts and gravels, the latest movement on fault B is interpreted to be older than 14,000 to 15,000 years ago.

Fault C

Fault C is mostly concealed by Lake Bonneville sediments, but has been exposed in gravel pits near the mouths of Cherry Creek and High Creek (NE¼ section 23, and NW¼ section 13, T. 14 N., R. 1 E., respectively; plate 1). The faulting in both pits is inferred to be the same event due to similarities in strike, displacement, and graben width. In the Cherry Creek pit and High Creek (also known as Christensen) pit, fault C is actually a narrow zone containing several small-displacement, high-angle normal faults that dip from 55 to 75 degrees to the east and west, and define about a graben 65 and 100 foot (20 and 30 m) wide in Provo-level deltaic sediments (Qd_3) (figures 5 and 6, respectively). The graben formed during the deposition of these deltaic sediments, approximately 13,500 to 13,900 years ago (McCalpin, 1989). Throw on faults in the Cherry Creek pit and Christensen pit is 1.8 to 3.5 feet (0.5 to 1.1 m) and 1.0 to 9.8 feet (0.3 to 3.0 m), respectively. In both pits, overall displacement across the graben is down to the west, with about 5.6 and 1.3 feet (1.7 and 0.4 m) of throw, respectively. The dip of the master fault beneath the graben is nowhere measurable, but is inferred to be 60° to 70° west (Brummer, 1991).

Fault D

Fault D is entirely concealed beneath Quaternary lacustrine and alluvial sediments (plate 1). The mapped fault trace is approximate and based on: (1) the location of the westernmost



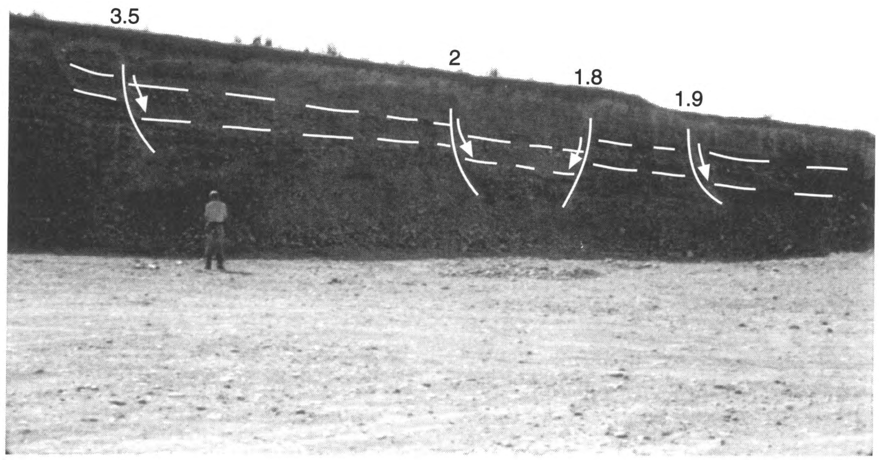


Figure 5. *Graben exposed in Cherry Creek gravel pit in Provo-level deltaic sediments (view is to the south). In lower photo, vertical displacement on individual faults is shown in feet. Photo courtesy of Dr. James P. Evans.*

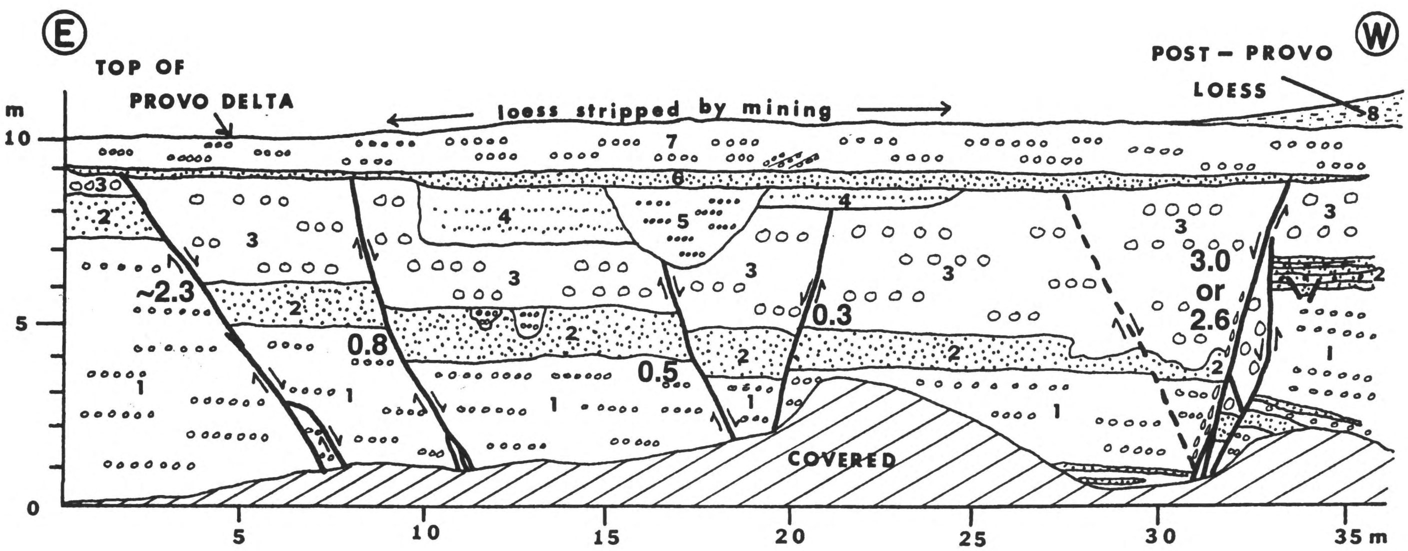


Figure 6. *Sketch of the graben exposed in the south wall of the Christensen gravel pit north of High Creek near Richmond Knoll. The graben is in Provo-level deltaic sediments (labeled 1 through 7, oldest to youngest). Vertical displacement on individual faults is shown in meters.*

outcrops of Precambrian and Paleozoic rocks (Є Zq west of Crow Mountain and Є ls? just west of Richmond), (2) the differences in depth to bedrock encountered in water wells (Mendenhall, 1975), (3) geophysical and well data from east of Lewiston, shown in Stanley (1972), and (4) gravity data portrayed in Mabey (1985). The dip of this fault was nowhere measurable, but is inferred to be 60 to 70 degrees west (Brummer, 1991). The throw on fault D after deposition of the Salt Lake Formation is estimated at approximately 1,000 feet (300 m) down to the west based on the relative position of the Tertiary-Quaternary contact in well logs east of fault D and the #1 Lynn Reese well. Stanley (1972) showed throw of at least 300 feet (91 m) on fault D. Because fault D does not break the surface (Bonneville lake-cycle lacustrine deposits), the latest movement on this fault is inferred to have occurred more than 13,500 years ago.

