Hurlow

GROUND-WATER RESOURCES, NORTHERN WASATCH RANGE, EASTERN BOX ELDER COUNTY, UTAH

UGS Circular 101

PRELIMINARY HYDROGEOLOGIC FRAMEWORK CHARACTERIZATION -- GROUND-WATER RESOURCES ALONG THE WESTERN SIDE OF THE NORTHERN WASATCH RANGE, EASTERN BOX ELDER COUNTY, UTAH

by

Hugh A. Hurlow

View to the north of the Wellsville Mountains and Brigham City.
Maximum vertical relief of the Wellsville Mountains is about 4,500 feet (1,373 m).

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UTAH GEOLOGICAL SURVEY
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CONTENTS

TABLES

ILLUSTRATIONS

APPENDICES

PRELIMINARY HYDROGEOLOGIC FRAMEWORK CHARACTERIZATION – GROUND-WATER RESOURCES ALONG THE WESTERN SIDE OF THE NORTHERN WASATCH RANGE, EASTERN BOX ELDER COUNTY, UTAH

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Hugh A. Hurlow
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ABSTRACT

The northern Wasatch Range is bounded on the west by the Wasatch fault zone, a system of normal faults that forms the abrupt topographic escarpment and geologic discontinuity that marks the range front. The northern part of the northern Wasatch Range, the Wellsville Mountains, consists mainly of a thick section of quartzite overlain by an even thicker sequence of limestone, all Paleozoic in age. The southern part of the study area, here informally designated the Willard mountains, is predominantly Proterozoic quartzite and metamorphosed granitic rock overlain by Cambrian quartzite and limestone. Layering in sedimentary formations throughout the study area is chiefly tilted to the northeast, and the age of exposed formations generally decreases to the north.

All bedrock formations in the study area are well cemented, so their hydraulic conductivity is secondary and is derived from fractures, predominantly joints. Proterozoic to Cambrian quartzite and dolomite formations have the highest fracture density and cleanest joint surfaces, likely resulting in relatively high hydraulic conductivity. Joint density in the limestone formations is variable, and joint surfaces in these units are commonly mineralized. The best prospective aquifers are formations having high fracture density, where they are cut by faults and/or overlain by a unit with lower hydraulic conductivity. The Tintic Quartzite, Geertsen Canyon Quartzite, Blacksmith Formation, and Nounan Limestone, all Cambrian, locally meet these criteria.

Public-supply springs in the study area can be classified as either fracture or compound fracture-contact springs. Several public-supply springs occur in canyon bottoms where a northeast-striking fault juxtaposes a more permeable unit to the southeast against a less permeable unit to the northwest, forcing ground water to the surface. The faults strike into the topographically high parts of the ranges, perhaps providing high-hydraulic conductivity conduits between areas receiving high snowfall and the springs.

Based solely on geologic criteria, Calls Fort and Cottonwood Canyons in the Wellsville Mountains provide the most favorable potential well sites, whereas sites north of Willard Canyon and in Perry Basin (both in the Willard mountains), Flat Bottom and Coldwater Canyons (Wellsville Mountains), and along the western boundary of the Wellsville Mountains north of Brigham City are also favorable but have potential drawbacks.

INTRODUCTION

Bedrock in the northern Wasatch Range in eastern Box Elder County, Utah, will likely become an important source of culinary water as population growth and development along the Wasatch Front continue. The geology of the range strongly influences the occurrence and movement of ground water in bedrock, so describing the lithology and structure of rocks in these mountains is an important first step in evaluating their water resources.

This report summarizes the bedrock geology of the western part of the northern Wasatch Range in eastern Box Elder County, Utah (figure 1), and its relation to ground-water resources. The southern part of the northern Wasatch Range is herein informally designated the Willard mountains; the northern part of the northern Wasatch Range is the Wellsville Mountains (Stokes, 1977). Box Elder Canyon is the boundary between these mountains (figure 1). The work was performed at the request of the Bear River Water Conservancy District and the Utah Division of Water Resources, and represents a preliminary step in the evaluation of ground-water resources in bedrock and their potential development in eastern Box Elder County.

The primary products of this report are 17 new geologic cross sections with corresponding location maps (appendix A) that show the geology near important public-supply springs and wells, an explanation of geologic units depicted on the cross sections and location maps (appendix B), a stratigraphic correlation chart (appendix C) showing the names and temporal relations among geologic units, and a table (appendix D) summarizing the stratigraphy, lithology, and fracture characteristics of bedrock formations in the study area. The cross sections were constructed by the author directly from published geologic maps (except in part of the southern Wellsville Mountains, in which some unpublished mapping was

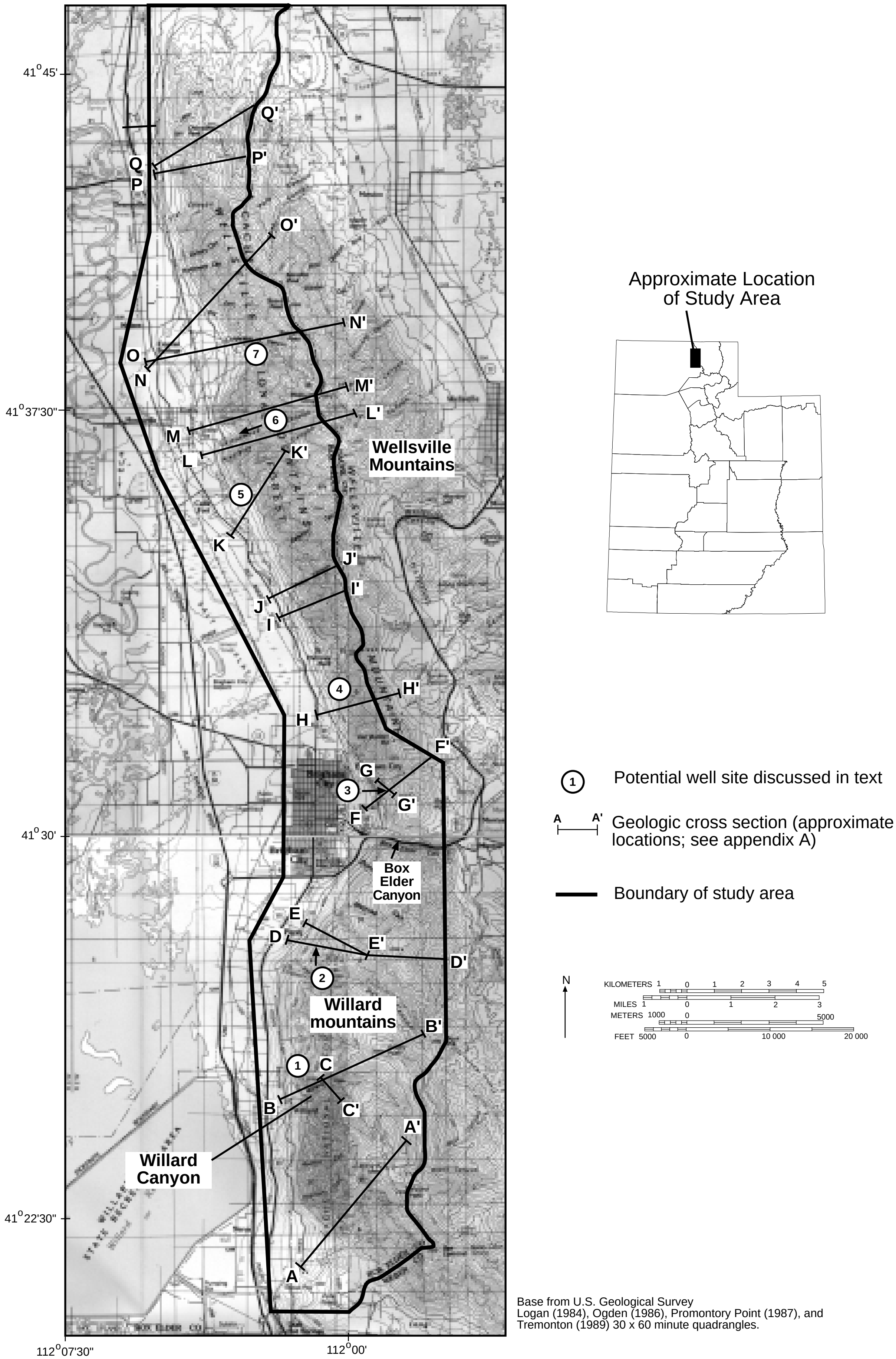

Figure 1. *Generalized location map of northern Wasatch Range, including locations of geologic cross sections in appendix A and potential well sites discussed in text.*

used; see appendix A), but in different locations than the cross sections accompanying the published maps. The new cross sections also employ structural data, principally strikes and dips of bedding, collected by the author. Geologic units in the new cross sections are consistent with those of the corresponding geologic maps, but the designations and symbols for geologic units differ slightly among the maps, which were published at different times by various authors and institutions. Consequently, the names and symbols of some geologic units vary among cross sections.