Westernmost Fault

Stanley (1972) inferred a west-dipping, down to the west, high-angle normal fault west of Lewiston from geophysical and well data. Because these data poorly constrain the location of the fault, such that it might be in the Richmond quadrangle or the Trenton quadrangle to the west, this fault is not shown on the geologic map.

Gravity-Slide Blocks

Isolated blocky exposures of brecciated Precambrian, Cambrian, and Ordovician rocks are located in the southeast portion of the quadrangle, west of the mountain front (plate 1). Crow Mountain is the largest such feature in the quadrangle. These isolated exposures are mantled by the Salt Lake Formation (Tertiary) and Quaternary deposits, and are thought by Brummer (1991) to rest in the Salt Lake Formation and possibly Quaternary sediments. Similar Ordovician, Cambrian, and Precambrian units are present upslope along the mountain front (plate 1). Therefore, these isolated exposures are interpreted as unrooted, largely intact blocks that slid downslope (gravity sliding) from bedrock outcrops farther to the east. These gravity slides (mass movements of Brummer, 1991) are late Tertiary and possibly Quaternary in age, with sliding presumably enhanced by saturated Cenozoic sediments, and generation of a free face and seismicity along high-angle normal faults. These unrooted gravity-slide blocks (landslides of Galloway, 1970) are here considered to be different features from the low-angle normal fault block, and were emplaced after low-angle normal faulting. This interpretation is similar to that of Galloway (1970), while Mendenhall (1975) thought that all the allochthonous rocks were part of one big Tertiary landslide or low-angle normal fault block.

Structural History

The structural history in the area includes thrust faulting, folding, and several phases of normal faulting. During the Sevier orogeny, Precambrian and Paleozoic rocks were thrust eastward from their original site of deposition and were arched and folded into the Logan Peak syncline. In the early Tertiary after deposition of the Wasatch Formation, the low-angle normal fault formed in response to an intermediate stress state during the transition from compressional tectonism to basin-and-range-style extensional tectonism (Brummer, 1991). As basin-and-range extensional tectonics became established, high-angle normal faulting occurred, and was accompanied by gravity sliding. The deposition of the Salt Lake Formation was syntectonic with high-angle normal faulting on fault A in the Miocene and Pliocene. Late Tertiary movement on the other high-angle normal faults is uncertain. During the Quaternary, movement on fault A did not occur, but movement on the other high-angle normal faults either continued or began. Movement occurred up to approximately 14,500 to 15,000 years ago on fault B, about 13,500 to 13,900 years ago on fault C, and probably to about 13,500 years ago on fault D. Even though no surface fault rupture has occurred since then in the quadrangle, the area is still tectonically active as evident from the numerous historic earthquakes in the area (Westaway and Smith, 1989; Goter, 1990).

ECONOMIC GEOLOGY

Potential geologic resources in the quadrangle consist of sand and gravel, building stone, non-metallic and metallic minerals, and oil and gas. No surface evidence was found in the quadrangle to substantiate the existence of geothermal resources, and de Vries (1982) concluded that the quadrangle did not contain geothermal potential.

Sand and Gravel

Sand and gravel are the most widely exploited geologic resources in the quadrangle. These materials are used as aggregate in asphalt and concrete, and as road metal and road base. Sand and gravel deposits are found in gravelly shoreline and deltaic deposits of Lake Bonneville. Clasts in the deposits are composed of quartzite, limestone, and dolostone. Provo-level deposits (Qd_3, Qlg_3, Qdg) are more readily accessible and contain a much larger volume of material than Bonneville-level deposits (Qlg_4). This point is supported by table 2 and plate 1, because most documented gravel pits are in Provo-level deposits in the quadrangle. Williams (1962) depicted three pits in the quadrangle, which on 1966 aerial photographs appeared to be long abandoned, because they were occupied by trees (J.K. King, verbal communication, February 1993). In 1989, commercial gravel pits were operating at the mouth of High Creek. Numerous undocumented small pits are also likely present in the quadrangle. More information is available on documented pits in the Utah Geological Survey (UGS) Utah Mineral Occurrence System (UMOS) files, and from the Utah Department of Highways (UDH, 1967).

Building Stone

No stone quarries are known in the quadrangle, but suitable stone does exist. The quartzites in the Mutual Formation (Zm) and Geertsen Canyon Quartzite (Єgc) in the quadrangle are very

Table 2. *Summary of information on sand and gravel pits in the Richmond quadrangle (numbers correspond to those on plate 1).*

Pit #	Name(s)	Other Information
1	unnamed	Williams (1962) location
2	unnamed (High Creek)	see UGS-UMOS files
3	Lewiston (Christensen)	tested; see UGS-UMOS files and UDH, 1967
4 & 5	Parsons Ready-Mix	tested; see UGS-UMOS files
6	unnamed	Williams (1962) location
7	unnamed (Cherry Creek graben)	
8	unnamed (Cherry Creek)	see UGS-UMOS files
9	unnamed	Williams (1962) location
10	unnamed (Richmond)	see UGS-UMOS files
11	unnamed	
12	Cyril Funk	tested; see UGS-UMOS files and UDH, 1967

UGS-UMOS - Utah Geological Survey Utah Mineral Occurrence System
UDH - Utah Department of Highways

durable and resistant to weathering. At sites outside the quadrangle, these quartzites have been quarried for road gravel and for decorative building facing. On the west flank of the Bear River Range, limestone in the Garden City Formation (Ogc) has been used locally as building stone and a source of lime (Dover and Bigsby, 1983). However, because of the small volume of limestone, poor accessibility of outcrops of quartzite and limestone, and the existence of more easily accessible stone quarries outside the quadrangle, the potential for economic stone quarries in the quadrangle is limited.

Non-Metallic Minerals

Zeolites, volcanic ash, and clays are non-metallic minerals that have potential for exploitation in the quadrangle. Further evaluation such as laboratory testing, volumetric calculations, local marketability, and exploratory drilling would be necessary to determine the economic potential for these materials.

The potential occurrence of zeolites in the Salt Lake Formation in the quadrangle is supported by two nearby occurrences in this formation in the Cache Valley (Mayes and Tripp, 1991). The zeolite clinoptilolite has been documented in the Salt Lake Formation near Trenton, on Little Mountain about 9 miles (14 km) southwest of Richmond (figure 1). About 20 to 70 feet (6-20 m) of laterally extensive, greenish altered tuff that contains 20 to 70 percent clinoptilolite is present on Little Mountain. Percentages are from semi-quantitative x-ray diffraction analyses, and more details are available in Mayes and Tripp (1991). During the present study, clinoptilolite was found in drill cuttings from the #1 Lynn Reese well of Amoco Production Company near Logan, Utah. The zeolite-bearing bed, in tuff in the Salt Lake Formation (Tslt), was first encountered at a depth of approximately 3,460 feet (1,055 meters) below the surface, and is approximately 100 to 130 feet (30 - 40 meters) thick. Cuttings from an interval about 40 to 100 feet (12 - 30 m) thick contained an estimated 50 to more than 75 percent zeolite. The clinoptilolite observed in the cuttings is yellow, white, or tan, with a rough, platy texture resembling corn flakes, and the mineral identification was confirmed by x-ray diffraction. The existence of these zeolite-bearing beds in the Richmond quadrangle is not documented because of poor exposures, the lack of exploratory drilling, and the great lateral variance in the facies of the Salt Lake Formation. The volume of these occurrences is not known, but the depth to the mineralization in the Richmond quadrangle prohibits economic exploitation. Given variations in zeolitization in other Tertiary tuffaceous units in the western United States, other clinoptilolite-bearing beds might be present at shallower depths in the Salt Lake Formation in the quadrangle.

Mostly unaltered volcanic ash is mixed with claystone in the tuffaceous map unit of the Salt Lake Formation (Tslt). This unit is poorly exposed in the quadrangle, so ash-rich beds might be present but obscured. Tuffaceous Salt Lake Formation is also present in the Cache Valley beneath Quaternary sediments. The economic potential of this resource is probably not high because the ash is impure and does not appear to be in large enough volume at or near the surface to facilitate bulk mining.

Because fine-grained Quaternary sediments contain clay and cover most of the valley floor, clay minerals are abundant at the surface in the quadrangle. The clay minerals present have not been identified by x-ray diffraction but, based on field observations for this report and the soil study of Erickson and Mortensen (1974), some of the surficial deposits (Qlf and Qal1) apparently contain swelling, montmorillonitic clays. These montmorillonitic clays might be used locally for lining irrigation canals (Williams, 1962), but national markets are dominated by related, purer clays know as bentonites.

Because barite mineralization was not seen in the quadrangle and is intimately associated with metallic mineralization just east of the quadrangle, it is discussed in the following subsection.

Metallic Minerals

The Richmond mining district, named for the city of Richmond, probably encompassed workings about a mile east of the Richmond quadrangle in the Naomi Peak quadrangle. The district was formed in 1894 and included 15 workings; the workings have been inactive for many years. Small tonnages of copper, lead, zinc, silver, and gold ores were reportedly shipped from mines on the west side of the Bear River Range, including mines in the Richmond district. The mineralization in the Richmond district is lead, zinc, copper, and silver in veinlets and disseminations parallel to bedding in Middle Cambrian limestones. Barite veins and veinlets are often associated with the metallic mineralization. Recorded production for the district was less than 500 short tons (454 tonnes) (for details see Butler and others, 1920, p. 217-218; Chappelle, 1975; Bigsby, 1982; Dover and Bigsby, 1983). Dover and Bigsby (1983) concluded that the Mount Naomi Roadless Area, including the Richmond district, had a low resource potential for all reported metallic minerals.

Oil and Gas

Oil and gas exploration in the Cache Valley began around 1920 (table 1). The hydrocarbon targets of these wells were initially shallow biogenic (marsh) gas. In the late 1970s and early 1980s, Amoco apparently explored for hydrocarbons that were thermally generated from lacustrine deposits (after Patton and Lent, 1980; Bortz, 1984). At least 16 wildcat wells have been drilled in the valley, in a northwest trend north of Logan (table 1), although only one of these wells is located in the Richmond quadrangle. Of the 16 wells, five had shows of gas, and none had shows of oil. One of the wells with reported gas shows (Lynn Erickson Fee #2; table 1) is located approximately six miles (10 km) southwest of Richmond, Utah. This well is reportedly about 200 feet (60 m) deep, and produces or produced marsh gas for private use (UGS files; Clem and Brown, 1985). A water well drilled to a depth of 186 feet (57 m) in 1975 about four miles (6 km) northwest of Richmond encountered marsh gas that blew out the well (Ritzma, 1975). The current status of this well is not known. Tertiary gas shows were reported in three deeper wells 1,650 to 5,500 feet (500 - 1,676 m) deep; two of these three wells also exhibited Quaternary gas shows (table 1; UGS files).

Present exploration targets in the Cache Valley are shallow biogenic (marsh) gas in thin, lenticular, sandy, lacustrine sediments of Quaternary age, and rocks of Tertiary age. Sources of the gas are probably bacterially attacked peat deposits in Lake Bonneville sediments (Clem and Brown, 1985) and possibly in the Salt Lake Formation (UGS files). Thermally generated oil and gas from Tertiary lacustrine sources have been reported in the Great Salt Lake basin in Miocene and Pliocene reservoir rocks (Patton and Lent, 1980; Bortz, 1984). The #1 Lynn Reese well of Amoco (table 1) was apparently designed to explore for similar hydrocarbons and test for thermal maturity in the Miocene and Pliocene Salt Lake Formation and Eocene Wasatch Formation in the Cache Valley.

Potential hydrocarbon reservoir rocks in the quadrangle are the Mesozoic (Jurassic and Triassic) strata that might exist beneath the Bear River Range allochthon at depths up to 20,000 to 30,000 feet (6,100 - 9,100 m) (after Royse and others, 1975; Dover and Bigsby, 1983). Coogan (1992) examined the allochthon and produced cross sections which do not show Mesozoic strata below most of the Bear River Range and show even greater depths to the base of the allochthon than those of previous workers. Exploratory drilling for a deep target is prohibitively expensive in the quadrangle (Chidsey, 1984).

WATER RESOURCES

Surface water used in the quadrangle comes from the Bear and Cub Rivers and their numerous tributaries. This water is used mainly for irrigation, but is also used for livestock and recreation. Ground water in the area occurs primarily in unconsolidated Quaternary sands and gravels of Lake Bonneville deltaic (Qd_3, Qds, Qdg) and shoreline (Qls_3, Qls_4, Qlg_3, Qlg_4) deposits, and alluvial fans (mostly concealed by Lake Bonneville deposits) (Bjorklund and McGreevy, 1971). Municipal water supplies in the quadrangle apparently are from these major aquifers, as well as Quaternary alluvium and possibly the Mutual Formation (Zm) (after Bjorklund and McGreevy, 1971, table 10; this report, plate 1). Abundant clays and silts that are interbedded in the sands and gravels locally give rise to artesian conditions. The main source of surface-water and ground-water recharge in the area is precipitation in the form of snowmelt from the mountains. Other ground-water recharge is by infiltration from streams and irrigation water, and subsurface inflow from bedrock aquifers along the mountain front (see Bjorklund and McGreevy, 1971 for details). Ground water in the area is generally suitable for domestic and livestock use, but should be tested in new wells and tested periodically in older wells. Most water in the area is classified as hard to very hard based on $CaCO_3$ content (Bjorklund and McGreevy, 1971). See Clyde and others (1981) for information on the potential for ground-water contamination.