GEOLOGIC HISTORY

The structural architecture of the western part of the northern Wasatch Range results from a protracted evolution spanning over three billion years of geologic time (Hintze, 1988). Bedrock formations in the study area are predominantly Proterozoic and Paleozoic in age (figure 2; appendices B, C, and D). Strata are tilted to the northeast, and progressively younger units are exposed from south to north. Numerous folds and faults deform these rocks, and the range front is bounded by the Wasatch fault zone, which uplifts the Willard and Wellsville Mountains.

The oldest rock unit in the study area is the Farmington Canyon Complex, which consists of 1.8 Ga (billion years old) granitic rocks intruding a sequence of 2.8 to 3.6 Ga metamorphosed (recrystallized) sedimentary and volcanic rocks (Bryant, 1988). A sequence of Proterozoic to Cambrian quartzite and shale (deposited as marine sand, silt, and mud) over 23,000 feet (7,215 m) thick was deposited on the Farmington Canyon Complex in response to rifting of the North American continental crust and formation of a wide ocean basin. The eastern margin of the rifted area lay approximately along the longitude of the Wasatch Range. Areas west of the rift margin subsided slowly, creating an ocean basin in which very thick sequences of carbonate strata accumulated during Cambrian through Pennsylvanian time. Subsidence became more localized and rapid during Permian time in western Utah, resulting in deposition of the Oquirrh Group, a sequence of interbedded limestone and sandstone that is up to 25,000 feet (7,620 m) thick in central Utah (Hintze, 1988). Marine and continental sedimentation continued through Mesozoic time, but these rocks have been eroded from the study area.

During Cretaceous to Eocene time, the continental crust of western North America experienced compression due to plate tectonic processes to the west. This compression produced large folds and a series of thrust faults which collectively transported thick sections of rock about 100 miles (160 km) from west to east (Royse, 1993). The study area contains one major thrust fault, the Willard thrust (Crittenden and Sorensen, 1985a and 1985b). The Willard thrust juxtaposes sedimentary rocks of similar age and lithology but very different thickness. For example, the Geertsen Canyon Quartzite above the Willard thrust (3,900 to 4,500 feet [1,189-1,372 m] thick)

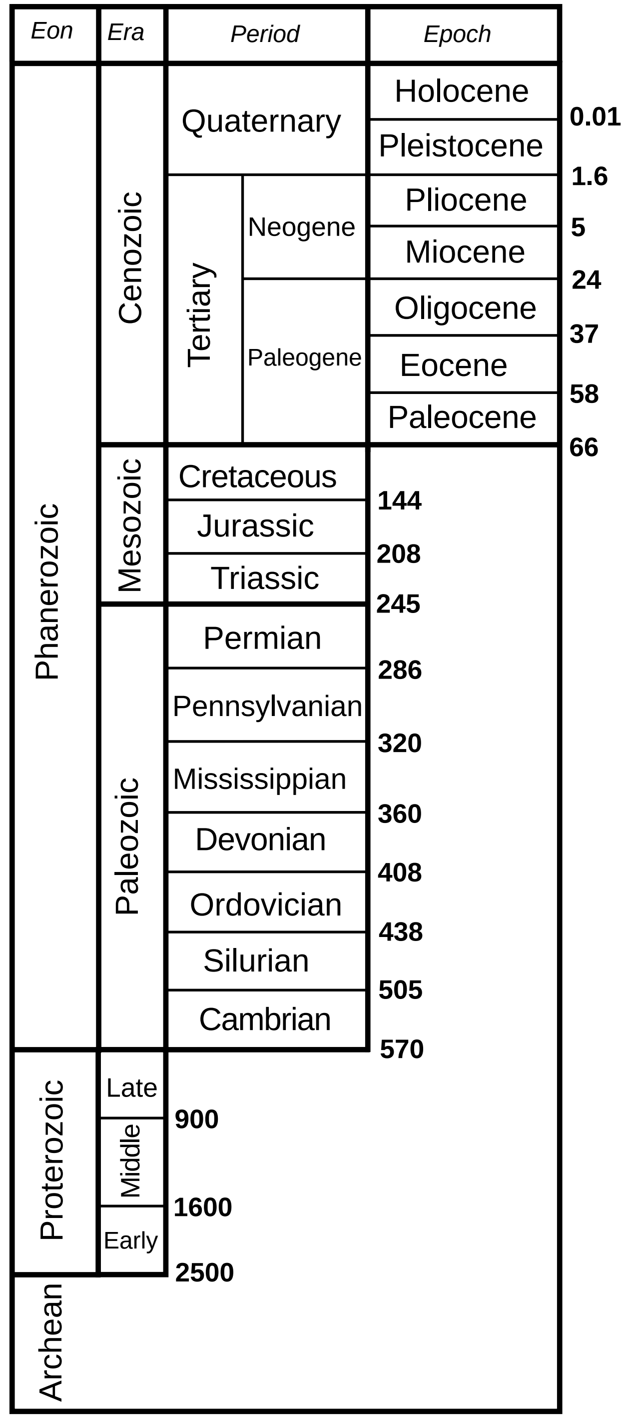

Figure 2. *Geologic time scale, with dates in millions of years before present. Holocene-Pleistocene boundary is 10,000 years before present.*

and the Cambrian Tintic Quartzite (1,200 to 1,400 feet [366-427 m] thick) below the Willard thrust are the same age and have similar compositions, but the Geertsen Canyon Quartzite was deposited west of its present location, where subsidence of the ocean basin was greater and therefore more sediment could accumulate. The Tintic Quartzite in the Willard mountains is closer to its original site of deposition, but has been transported eastward on thrust faults located below the surface.

The geologic setting of western North America changed greatly after Eocene time, and was characterized by coeval volcanism and rifting (normal faulting). The Wasatch fault zone is a world-class example of a large normal fault in continental crust. Pleistocene time was characterized by a series of alpine glaciation events and, in latest Pleistocene time, Lake Bonneville, which covered most of western Utah. The flat benches along the western base of the Wasatch Range are remnants of Lake Bonneville shorelines, and the largest gravel deposits along the range front formed in delta environments where streams, such as Box Elder Creek, dumped their sediment load into the lake.

HYDROGEOLOGIC FRAMEWORK

Introduction

The bedrock hydrogeology of the Willard and Wellsville Mountains has not been studied in detail and few data exist, so this report relies on general principles to qualitatively predict ground-water behavior. Recharge to bedrock is likely derived chiefly from snowmelt at high elevations and, to a lesser degree, intense rainstorms. Average annual precipitation and snowfall vary within the study area, with maximum values of 40 to 49.9 inches (15.8-19.7 cm) at the highest elevations (Ashcroft and others, 1992). Precipitation increases with elevation, and generally decreases from southeast to northwest; the northwestern Wellsville Mountains receive 20 to 39.9 inches (7.9-15.7 cm) annually (Ashcroft and others, 1992). The range crest defines a surface-water drainage divide, but the position of the ground-water divide is uncertain and may be influenced by the structure of bedrock units.

Geologic Influences on Ground-Water Occurrence and Movement

Lithology and Stratigraphy

The lithology of a rock unit is its composition and internal textures, such as grain size and bedding characteristics, and stratigraphy refers to the vertical succession of lithologically defined rock formations. These two characteristics strongly influence the hydrogeology of bedrock masses in the manners summarized below.

In the study area, all sedimentary bedrock units are highly cemented, so their primary porosity and permeability features are likely filled or disconnected, and therefore do not accommodate movement of ground water. The only igneous formation in the study area, the Farmington Canyon Complex, is chiefly metamorphosed granitic rock that contains no significant primary porosity. As a result, ground water in bedrock in the study area likely moves through secondary permeability features such as joints and faults. All of these rock units experienced approximately the same stress history during the deformation (faulting and folding) events outlined in the Geologic History section, but their physical response to this stress varied according to lithology. Strongly cemented quartzite formations, such as the Cambrian Tintic Quartzite, were densely jointed and cut by discrete faults, whereas softer units with greater clay contents deformed in a more plastic style, with fewer discrete joints or faults (figure 3A and appendix D). Limestone units responded according to their composition and cementation; joint density generally increases with greater degree of cementation, lower clay content, and thinner individual beds. Thus, some formations are distinctly better potential aquifers than others, and some are confining units.

The lithologic succession (stratigraphy) also influences the occurrence of ground water. Buried formations with high fracture density overlain by more shaly, less densely fractured formations are potential confined aquifers, for example: the Cambrian Tintic Quartzite overlain by the Cambrian Ophir Formation (figure 3A); the Cambrian Geertsen Canyon Quartzite below the Cambrian Langston Formation (figure 3B); dolomite of the Cambrian Blacksmith Formation below the Hodges Shale member of the Bloomington Formation; and the Cambrian Nounan Limestone below the lower member of the Cambrian St. Charles Formation. The thick sequence of Proterozoic to Cambrian quartzite is characterized by very high fracture density, and these units are also good potential aquifers (figure 4). The middle Cambrian through Silurian limestone formations, which are moderately to highly fractured with few significant confining layers, are also potentially a large, moderately transmissive aquifer.

Joints and Faults

Joints are planar to gently curved breaks (fractures) in rock along which no relative movement has occurred. Joints provide important pathways for flow of ground water. The characteristics of joint systems that most significantly affect ground water are density, aperture, and connectivity. Joint density is the area of joints per volume of rock, expressed in ft^2/ft^3 (or m^2/m^3), or the total joint length on a two-dimensional outcrop face (ft/ft^2, or m/m^2). Aperture is the width of open space between joint surfaces, and it is usually 1 millimeter or less in rocks below the weathered zone. Joint aperture is significantly reduced or eliminated by mineralization of joint faces. Connectivity refers to the degree of interconnection of individual joints or joint sets throughout a rock mass. The hydraulic conductivity of a jointed rock mass increases with greater joint density, aperture, and connectivity.

Appendix D presents preliminary, qualitative evaluations of joint characteristics for each formation in the study area. This information helps to determine the relative degree of hydraulic conductivity of the formations. The evaluations are based on a limited number of observations, but likely represent average joint characteristics

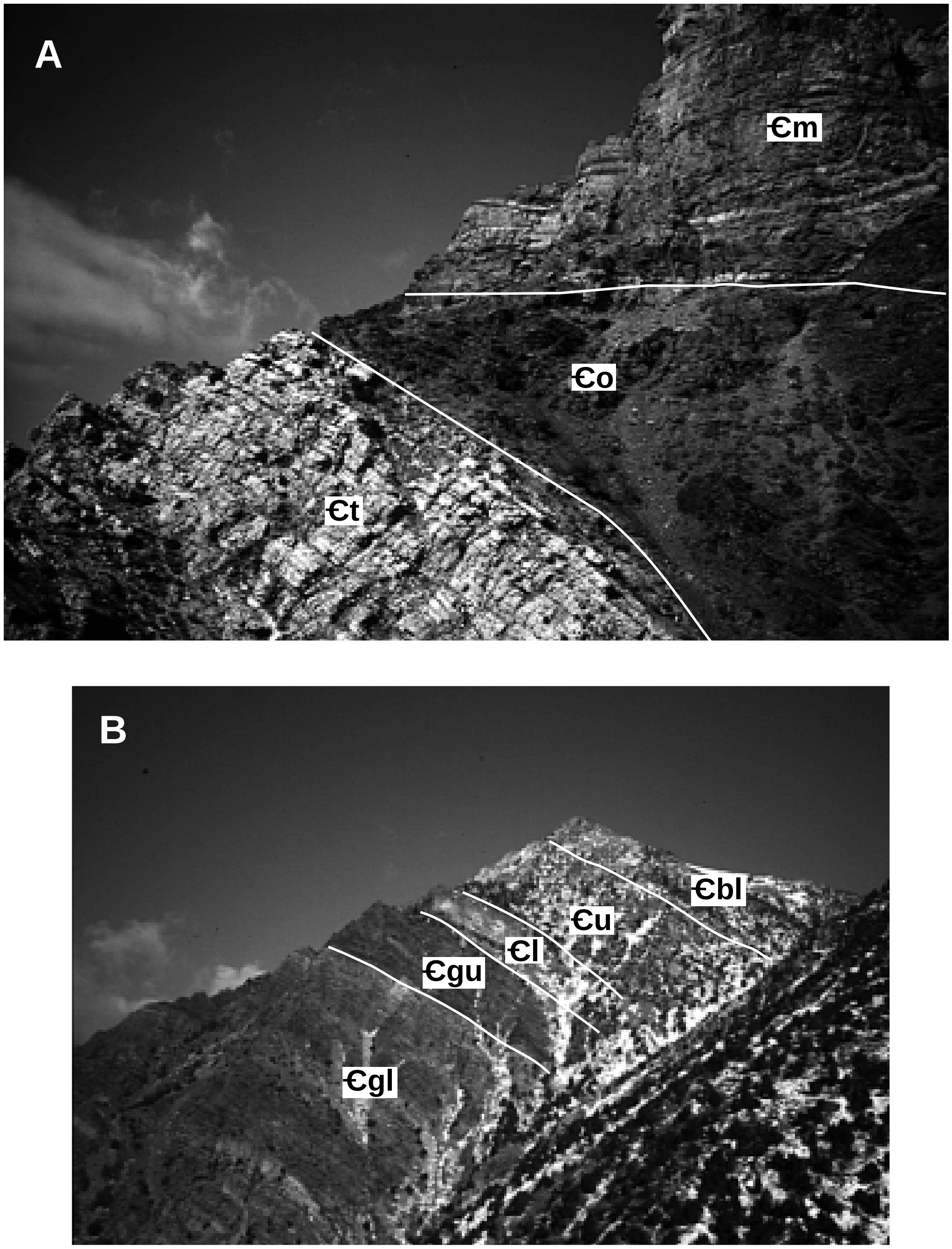

Figure 3. *Densely jointed Cambrian quartzite formations overlain by less permeable formations. These examples are exposed, but where the sequences are buried the quartzite formations are good potential aquifers. (A) Cambrian Tintic Quartzite (Єt) overlain by Cambrian Ophir Shale (Єo) and Cambrian Maxfield Limestone (Єm), north wall of Willard Canyon, Willard mountains. The Єo - Єt contact is a ductile fault zone in which Єo is strongly deformed, explaining its drastic thickness change. Bedding in Єt dips to the northeast (right), and a prominent joint set dips steeply to the southwest (left). (B) Cambrian Geertsen Canyon Quartzite (Єgl and Єgu) overlain by Cambrian Langston Formation (Єl) in the Wellsville Mountains. Єu is Ute Formation and Єbl is Blacksmith Formation. View is to the north from the ridge north of Kotter Canyon. Vertical relief is about 2,000 feet (610 m).*

for each formation. Joint characteristics in a particular formation may vary with location, and joint density may increase considerably near faults (Caine and others, 1996). Most formations in the study area contain two to four joint sets (preferred joint orientations), including bedding planes in sedimentary rocks (figure 5). Typically, two steeply inclined, approximately perpendicular joint sets intersect joints formed along bedding planes, providing a high degree of connectivity within the joint system. Thus, thinly bedded formations may have higher connectivity than thick-bedded formations because they have a greater density of bedding-plane joints. Mineral deposits on joint surfaces are most common in the limestone formations but are not pervasive in the study area.

Figure 4. Densely jointed orthoquartzite of the Proterozoic Facer Formation, on ridge west of Grizzly Peak, north of Willard Canyon, Willard mountains. Hammer is 11 inches (23 cm) long.

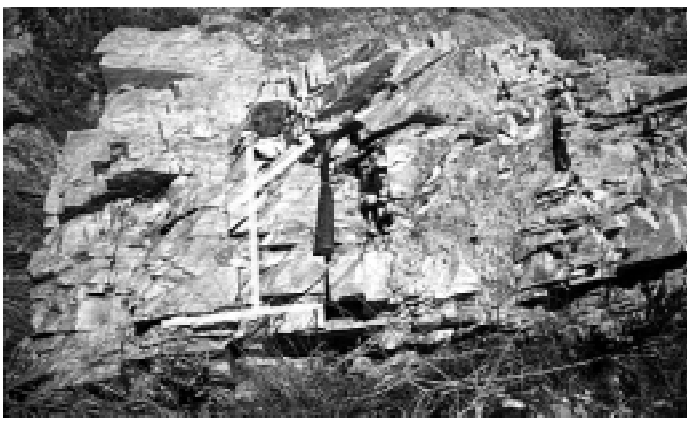

Figure 5. Joint sets in quartzite of the Proterozoic Facer Formation, on ridge west of Grizzly Peak, north of Willard Canyon, Willard mountains. Approximately horizontal white line shows orientation of bedding-plane joint set. Three other joint sets are present: a vertical set, a set that dips to the left (both shown by white lines), and a set parallel to the outcrop face. Hammer is 11 inches (23 cm) long.

Faults are breaks (fractures) that have accommodated relative movement in rock masses. The internal structure of faults and their hydrogeologic characteristics are more complicated than those of joints. Faults in highly cemented rocks provide ground-water conduits for flow parallel to the fault plane, but may act as barriers to fluid flow if abundant fine-grained material formed within the fault zone during movement (Caine and others, 1996). Faults may also influence ground-water movement by juxtaposing geologic formations with different hydraulic conductivities (Ashland and others, 1996; Caine and others, 1996).

Regional Structure

The large-scale geometry of rock formations and the locations of faults and folds also influence ground water. Compositional (sedimentary) layering may influence ground-water flow by defining discrete slabs of material with high (or low) hydraulic conductivity, primarily due to variations in fracture density. Regional-scale ground-water flow rates parallel to layering may be greater than those perpendicular to layering. The regional northeast tilt of the compositional layering in the study area may, therefore, direct ground-water flow preferentially to the northeast, potentially causing the ground-water divide to be west of the surface-drainage divide. This suggestion has not been tested.