The Cub River subvalley and Fairview-Lewiston-Trenton aquifer systems of Bjorklund and McGreevy (1971) are in the central and western thirds, respectively, of the Richmond quadrangle. Because sand and gravel comprise the Cub River subvalley aquifer system, this system is the more productive of the two. The gravelly sediments of the Cub River system were deposited on the margin of the Cache Valley in alluvial fans, and in Lake Bonneville shoreline and deltaic deposits. This subvalley system is mostly confined by younger, fine-grained Lake Bonneville deposits. Yields are greatest where subsurface alluvial fans are thickest, such as at the mouths of High and Cherry Creeks. Ground water in the Fairview-Lewiston-Trenton aquifer system is mostly in the distal Bear River delta (Qds), and is unconfined and near the land surface. The delta is underlain by lake-bottom clays (Qlf) that provide little ground water (Bjorklund and McGreevy, 1971; plate 1, this report).

GEOLOGIC HAZARDS

Geologic hazards, as discussed in this report, are evaluated on a quadrangle scale. The following descriptions of flooding, mass movement, problem soils, shallow ground water, and seismic hazards are intended to be used to identify potential problem areas and should not be used in place of site-specific investigations. Potential problem areas are shown on figure 7 and described in the text.

Flooding

Flooding in the area has occurred in the past due to cloudburst storms and spring snowmelt runoff. Overbank flooding along major drainages in the area may lead to scouring and undercutting of bridges, building foundations, roads, culverts, and embankments (after Christenson, 1983). Cloudburst events produced some flooding in the area on July 24, 1923 (Woolley, 1946); July 13, 1962; June 6 and 7, 1964; August 3, 1969 (Butler and Marsell, 1972); and in 1980 and 1981 (Utah Division of

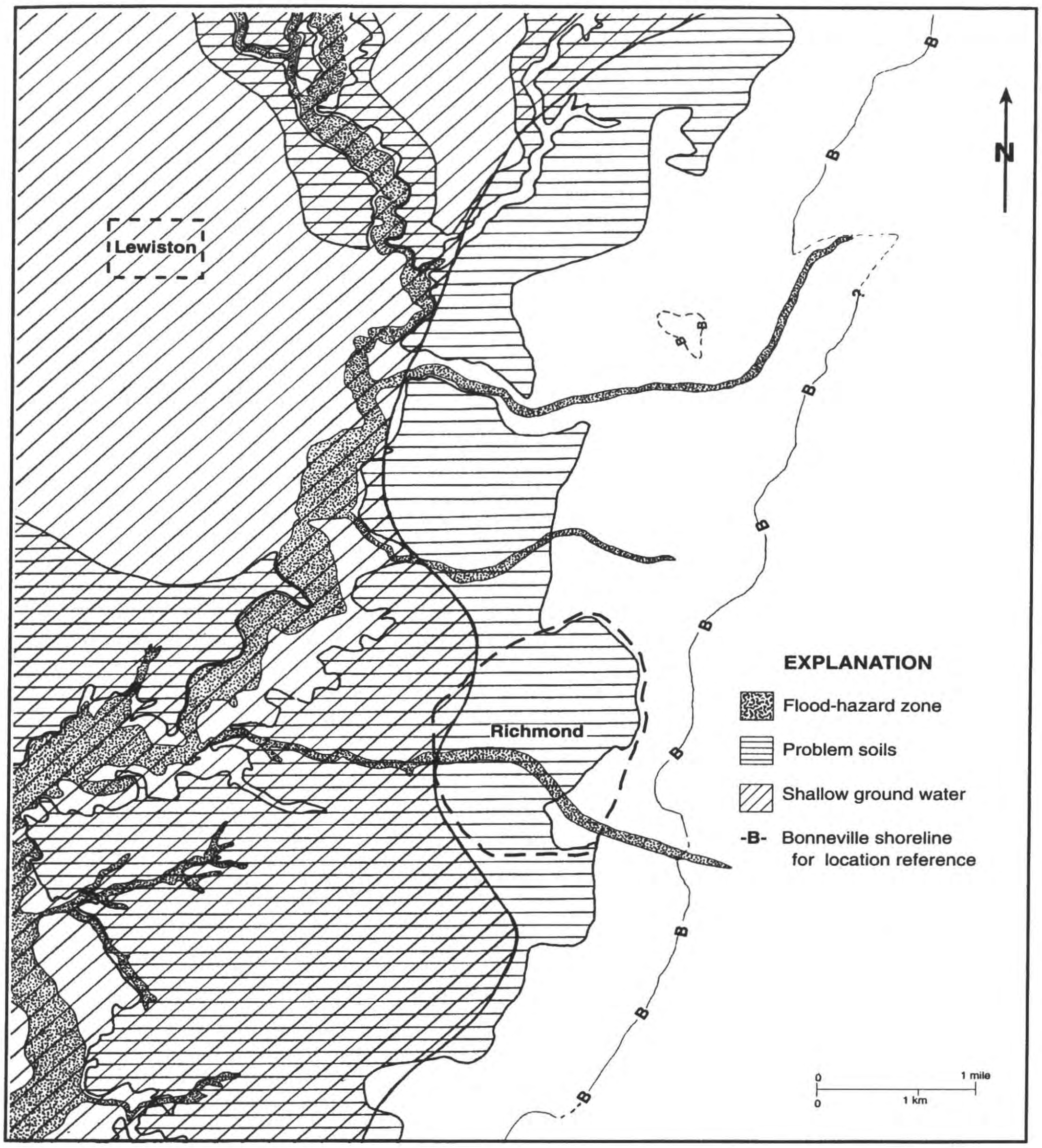


Figure 7. *Generalized geologic-hazards map of the Richmond quadrangle. This map should not be used as a substitute for site-specific investigations. Features shown are: flood-hazard zone (stippled) (modified from Federal Insurance Administration, 1974, 1980, 1981), areas of problem soils (horizontal line) (this report), and shallow ground water (45 degree lines) (after Bjorklund and McGreevy, 1971, plate 3). See text for details.*

Comprehensive Emergency Management, 1981). Peaks in snowmelt runoff in the Cub River occurred in 1982, 1984 and 1986 (840 cfs [23.8 cms]-June 18; 813 cfs [23.0 cms]-May 16; and 1,070 cfs [30.3 cms]-June 2), respectively, while peaks in High Creek occurred in 1983 and 1986 (485 cfs [13.7 cms]-May 30; and 702 cfs [19.9 cms]-June 1)(U.S. Geological Survey, 1982; ReMillard and others, 1983, 1984, 1985, 1986, 1987, 1988, 1989, 1990). The June 2, 1986 flow on the Cub River exceeded the 100-year flow as estimated by James and others (1980). Large volumes of snowmelt runoff in the spring of 1983 resulted in floods, debris flows, and landslides along mountain fronts in most of Utah, but damage in Cache County was minimal (Anderson and others, 1984).