The Wasatch fault zone bounds the western front of the entire Wasatch Range, including the Willard and Wellsville Mountains, and is responsible for the major topographic and geologic discontinuities there. Most of the cross sections (appendix A) illustrate the Wasatch fault zone as a single strand, but this is a simplification because the fault is largely covered by Quaternary sediments, so the details of its geometry are unknown. The Wasatch fault zone juxtaposes bedrock against unconsolidated to weakly consolidated Quaternary and Tertiary sediments that are up to 4,500 feet (1,372 m) thick (Jensen and King, 1995). Numerous fault strands likely cut the bedrock, providing conductive pathways for ground-water flow parallel to the range front and adding uncertainty to illustrations of bedrock geometry below Quaternary sediments. Thus, the hydrogeology near the range front is likely complex and difficult to predict.

The Willard and Wellsville Mountains are cut by numerous faults that strike northeast, perpendicular to the strike of the sedimentary layering and the Wasatch fault zone. These faults likely provide high-conductivity pathways for ground-water flow from the areas of main recharge at high elevations to the western range front. Prominent examples include: the Wellsville Mountains transverse fault, near Miners Hollow in the Brigham City quadrangle (Jensen and King, 1995); faults in and adjacent to Calls Fort, Yates, and Baker Canyons, all in the Brigham City quadrangle (Jensen and King, 1995); and faults near Box Elder Peak and Big Canyon in the Honeyville quadrangle (Oviatt, 1986). The locations of Yates Canyon Spring, Baker Spring, and Honeyville Springs are likely influenced by northeast-striking faults (see below).

Geology of Springs

This section presents brief descriptions of the geologic setting of selected public-supply springs, and one spring whose rights are privately held, to define the types of springs present in the study area and to illustrate the possible geologic influences on their locations. The inferences about the relation between geology and spring hydrology provided below are based solely on geologic observations and have not been hydrologically tested. Cross sections in appendix A not referenced in this section are discussed in later sections.

According to Baker and Foulk (1975), springs may be classified according to their geologic setting as artesian, contact, depression, fracture, geyser, perched, seep, or tubular. Their terminology is adopted here, with the provision that more complicated geologic settings and, therefore, multiple-classification springs are possible.

Maple Grove Spring

Maple Grove Spring (cross section A-A´, figures A.2 and A.3) is located at the contact between Quaternary alluvial-fan deposits and deposits of Lake Bonneville. The latter are presumably less permeable, forcing ground water to the surface. Personius (1990) notes that Lake Bonneville sediments are commonly partially or entirely cemented. The trace of the Wasatch fault zone is about 350 feet (107 m) northeast of the spring. Although it is uncertain whether this or other related, buried fault splays play any role in localizing the spring, Lowe and others (1996) believe that this and other nearby springs are associated with northwestward flow of ground water parallel to the Wasatch fault zone. The source of the spring water is likely ground water leaking from fractures in the Farmington Canyon Complex in the footwall of the Wasatch fault zone, because the wash above which the spring is located flows intermittently. Maple Grove Spring can be classified as a contact spring.

Willard City Spring

Willard City Spring (cross section C-C´, figures A.4 and A.6) is on the south wall of Willard Canyon, about 400 feet (122 m) above Willard Creek. Cross section B-B´ (figures A.4 and A.5), located just north of Willard Canyon, is also useful in understanding the geology in the vicinity of the spring. The spring emanates from the lower part of the Cambrian Maxfield Limestone, which overlies the less permeable Cambrian Ophir shale. Both units dip gently southeast, and the spring is likely a contact spring, although the difference in hydraulic conductivity between the two units may be due primarily to different fracture densities.

Basin Spring

Basin Spring (cross section D-D´, figures A.7 and A.8) emanates about 300 feet (91 m) above the floor of Perry Basin, from the Proterozoic Papoose Creek Formation above its contact with shale of the Kelley Canyon Formation. The Papoose Creek Formation consists of interlayered quartzite and shale. Both rock types are fractured, but the quartzite has a higher fracture density and many fractures in the quartzite terminate at shale contacts. Bedrock is not exposed near the spring, so it could not be determined whether the spring emanates from quartzite or shale. Basin Spring is likely a compound fracture-contact spring, with less permeable shale layers in the Papoose Creek and Kelley Canyon Formations forcing ground water to the surface.

Perry Springs

These unnamed springs (cross section E-E´, figures A.7 and A.9), used by Perry City, are located within Quaternary sediments along shorelines of Lake Bonneville (Personius, 1990). They are contact springs relative to the Quaternary deposits, but their relation to bedrock geology is uncertain. Bedrock below the Quaternary deposits is likely the Proterozoic Papoose Creek Formation (Crittenden and Sorensen, 1985a). Strands of the Wasatch fault zone may also cut the bedrock and affect ground-water movement in this area.

Flat Bottom Canyon

Two springs are present along the north wall of Flat Bottom Canyon near its mouth (cross sections F-F´ and G-G´, figures A.10, A.11, and A.12), which lies at an abrupt topographic escarpment formed by the Wasatch fault zone. The springs emanate from densely jointed Cambrian Geertsen Canyon Quartzite and are clearly fracture springs. The springs are located above the Box Elder thrust, whose trace is concealed by Quaternary sediments in and immediately north of the canyon (Sorensen and Crittenden, 1976). The Box Elder thrust moved Geertsen Canyon Quartzite westward above Proterozoic quartzite and shale formations (Sorensen and Crittenden, 1976; Crittenden and Sorensen, 1985a). The thrust surface may be a low-hydraulic conductivity barrier, causing the ground water to emerge along the canyon wall rather than in the canyon bottom or along the range front.

Baker Spring

Baker Spring (cross section I-I´, figures A.15 and A.16) emanates from the Cambrian Nounan Limestone, just above its faulted contact with the Cambrian Calls Fort Shale Member of the Bloomington Formation. The Nounan has higher fracture density, and the Calls Fort Shale likely acts as a barrier which forces ground water to the surface. Baker Spring can be classified as a compound fracture-contact spring.

Yates Canyon Spring

Yates Canyon Spring (cross section J-J´, figures A.15 and A.17) is in the canyon bottom along a northeast-striking, steeply dipping fault that juxtaposes the very densely jointed Cambrian Blacksmith Formation to the southeast against the weakly jointed Langston Formation to the northwest. Although different geologic formations are present, the structural setting of Yates Canyon Spring is similar to that of Baker Spring. Yates Canyon Spring can be classified as a compound fracture-contact spring.

Honeyville Springs

Honeyville Springs (cross section L-L´, figures A.20 and A.21) emanate from or near a northeast-striking, steeply dipping fault that juxtaposes the more permeable Cambrian Nounan Limestone and the less permeable Calls Fort Shale Member of the Cambrian Bloomington Formation. Both units are highly cemented, and the Nounan likely derives its higher hydraulic conductivity from greater fracture density. The spring occurs along a topographic bench formed by the Bonneville-stage shoreline of Lake Bonneville (Oviatt, 1986; Personius, 1990). Honeyville Springs are, therefore, compound fracture-contact springs.

Bluerock Spring

This privately owned spring (cross section M-M´, figures A.20 and A.22) emanates from the lower part of the upper member of the St. Charles Formation, which consists of massive, moderately fractured limestone. The lower member of the St. Charles consists of interbedded shale and limestone, is likely less permeable than the upper member, and apparently forces ground water to the surface. The spring is located uphill from the trace of the Wasatch fault zone and a topographic bench associated with a Provo-stage shoreline of Lake Bonneville. The spring is not likely related to these features, and can be classified as a contact spring.

Coldwater Spring

Coldwater Spring (cross section N-N´, figures A.23 and A.24) is in Coldwater Canyon, along a northeast-striking fault that juxtaposes the upper (Dwcu, northwest of drainage) and middle (Dwcm, southeast of drainage) members of the Devonian Water Canyon Formation (Oviatt, 1986). The fault and depositional contacts combine to make a triangle of Dwcu in map view, with the spring at the southwest apex. Apparently, Dwcm is less permeable and forms a barrier which forces ground water to the surface, and the fault provides a conduit for flow to and localization of the spring. The fault projects into the higher part of the range, where it may collect greater amounts of snowmelt than are available along the range front. Dwcm is interbedded limestone and sandstone and appears less densely fractured and, therefore, less permeable than the hard dolomite of Dwcu. This interpretation is consistent with the setting of an unnamed spring in the next canyon north, which emerges in the lowermost part of Dwcu (figure A.23), also indicating that Dwcm is less permeable and forces ground water to the surface. Based on these observations, Coldwater Spring is a compound contact-fracture spring, whereas the spring to the north is a contact spring.

Garland and Gardner Springs

Garland Spring and Gardner Spring (cross sections P-P´ and Q-Q´, respectively, figures A.27, A.28, and A.29) emanate from Quaternary gravel deposited in Lake Bonneville. They are located below isolated outcrops of Pennsylvanian and Mississippian limestones, respectively, that are bounded on the west by the Wasatch fault zone. The spring water may have multiple sources, including: (1) bedrock immediately west of the springs, (2) water concentrated in alluvial-fan sediments in and west of South Maple Canyon and which surfaces at the contact between the alluvial-fan and lake sediments, and (3) water rising along the fault plane. Garland and Gardner Springs may be compound fracture-contact springs.

Geology of Bedrock Wells

There is very limited information on bedrock hydrogeology in the study area. Only one public-supply well currently produces water from bedrock, and a non-production geothermal test well was drilled near Crystal Hot Springs north of Honeyville. This section briefly describes these wells.

Corinne City Wells

Corinne City has drilled two water-supply wells near the mouth of Yates Canyon, north of Brigham City (cross section J-J´, figures A.15 and A.17). Corinne City well number 1, drilled in 1977 and 1978 but now abandoned, penetrates unconsolidated sediments to a depth of 265 feet (81 m); limestone and dolomite between 265 and 370 feet (81-113 m); no record between 371 and 480 feet; and white, purple, and brown quartzite between 481 and 509 feet (147-155 m) (Utah Division of Water Resources unpublished data). The entire well was cased, and the casing was perforated between 451 and 480 feet (137-146 m). The well yielded about 40 gallons per minute (2.5 L/sec) during a preliminary bailer test (Utah Department of Water Rights data). Based on descriptions of the well cuttings provided by geologists of the Utah Division of Water Resources, the limestone and dolomite are interpreted here as the lower member of the Cambrian Langston Formation, and the quartzite is interpreted as the upper member of the Cambrian Geertsen Canyon Quartzite.

Corinne City well number 2, drilled in 1989, is located about 250 feet (76 m) east-northeast of well number 1. This well penetrates 150 feet (46 m) of unconsolidated deposits; brown, gray, purple, and white quartzite and sandstone between 150 and 310 feet (46-94 m); and white quartzite and sandstone between 310 and 442 feet (94-135 m) (Utah Division of Water Resources unpublished data). The well yielded up to 363 gallons per minute (23 L/sec) during a development test (C. Wight, Hansen and Associates, written communication, 1998). The multicolored and white quartzite and sandstone are interpreted here as the upper and lower members, respectively, of the Cambrian Geertsen Canyon Quartzite. These interpretations require a west-side-down fault, likely a strand of the Wasatch fault zone, between the two wells (cross section J-J´, figures A.15 and A.17), as noted by the geologists of the Division of Water Resources who originally examined the cuttings. This fault may strongly influence ground-water flow to the wells.

Crystal Springs Well

A geothermal test well near Crystal Hot Springs was completed in 1979 as part of a joint study of geothermal resources in northern Utah by the U.S. Department of Energy/Division of Geothermal Energy and the Utah Geological Survey (Murphy and Gwynn, 1979). The well is south of Crystal Springs and west of a topographic escarpment characterized by outcrops of interbedded limestone and sandstone of the Permian Oquirrh Group, mantled by thin Quaternary alluvium and lake sediments (cross sections N-N´ and O-O´, figures A.23 through A.26). Personius (1990) interpreted the topographic salient east of the well, known as Madsen spur, as a structural salient related to a segment boundary along the Wasatch fault zone. Alternatively, Oviatt (1986) interpreted Madsen spur as a very large mass-movement deposit derived from the range front.

The well penetrated 215 feet (66 m) of unconsolidated to weakly cemented sand, gravel, and clay, then encountered fractured sandstone and limestone, similar to the exposures east of the well, to its final depth of 280 feet (85 m). The significant difference in thickness of unconsolidated deposits on either side of the escarpment suggests that it is bounded by a down-to-the-west normal fault, the likely source of the thermal waters and part of the Wasatch fault zone (Murphy and Gwynn, 1979). The well produced 60 to 125 gallons per minute (227-473 L/min) during drilling, but production from the bedrock alone was not specified. This well, therefore, provides no information about the transmissivity of the Oquirrh Group but indicates that fault zones in this formation may be highly permeable.

DISCUSSION: POTENTIAL WELL SITES

This section describes locations in the study area that may be suitable for public water-supply wells. These suggestions are preliminary and are based solely on geologic characteristics; water rights, environmental, and logistical factors were not considered. Any prospective well site should receive a more detailed site-specific geologic study than is presented here. Figure 1 and appendix A show the site locations.

The following geologic relations were considered favorable to high well yield: (1) the target formation likely has high hydraulic conductivity, as determined from fracture characteristics and the presence of springs in the study area; (2) the target formation is overlain by a unit with low hydraulic conductivity (confining unit), providing confined conditions and protection from surface contamination; (3) location in or near a northeast-striking fault to enhance recharge, as described in the Geology of Springs section; (4) presence of thick (greater than about 50 feet [15 m]), saturated unconsolidated deposits to provide additional recharge to the fractured-bedrock aquifer during times of low runoff (Ashland and others, 1996); and (5) location in a canyon bottom east of the Wasatch fault zone. Wells located along the Wasatch fault zone may benefit from high bedrock hydraulic conductivity related to fracturing, but the detailed structural geometry in and near the fault zone is impossible to predict. Also, the risk of contamination and/or interference with other wells and springs may be high due to localized high hydraulic conductivity parallel to the range front.

Location 1 - North of Willard Canyon

The Cambrian Tintic Quartzite, Ophir Formation, and Maxfield Limestone dip northeast, and project into the subsurface north of Willard Canyon where they are covered by a Quaternary landslide deposit (figure 1; cross section B-B´, figures A.4 and A.5). The Tintic Quartzite is an excellent target due to its high fracture density and location below the Ophir Formation, a confining unit. A well at this site would penetrate landslide material and Ophir Formation before reaching the Tintic Quartzite. The subsurface position of the Tintic Quartzite should be predicted using a structure-contour map based on detailed outcrop observations. The landslide does not appear to be active but its stability should be carefully studied before siting a well in it.

Location 2 - Perry Basin

Perry Basin is underlain by the densely fractured quartzite of the Proterozoic Maple Canyon Formation mantled by thin, unconsolidated deposits of Lake Bonneville (figure 1; cross section D-D´, figures A.7 and A.8). The Maple Canyon Formation is 984 to 1,476 feet (300-450 m) thick (Crittenden and Sorensen, 1985a), dips about 25 degrees east-northeast, and its upper contact follows the basin floor, so a substantial thickness of the formation underlies this site. A well at this site would lack an overlying confining unit.

Location 3 - Flat Bottom Canyon

Flat Bottom Canyon is underlain by a northeast-striking fault that juxtaposes the lower member of the Cambrian Geertsen Canyon Quartzite to the northwest and the Proterozoic Papoose Creek Formation to the southeast (figure 1; cross sections F-F´ and G-G´, figures A.10, A.11, and A.12). Typically, both formations are densely fractured, and joint surfaces lack mineralization (appendix D), likely resulting in high hydraulic conductivity. Bedrock is covered by a thin layer of unconsolidated Lake Bonneville sediments and by sediment eroded from the adjacent canyon walls. A well located at this site would derive water from both quartzite formations and from the fault zone along the canyon bottom, but would lack an overlying confining unit

Location 4 - Kotter Canyon to Hansen Canyon

The Geertsen Canyon Quartzite, an excellent target based on its high fracture density, crops out along the front of the Wellsville Mountains 0.5 to 2 miles (0.8-3.2 km) north of Brigham City. Wells drilled along the range front east of the trace of the Wasatch fault zone would penetrate a substantial thickness of this formation (figure 1; cross section H-H´, figures A.13 and A.14). Several of the canyons in this area are underlain by northeast-striking faults, which likely provide additional recharge. Lack of an overlying confining unit is a potential problem for such sites.

Location 5 - Calls Fort Canyon

Calls Fort Canyon (figure 1; cross section K-K´, figures A.18 and A.19) has numerous geologic conditions favorable to high well yield: (1) the subsurface of the canyon floor contains the low-hydraulic conductivity Langston Formation overlying the high-hydraulic conductivity Geertsen Canyon Quartzite; (2) the entire thickness of the Geertsen Canyon Quartzite is accessible to a well; (3) there are several northeast-striking faults to the east, potentially providing high-hydraulic conductivity pathways to areas of the range receiving high snowfall; and (4) unconsolidated deposits in the canyon bottom may be relatively thick (25 to 50 feet [8-15 m]). A well would penetrate approximately 200 to 300 feet (61-91 m) of overburden (unconsolidated deposits and Langston Formation) before intercepting the Geertsen Canyon Quartzite. Farther northeast up the canyon, densely fractured dolomite of the Cambrian Blacksmith Formation is an excellent secondary target where it underlies the Hodges Shale member of the Cambrian Bloomington Formation.

Location 6 - Cottonwood Canyon

The geologic setting of Cottonwood Canyon (figure 1; between cross sections L-L´ and M-M´, figures A.20, A.21, and A.22) is generally similar to that of Calls Fort Canyon, although younger geologic formations are present. The canyon floor contains relatively thick alluvial-fan deposits, and is underlain by the Cambrian St. Charles Formation overlying the Cambrian Nounan Formation. The lower member of the St. Charles may provide a confining unit above the Nounan, which typically has moderate to high fracture density and which, including upper and lower members, is 1,175 to 1,195 feet (364-388 m) thick (appendix D). Several northeast-striking faults intersect the drainage basin.