The areal extent of the 100-year-flood zone in the Richmond quadrangle has been defined by the Federal Insurance Administration (1974, 1980, 1981). These zones are shown on figure 7 and represent areas with a 1 percent probability of flooding annually. The largest areas of potential flooding are on the Cub and Bear River floodplains, with smaller areas of potential flooding along High, Cherry, and City Creeks, and in other areas covered by young alluvium (Qal_1) (plate 1).

Cloudburst events can cause debris floods and debris flows; debris flows are a type of mass movement. Debris floods, often called "mud floods", are a mixture of soil, rock, and debris that contain more than 50 percent water; so they are like a debris flow with more water (Wieczorek and others, 1983). Therefore, areas subject to debris floods are the same as those for debris flows (discussed under Mass Movement). Because debris flows are a component of alluvial-fan deposits, the Holocene alluvial fans (Qaf_1) in the Richmond quadrangle are susceptible to debris floods. These young fans are found along High Creek, Oxkiller Hollow, and Cherry Creek. Undifferentiated debris-flow deposits are also present in Holocene alluvium and colluvium (Qac). Areas of these deposits (Qaf_1 and Qac) should be considered potentially hazardous until site-specific studies indicate otherwise.

Mass Movement

Mass movement is a natural hillslope process in which rock and soil move downslope under the direct influence of gravity. Excessive moisture and earthquakes can contribute to mass movement. Common forms of mass movement in the quadrangle include debris flows, landslides (slides and slumps), and rock falls. Major mass-movement hazards in the quadrangle are debris flows, and slides and slumps. Little historic mass movement is seen in the quadrangle; a small slide (not shown to scale) is present near the head of an unnamed creek between City and Cherry Creeks (locality dot in NW¼ section 32, T. 13 N., R. 2 E.) and sliding has taken place within the mass movement (Qms) mapped north of Cherry Creek on the foothills underlain by the Salt Lake Formation. Neither of these two historic landslides damaged or threatened property or life.

Because debris flows are a component of alluvial-fan deposits, the Holocene alluvial fans (Qaf_1) in the Richmond quadrangle are potential hazard areas (Lowe, 1987). These young fans are located along High Creek, Oxkiller Hollow, and Cherry Creek. Undifferentiated debris-flow deposits are present in Holocene alluvium and colluvium (Qac). Areas covered by these two types of deposits should be considered potentially hazardous until site-specific studies indicate otherwise.

Landslides (slides, slumps, and flows)(Qms) in the quadrangle are mostly developed on the Salt Lake Formation. Small slides and slumps are present in hillslope colluvium (Qmc), usually where the colluvium formed on the Salt Lake Formation, and in undivided alluvium and colluvium (Qac). Initiation of movement depends on amount of moisture, type and density of vegetation, steepness of slopes, and type of material involved.

Other mass movements have occurred in the quadrangle, but were not mapped due to their limited extent. Rock falls have occurred on steep bedrock slopes with little soil or colluvial cover around Crow Mountain and at higher elevations along quartzite cliffs of the mountain front. Lake Bonneville lacustrine deposits are susceptible to failure where streams have incised deltas to create steep slopes (Lowe, 1987). Flows, slumps, or slides were not noted in Lake Bonneville units in the quadrangle, but alluvial fans (Qaf_1) cutting the deltas (Qd_3) along High Creek might contain mass-movement deposits.

Areas of potential mass-movement hazards are too poorly constrained to show individually on figure 7. From the preceding descriptions, most potential debris-flow hazard areas are on young alluvial fans (Qaf_1), and most potential landslide-hazard areas are underlain by the Salt Lake Formation (Tslc, Tslt). Mapped landslide deposits (Qms) show where mass movements have occurred in the past, though few historic slides or flows are in the quadrangle. However, changes in conditions such as above-average precipitation, devegetation, irrigation, or regrading of slopes might induce slope failures in the future (after Christenson, 1983).

Problem Soils

Potential construction problems exist where expansive soils are found. Expansive soils expand (swell) and contract (shrink) as moisture content increases and decreases, respectively (Schuster, 1981). Montmorillonite clay of the smectite group is the principal material susceptible to such changes. Clay soils with moderate to high shrink-swell potential, classified as CL or CH (CL = low plasticity clay; CH = high plasticity clay) in the Unified Soil Classification System, are the potential problem soils in Cache County (after Erickson and Mortensen, 1974, table 4). Soils containing high plasticity clays have a high shrink-swell potential and pose possible problems to engineered structures such as roads, concrete foundations, and pipelines. According to Erickson and Mortensen (1974), soils containing low plasticity clays, when associated with high plasticity clays, may contribute to shrink-swell problems. These problem soils are associated with clayey lake-bottom (unit Qlf) and young floodplain sediments (unit Qal_1) in the quadrangle (see plate 1). The hazard area shown on figure 7 includes soils containing high and low plasticity clays, so as to highlight all potential problem areas. Erickson and Mortensen (1974) did not note any collapsible soils in the quadrangle.

Shallow Ground Water

Ground water is within 10 feet (3 m) of the surface in the western half of the Richmond quadrangle (figure 7; after Bjorklund and McGreevy, 1971, plate 3). Seasonal variations in precipitation and runoff can alter the water level slightly (Bjorklund and McGreevy, 1971). Problems related to shallow ground water include poor performance of septic tank soil-absorption fields, flooding of basements and other subsurface structures, and buoyancy of structures that don't leak. For these reasons, a site-specific geotechnical investigation should be performed prior to subsurface construction and tank installation in the west half of the quadrangle. Shallow ground water might also contribute to liquefaction during seismic ground shaking (see Seismic Hazards sub-section).

Seismic Hazards

The Richmond quadrangle is on the East Cache fault zone (ECFZ), which has been active in the last 10,000 years (see Structure section). Seismic hazards in the quadrangle include surface rupture, ground shaking, ground failure, and liquefaction. Goter (1990) shows that the epicenters of several large (Ms 4) earthquakes are in the area, though none are within the quadrangle. The largest earthquake in the area (M_s 5.7) occurred in August, 1962, and is known as the Richmond, Cache Valley, and Logan quake. The earthquake epicenter was approximately 4.7 miles (7.5 km) east of Richmond, Utah, in the Bear River Range in the Naomi Peak quadrangle; the focus was not on the ECFZ and might have been on the Temple Peak fault zone (Westaway and Smith, 1989). This earthquake was the most damaging in Utah's history due to the magnitude and proximity to populated areas (Christenson, 1983). Over three-fourths of the houses in Richmond were damaged, and major structural damage was also incurred in Lewiston, Logan, and Smithfield, Utah (Lander and Cloud, 1964). McCalpin and Forman (1991) showed that earthquakes of about Ms 7.0 have occurred along the ECFZ, with the most recent event occurring roughly 4,000 to 7,000 years ago. Therefore, the potential exists for much greater earthquake damage than that sustained during the 1962 earthquake.