Location 7 - Coldwater Canyon

West of Coldwater Springs and east of the Wasatch fault zone (figure 1; cross section N-N´, figures A.23 and A.24), the middle member of the Devonian Water Canyon Formation (Dwcm) crops out and overlies the lower member of the Water Canyon Formation (Dwcl) and the Silurian Laketown Dolomite. Dwcm likely has lower hydraulic conductivity than Dwcl, which is a hard dolomite with moderate joint density, and lower hydraulic conductivity than the Laketown Dolomite. A well that penetrates through Dwcm to Dwcl may receive good yield from Dwcl and from the Laketown. However, there could be interference between such a well and the springs uphill, which are currently utilized for culinary water supply.

SUMMARY

1. The northern Wasatch Range in eastern Box Elder County consists of northeast-tilted Proterozoic through Paleozoic sedimentary rocks and, in the southernmost part of the study area, metamorphosed Proterozoic granitic rocks. Progressively younger rocks are exposed from south to north. During Cretaceous time, the Willard thrust fault transported Proterozoic and younger rocks from about 100 miles (160 km) west to their present longitude, placing them above Cambrian sediments that were deposited on crystalline granitic basement. The Wasatch fault zone cut the region during Tertiary to Holocene time, defining the modern topography. Lake Bonneville, which was present in the region during late Pleistocene time, deposited sediment that mantled the range front, and its shorelines cut numerous topographic benches in the bedrock and lake sediments.

2. Bedrock units possess secondary permeability derived primarily from joints. Units with the highest hydraulic conductivity are probably those with the greatest joint density, especially where two or more joint sets are subvertical and intersect gently dipping bedding-plane joints. Proterozoic quartzite formations and the Cambrian Tintic Quartzite, Geertsen Canyon Quartzite, Blacksmith Formation, and Nounan Limestone are the best prospective aquifers.

3. Public-supply springs in the study area are chiefly compound fracture-contact springs. Typically, springs occur in canyon bottoms where a northeast-striking fault juxtaposes a unit with high hydraulic conductivity on the uphill side against a unit with low hydraulic conductivity on the downhill side. The fault strikes into the topographically high part of the range, and may channel snowmelt to the springs.

4. The geologic setting of several locations in the study area may be favorable for siting public-supply water wells. Geologic characteristics thought to predict good well yield include a highly fractured target formation overlain by a unit with low hydraulic conductivity and/or relatively thick unconsolidated deposits, and northeast-striking faults that connect the site with mountain areas receiving high snowfall. Sites in Calls Fort and Cottonwood Canyons in the Wellsville Mountains meet these criteria well, and sites north of Willard Canyon, in Perry Basin, Flat Bottom and Coldwater Canyons, and along the base of the Wellsville Mountains north of Brigham City partially meet the criteria.

ACKNOWLEDGMENTS

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REFERENCES

Ashcroft, G.L., Jensen, D.T., and Brown, J.L., 1992, Utah Climate: Logan, Utah, Utah Climate Center, 127 p.

Ashland, F.X., Bishop, C.E., Lowe, Mike, and Mayes, B.H., 1996, The geology of the Snyderville basin and its relation to ground-water conditions: Utah Geological Survey Open-File Report 337, 124 p.

Baker, C.H., Jr., and Foulk, D.J., 1975, National water data storage and retrieval system - instructions for preparation and submission of ground-water data: U. S. Geological Survey Open-File Report 75-589, 159 p.

Bryant, Bruce, 1988, Geology of the Farmington Canyon Complex, Wasatch Mountains, Utah: U. S. Geological Survey Professional Paper 1476, 54 p.

Caine, J.S., Evans, J.P., and Forster, C.B., 1996, Fault zone architecture and permeability structure: Geology, v. 24, p. 1025-1028.

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

Crittenden, M.D., Jr., and Sorensen, M.L., 1985b, Geologic map of the North Ogden quadrangle and part of the Ogden and Plain City quadrangles, Box Elder and Weber Counties, Utah: U. S. Geological Survey Miscellaneous Investigations Series Map I-1606, scale 1:24,000.

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

Jensen, M.E., and King, J.K., 1995, Interim geologic map of the Brigham City 7.5-minute quadrangle, Box Elder and Cache Counties, Utah: Utah Geological Survey Open-File Report 315, scale 1:24,000.

Lowe, Mike, Jensen, M.E., Bishop, C.E., and Mayes, B.H., 1996, Protecting Utah's public water supplies -- An example from southeastern Box Elder County: Utah Geological Survey Notes, v. 28, no. 1, p. 2-3.

Murphy, Peter, and Gwynn, J.W., 1979, Geothermal investigations at selected thermal systems of the northern Wasatch Front, Weber and Box Elder Counties, Utah: Utah Geological and Mineral Survey Report of Investigation 141, 50 p.

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

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

Royse, Frank, Jr., 1993, An overview of the geologic structure of the thrust belt in Wyoming, northern Utah, and eastern Idaho, *in* Snoke, A.W., Steidtmann, J.R., and Roberts, S.M., editors, Geology of Wyoming: Geological Survey of Wyoming Memoir No. 5, p. 272-311.

Sorensen, M.L., and Crittenden, M.D., Jr., 1976, Type locality of Walcott's Brigham Formation, Box Elder County, Utah: Utah Geology, v. 3, no. 2, p. 117-121.

Stokes, W.L., 1977, Subdivisions of the major physiographic provinces in Utah: Utah Geology, v. 4, no. 1, p. 1-17.

PREFACE TO APPENDICES

Appendix A includes geologic cross sections, corresponding location maps including sources of geologic information, and an explanation of symbols used in the cross sections and location maps. The location maps are parts of previously published geologic maps, modified locally by unpublished mapping by the author and by M. Jensen (cross sections F-F´ and G-G´, figures A.10 through A.12; cross section H-H´, figures A.13 and A.14). The author also collected supplemental field data, principally strikes and dips of bedding, along each cross section line. Therefore, the cross sections represent the author's interpretation of previously published mapping, supplemented by his field structural data and, in some cases, his unpublished mapping. The cross sections were drawn to show the geologic setting of important public-supply springs and wells, and are in different locations than the cross sections accompanying the previously published maps. Most cross sections and location maps are at 1:24,000 scale, but several were reduced in size to fit them on letter-size pages. The scale of each location map and cross section is noted below the scale bar and, where appropriate, the percent reduction from 1:24,000 scale is noted in the caption.

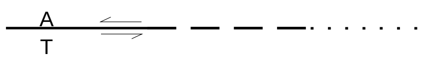
Appendices B and C present explanations and correlation charts, respectively, of geologic units shown on the cross sections of appendix A. Appendices B and C describe only the geologic units shown on the cross sections, but the location maps cover a wider area than the cross section lines, so some geologic units and symbols on the location maps do not appear in appendices B and C. Refer to the published maps cited on the location maps of appendix A for explanations of units and symbols not shown in appendices B and C.

APPENDIX A

Explanation of Symbols used in Location Maps and Cross Sections

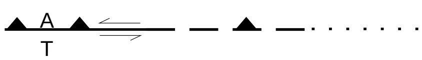
EXPLANATION

Contact. Dashed where approximately located or where subsurface geometry is highly uncertain.

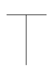


High- to medium-angle normal fault. Dashed where approximately located or where subsurface geometry is highly uncertain; dotted where concealed. Arrows show relative sense of movement in plane of cross section.

For faults with a component of movement out of the plane of cross section, A indicates movement away from observer and T indicates movement toward observer.



Thrust fault. Dashed where approximately located or where subsurface geometry is highly uncertain; dotted where concealed. Teeth on upthrown side. Arrows show sense of relative movement in plane of cross section. For faults with a component of movement out of the plane of cross section, A indicates movement away from observer and T indicates movement toward observer. Some thrust faults have been folded into dips greater than 30 degrees, or rotated so that their present apparent direction and/or sense of motion are the opposite of their original geometry.



Water well.

P Provo-stage shoreline of Lake Bonneville.

B Bonneville-stage shoreline of Lake Bonneville.

Figure A.1. *Explanation of geologic symbols in cross sections and location maps. See appendix B for explanation of geologic units and appendix C for correlation of geologic units.*

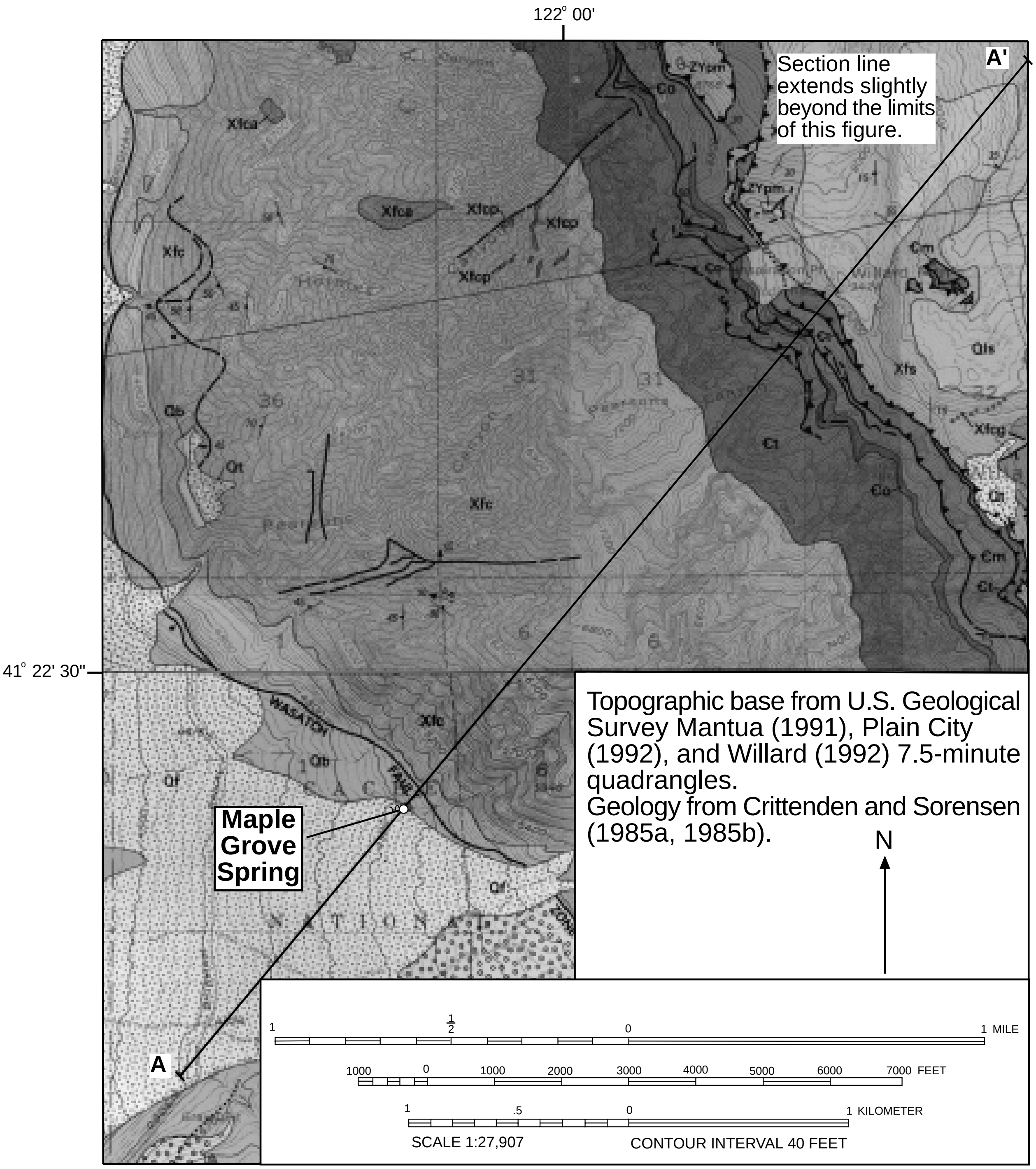


Figure A.2. *Location of cross section A-A'. Scale is 86% of 1:24,000.*

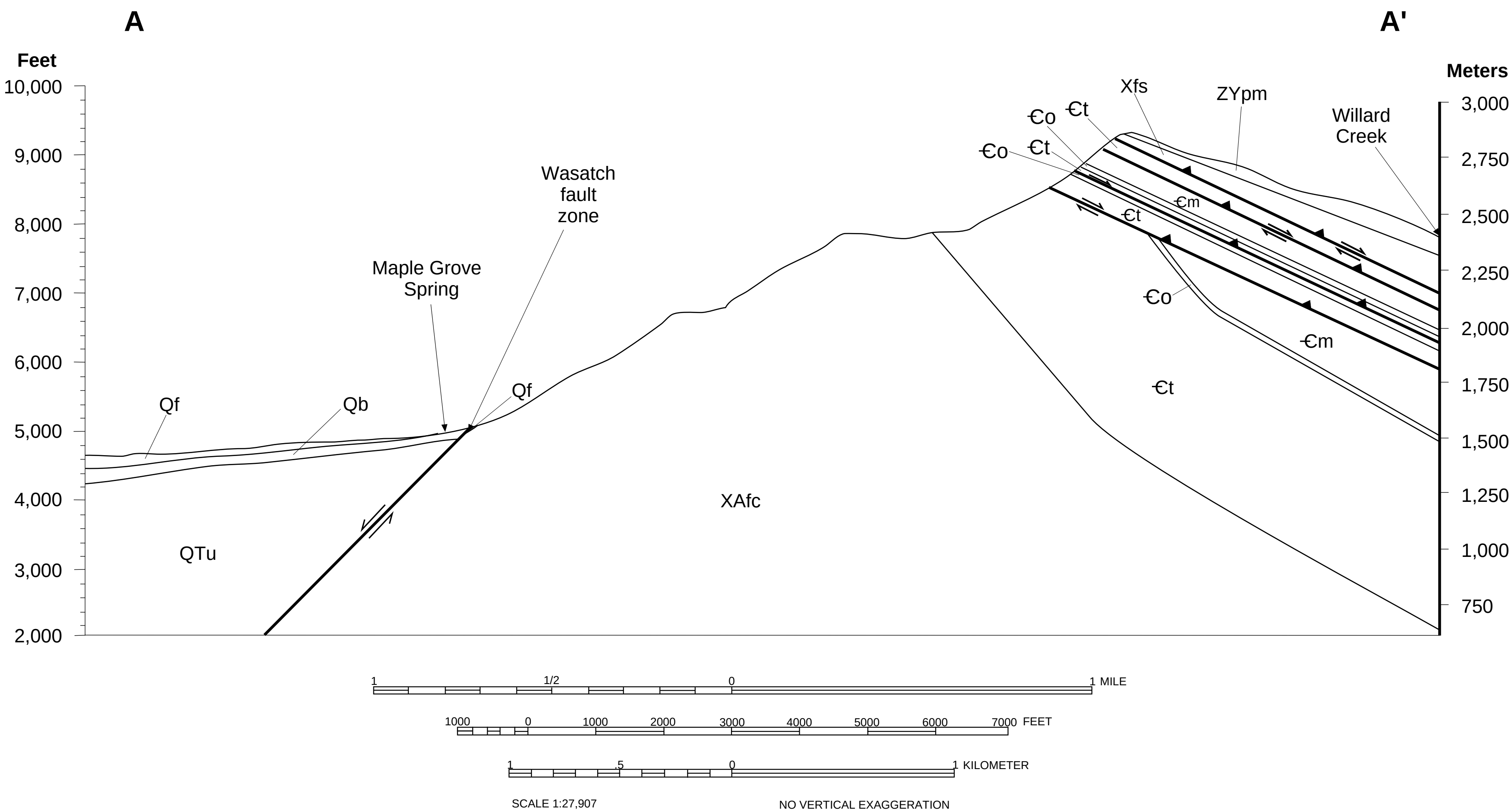
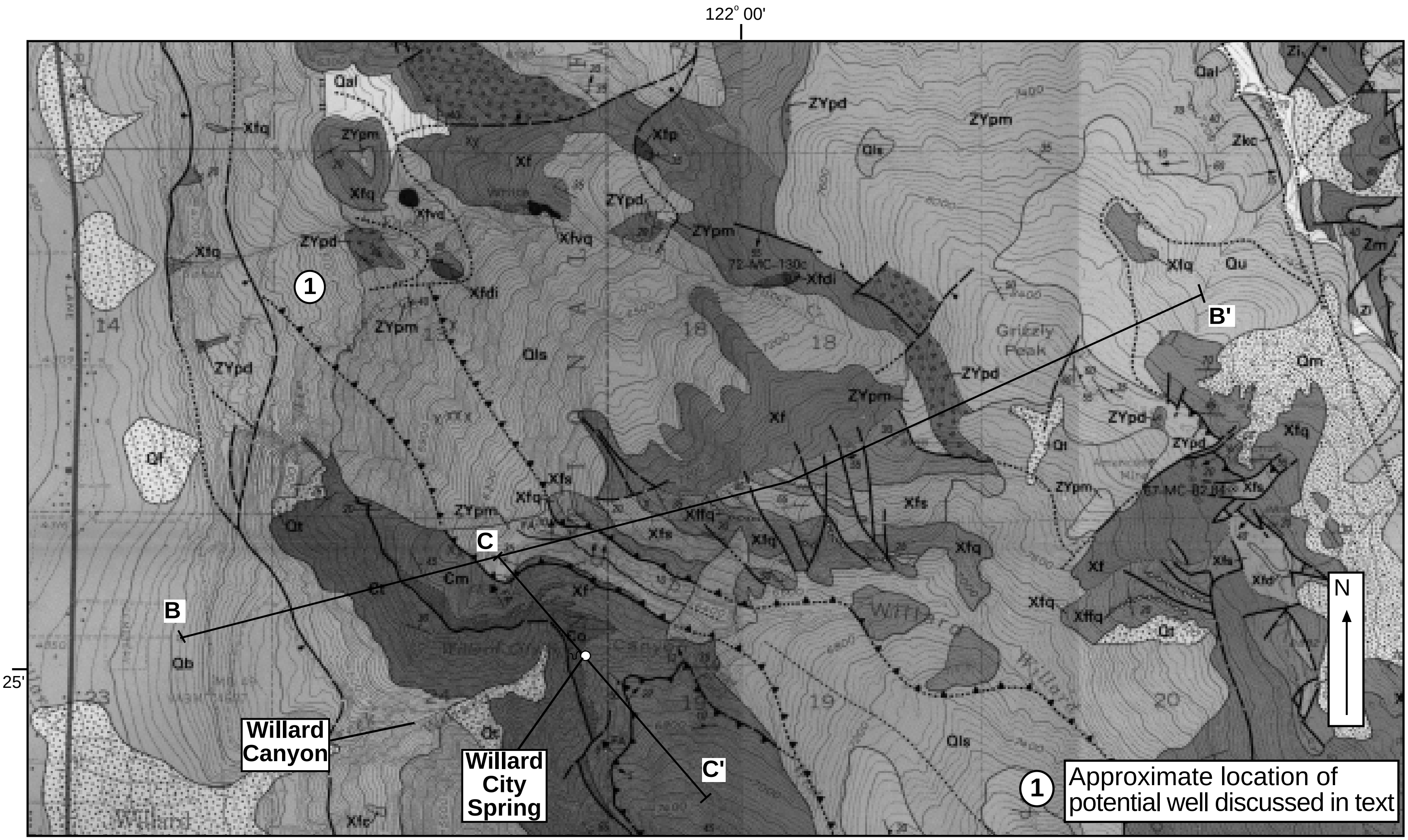
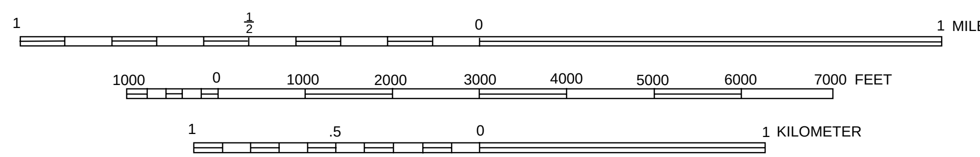