All four high-angle normal faults in the quadrangle (A-D, plate 1) are part of the northern segment of the East Cache fault zone (ECFZ). Unlike the central segment of the ECFZ, the northern segment has not undergone faulting-induced surface-rupture in the Holocene (McCalpin, 1989). In the quadrangle, the youngest surface-rupture faulting appears to be equivalent in age to Provo-level sedimentation of the Bonneville lake cycle, because faults exposed in gravel pits both cut, and are covered by, Provo-level deltaic sediments (unit Qd_3). Based on details of this relationship, shown in figures 5 and 6, the last documentable faulting event on the ECFZ in the quadrangle was approximately 13,900 to 13,000 years ago (see also McCalpin, 1989; McCalpin and Forman, 1991). These faults in the gravel pits form graben that have been interpreted as surface-rupture faulting by Brummer (this report) and ground failure above lateral spreads by McCalpin (McCalpin, 1989; McCalpin and Forman, 1991). Likely areas of future surface fault rupture are along the pre-existing high-angle normal faults shown on the geologic map (plate 1).

Given the age and uncertainty of surface rupture, the greater seismic hazards in the quadrangle probably are ground shaking and liquefaction. Ground shaking can trigger liquefaction-induced ground failure, and mass movements (slumps, slides, flows and falls) on unstable slopes. Reported mass movements due to the 1962 earthquake were slides along the Bear River in the Trenton quadrangle, a slide of fractured quartzite along Cherry Creek in the Naomi Peak quadrangle, and small rock slides in the Smithfield quadrangle (Lander and Cloud, 1964). Also see the mass movement sub-section for potential hazard areas in the quadrangle.

Ground-shaking potential has been mapped for the Cache Valley by Youngs and others (1987). However, their estimates of peak ground acceleration did not take into account local geology, such as the fine-grained, unconsolidated sediments in the steep-sided Cache Valley basin. These local geologic characteristics can increase ground acceleration. From other work, a M_S 7.0 earthquake is capable of producing peak ground accelerations that are three times greater than those estimated by Youngs and others (1987), and two times greater than the ground accelerations that brought down the Cypress Overpass in the 1989 Loma Prieta, California earthquake (after Olig, 1991).

During an earthquake, ground shaking or vibration in saturated soils or fine-grained sediments can increase pore-water pressure, leading to a loss of contact between grains. The material at this point behaves as a dense fluid and can flow. This transformation from a solid to a liquid state is termed liquefaction. Saturated fine-grained sand and silt are most susceptible to liquefaction (Youd, 1984). Anderson and others (1990) mapped liquefaction potential in the Cache Valley. From these data, surficial deposits on the valley floor associated with shallow ground water exhibit moderate to high susceptibility to liquefaction (unit Qal_1), and moderate to low susceptibility (units Qan, Qds and Qlf). Types of ground failures caused by liquefaction are lateral spreads, flow slope failure, ground oscillation, and bearing-capacity failure (Youd, 1984; Anderson and others, 1990). Note that the graben mapped at High and Cherry Creeks as fault C (plate 1) might have been produced by a lateral spread.

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UTAH GEOLOGICAL SURVEY
a division of
UTAH DEPARTMENT OF NATURAL RESOURCES

Plate 1
Utah Geological Survey Miscellaneous Publication 95-3
Geologic Map of the Richmond Quadrangle

Base map from U.S. Geological Survey
Richmond 7.5' Quadrangle, 1964

SCALE 1:24 000

CONTOUR INTERVAL 40 FEET
DOTTED LINES REPRESENT 10-FOOT CONTOURS

14° 23'
255.7 mills

1995 MAGNETIC DECLINATION
AT CENTER OF SHEET

UTAH
QUADRANGLE LOCATION

Field mapping by McCalpin 1986-88,
and Brummer 1988-89
Revisions by Jon K. King 1993
Lori J. Douglas, Cartographer

GEOLOGIC MAP OF THE RICHMOND QUADRANGLE, CACHE COUNTY, UTAH AND FRANKLIN COUNTY, IDAHO

by

Jon Brummer and

James McCalpin

1995

The Miscellaneous Publication Maps provide an outlet for authors who are not Utah Geological Survey staff. Not all aspects of this publication have been reviewed by the UGS.

DESCRIPTION OF MAP UNITS

Qlf — Lacustrine fine-grained deposits; undifferentiated levels- *Silt and clay; lake bottom sediments; Bonneville lake cycle; 40 to 50 feet (12 to 15 m) thick.*

Qls_3 — Lacustrine sand and silt deposits; Provo level- *Well stratified fine sand and silt; Bonneville lake cycle;< 17 feet (<5 m) exposed thickness.*

Qls_4 — Lacustrine sand and silt deposits; Bonneville level- *Coarse sand to fine silt; Bonneville lake cycle; <17 feet (<5 m) exposed thickness.*

Qlg_3 — Lacustrine gravel deposits; Provo level- *Cross-bedded cobbles to medium sand; delta-derived longshore drift; Bonneville lake cycle; <17 feet (<5 m) exposed thickness.*

Qlg_4 — Lacustrine gravel deposits; Bonneville level- *Cobbles to medium sand; bar and shoreline gravel; Bonneville lake cycle; <35 feet (<10 m) exposed thickness.*

Qdg — Deltaic gravel deposits; post-Provo level- *Pebbles and cobbles in sand matrix; Bonneville lake cycle; <17 feet (<5 m) exposed thickness.*

Qd_3 — Deltaic deposits; Provo level- *Pebbles and cobbles in sand matrix; Bonneville lake cycle; <85 feet (<25 m) exposed thickness.*

Qds — Deltaic sand deposits; Provo or post-Provo level- *Fine sand to silt; Bonneville lake cycle; <17 feet (<5 m) exposed thickness.*

Qan — Natural levee deposits of the Bear River - *Fine sand to silt; <17 feet (<5 m) exposed thickness.*

Qal_1 — Stream alluvium - *Pebble to cobble gravel in sand and silt matrix; modern floodplain and terrace sediments; <17 feet (<5 m) exposed thickness.*

Qal_2 — Stream alluvium - *Pebble to cobble gravel in sand and silt matrix; floodplain and terrace sediments more than 16 feet (5 m) above modern stream level; <17 feet (<15 m) exposed thickness.*

Qaly — Younger stream alluvium - *Pebble to cobble gravel in sand and silt matrix; undivided Qal_1 and Qal_2 (Holocene) floodplain and terrace sediments; variable thickness but at most <35 feet (<10 m).*

Qal_3 — Stream alluvium - *Pebble to cobble gravel in sand and silt matrix; terrace sediments graded to Provo level; Bonneville lake cycle; <17 feet (<5 m) exposed thickness.*

Qal_4 — Stream alluvium - *Pebble to cobble gravel in sand and silt matrix; sand lenses; terraces graded to the Bonneville level, Bonneville lake cycle; <17 feet (<5 m) exposed thickness.*

Qal_5 — Stream alluvium - *Pebble to cobble gravel; pre-Bonneville lake cycle deposits; <17 feet (<5 m) exposed thickness.*

Qaf_1 — Alluvial-fan deposits - *Pebbles and cobbles in sand, silt and clay matrix; locally bouldery; <17 feet (<5 m) exposed thickness.*

Qaf_2 — Alluvial-fan deposits - *Pebbles and cobbles in sand, silt and clay matrix; locally bouldery; <17 feet (<5 m) exposed thickness.*

Qap — Pediment-mantle deposits - *Rounded quartzite cobbles and boulders; <35 feet (<10 m) exposed thickness.*

Qac — Undifferentiated alluvium and colluvium - *Unknown thickness.*

Qmc — Hillslope colluvium - *Developed on Tertiary bedrock and pediment-mantle deposits; cobbles and boulders common; <17 feet (<5 m) exposed thickness.*

Qms — Slide, slump and flow deposits - *Unsorted, unstratified; on Tertiary bedrock; variable thickness.*

Tslc — Salt Lake Formation conglomerate - *Mostly quartzite and carbonate clasts in tuffaceous, sandy matrix; exposed thickness approximately 700 feet (213 m).*

Tslt — Salt Lake Formation tuffaceous rocks - *Tuffaceous claystone and ash; exposed thickness up to 500 feet (152 m).*

Ogc — Garden City Formation - *Gray limestone, usually brecciated; not in-place; incompletely exposed.*

Ꞓsc — St. Charles Formation - *Dark gray, brecciated dolostone and basal white to tan quartz arenite; not in-place; incompletely exposed.*

Ꞓu? — Ute(?) Formation - *Gray oolitic limestone; isolated block not in-place.*

Ꞓl? — Langston(?) Formation - *Olive-tan shale and gray limestone; isolated block not in-place.*

Ꞓls? — Cambrian(?) limestone - *Gray limestone; isolated block not in-place.*

Ꞓgc — Geertsen Canyon Quartzite - *Pink, tan, olive, and white quartzite with interbedded conglomerates; about 2,500 feet (762 m) thick.*

Zm — Mutual Formation - *Red, purple, and purple-white banded quartzite with interbedded conglomerate; about 3,000 feet (914 m) thick.*

ꞒZq — Undifferentiated Proterozoic and Cambrian quartzite - *Large blocks, slabs, and boulders; not in-place.*

MAP SYMBOLS

Thrust fault - *solid teeth on hanging wall, dashed where approximately located, arrow and number indicate dip direction and degree*

High-angle normal fault - *bar and ball on downthrown side, dashed where approximately located, dotted where concealed, queried where existence uncertain; arrows show direction of movement on cross sections; circled letter denotes identification for discussion in text*

Low-angle normal fault - *open teeth on hanging wall, dashed where approximately located*

Contact - *dashed where approximately located, dotted where concealed, queried where existence uncertain*

Trace of gravity-slide-block surface - *hachures on block, dotted where concealed such that locations are diagrammatic*

Bonneville-level shoreline

Provo-level shoreline

Strike and dip - *broken where measurement uncertain*

Locality - *mentioned in text; Tslt-claystone*

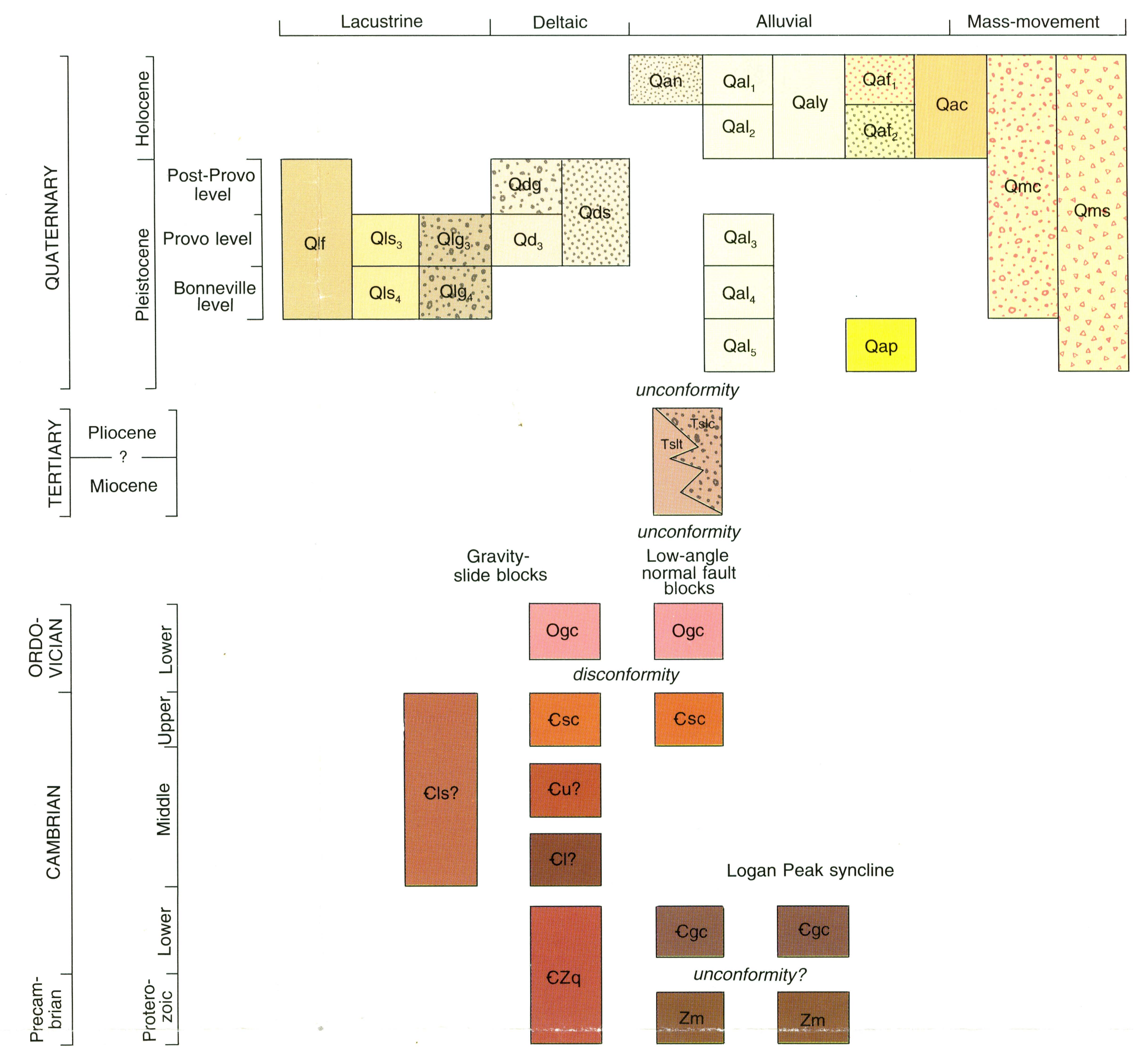
Spring

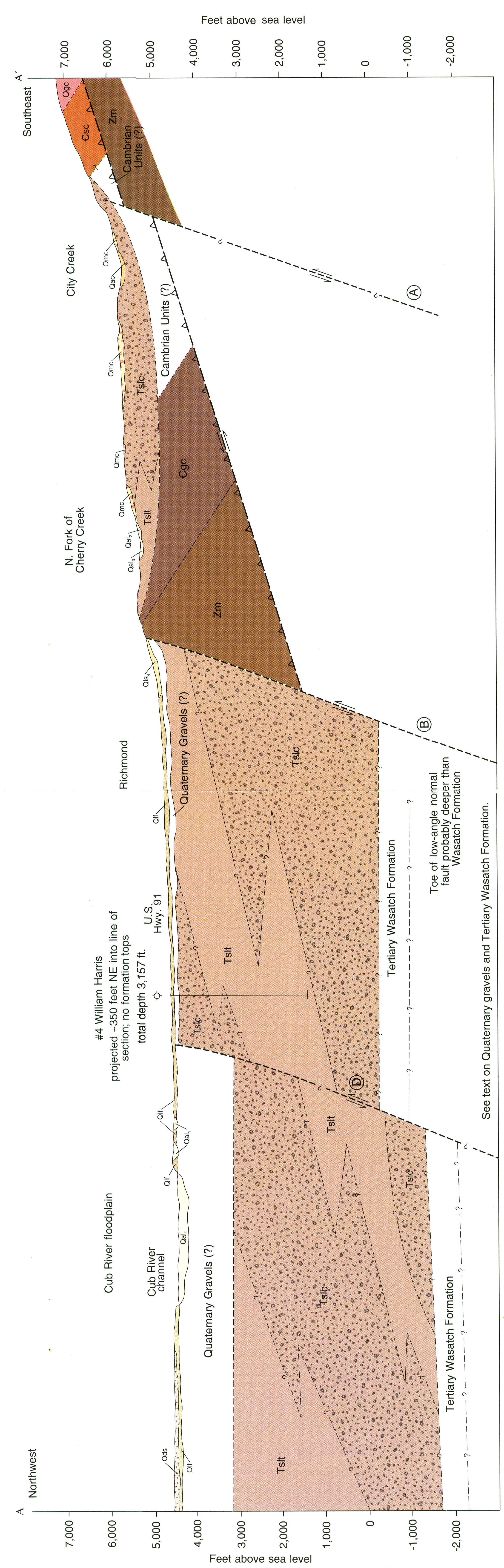
Gravel pit - *larger pits have hachured outlines; numbers correspond to those in table 2*

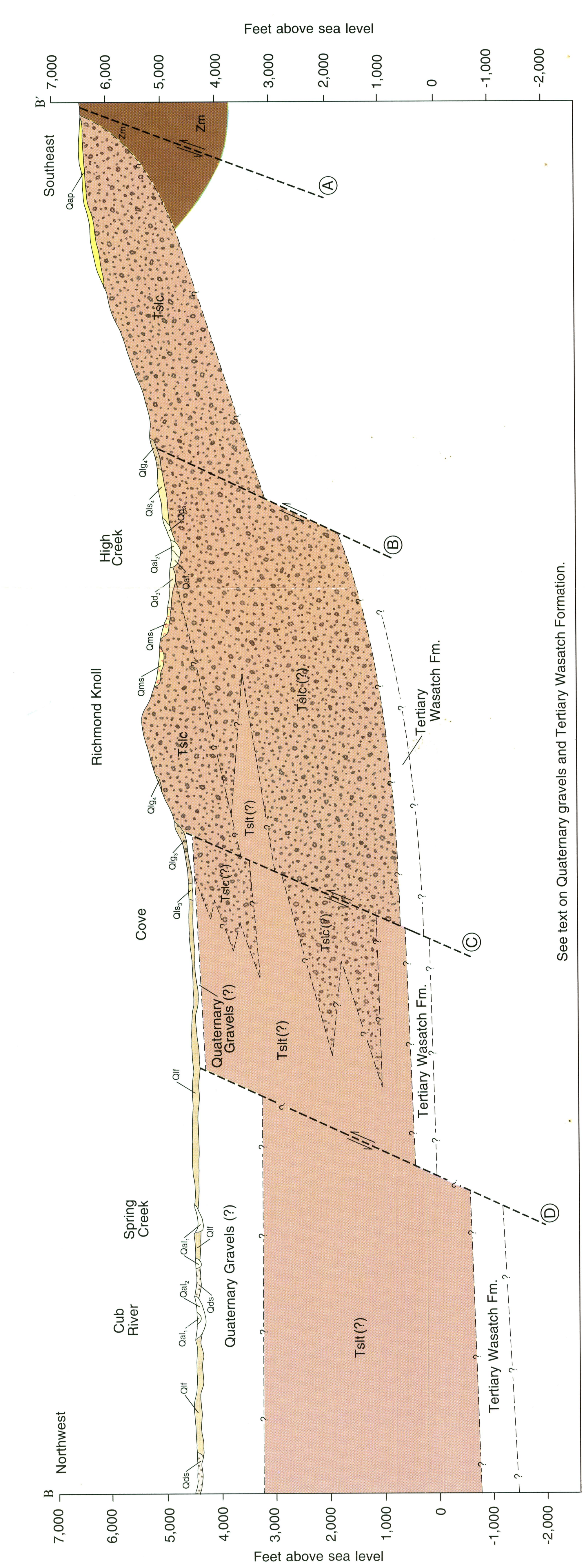
Line of cross section

Oil and gas exploration well - *dry hole, abandoned*

CORRELATION OF MAP UNITS







		FORMATION		SYMBOL	EXPOSED THICKNESS in feet (meters)	LITHOLOGY	COMMENTS
Tertiary	Miocene-Pliocene	Salt Lake Formation	conglomerate	Tslc	~700 (213 m)		
			tuffaceous rocks	Tslt	~500 (152 m)		Unconformity
Ordovician	Lower	Garden City Formation		Ogc	1,405 (428 m)		Brecciation; Disconformity
Cam-brian	Upper	St. Charles Formation		Ꞓsc	1,015 (309 m)		Worm Creek member
							Low-angle normal fault
Cambrian	Lower	Geertsen Canyon Quartzite		Ꞓgc	2,500 (762 m)		Unconformity (?)
Precambrian	Proterozoic	Mutual Formation		Zm	3,000 (914 m)		Base not exposed

Pre-Tertiary stratigraphy adapted from Mendenhall (1975) and Galloway (1970).