Figure A.3. *Cross section A-A'. Scale is 86% of 1:24,000.*



Topographic base from U.S. Geological Survey Mantua (1991) and Willard (1992) 7.5-minute quadrangles.
Geology from Crittenden and Sorensen (1985a).



SCALE 1:24,000 CONTOUR INTERVAL 40 FEET

Figure A.4. *Locations of cross sections B-B' and C-C'. Scale is 90% of 1:24,000.*

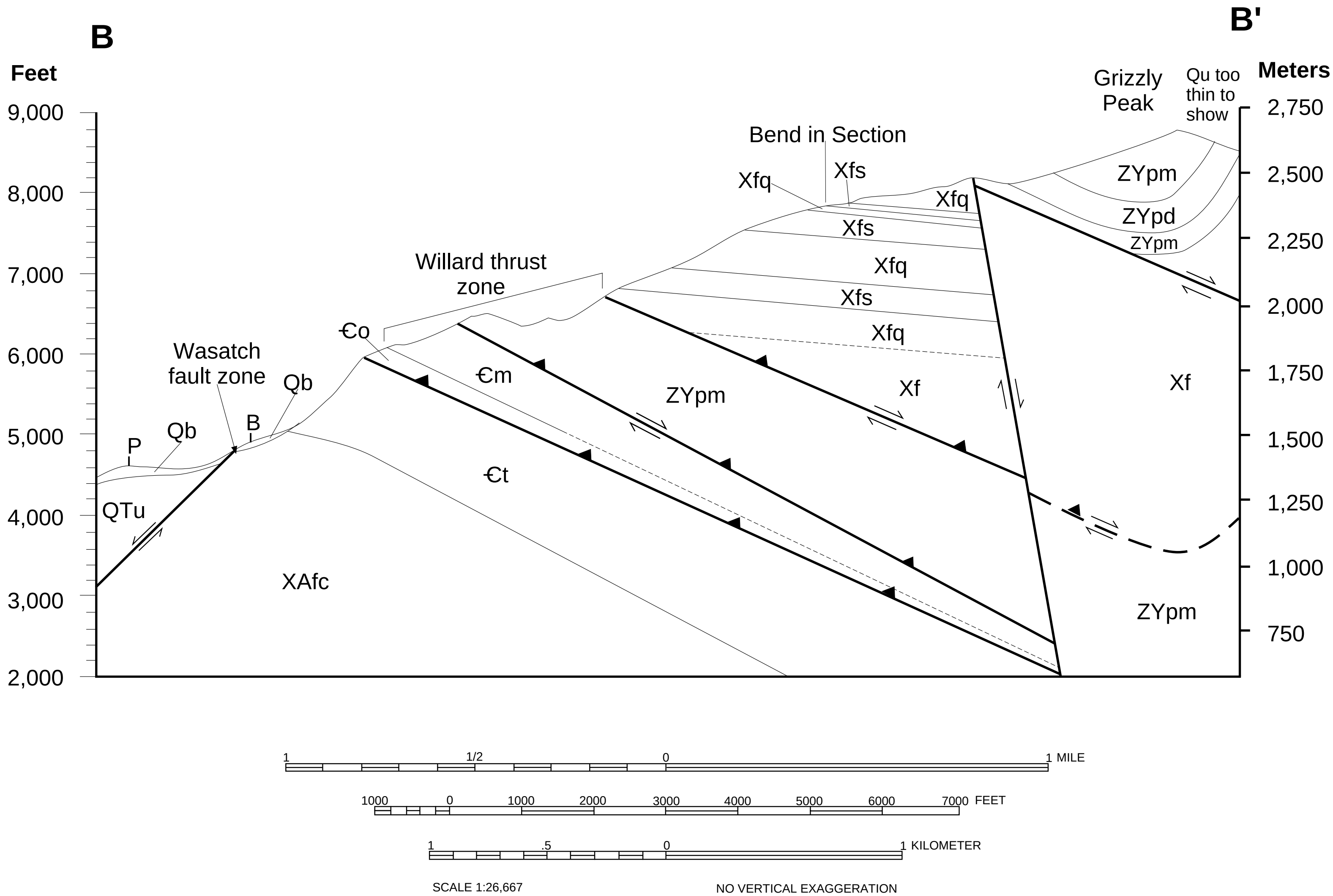


Figure A.5. *Cross section B-B'. Scale is 90% of 1:24,000.*

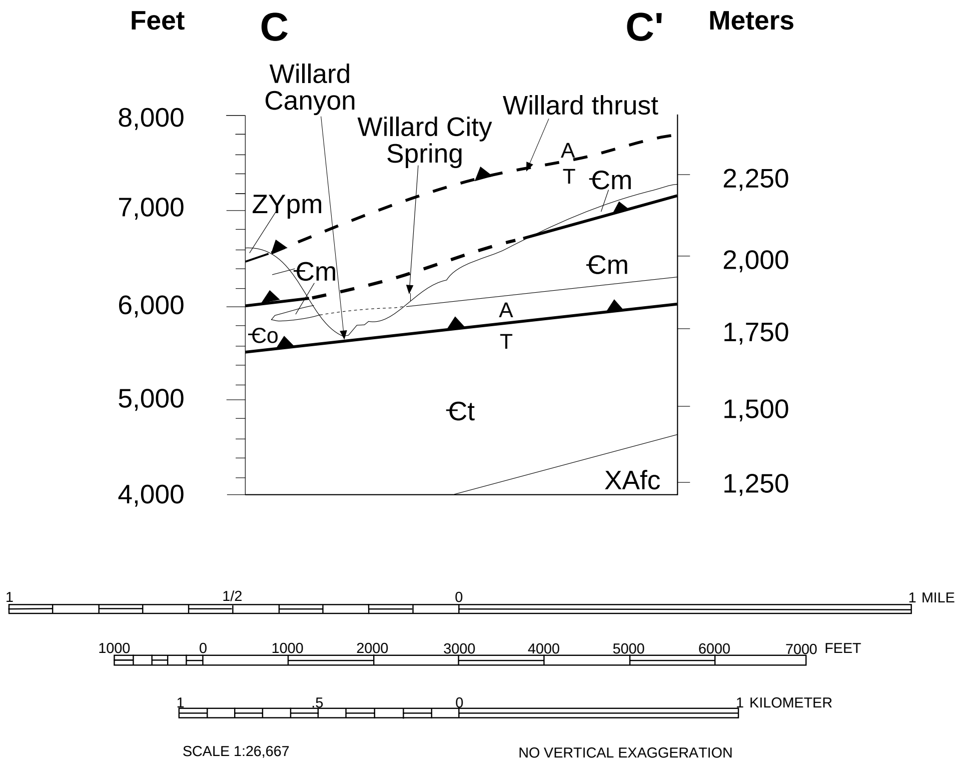
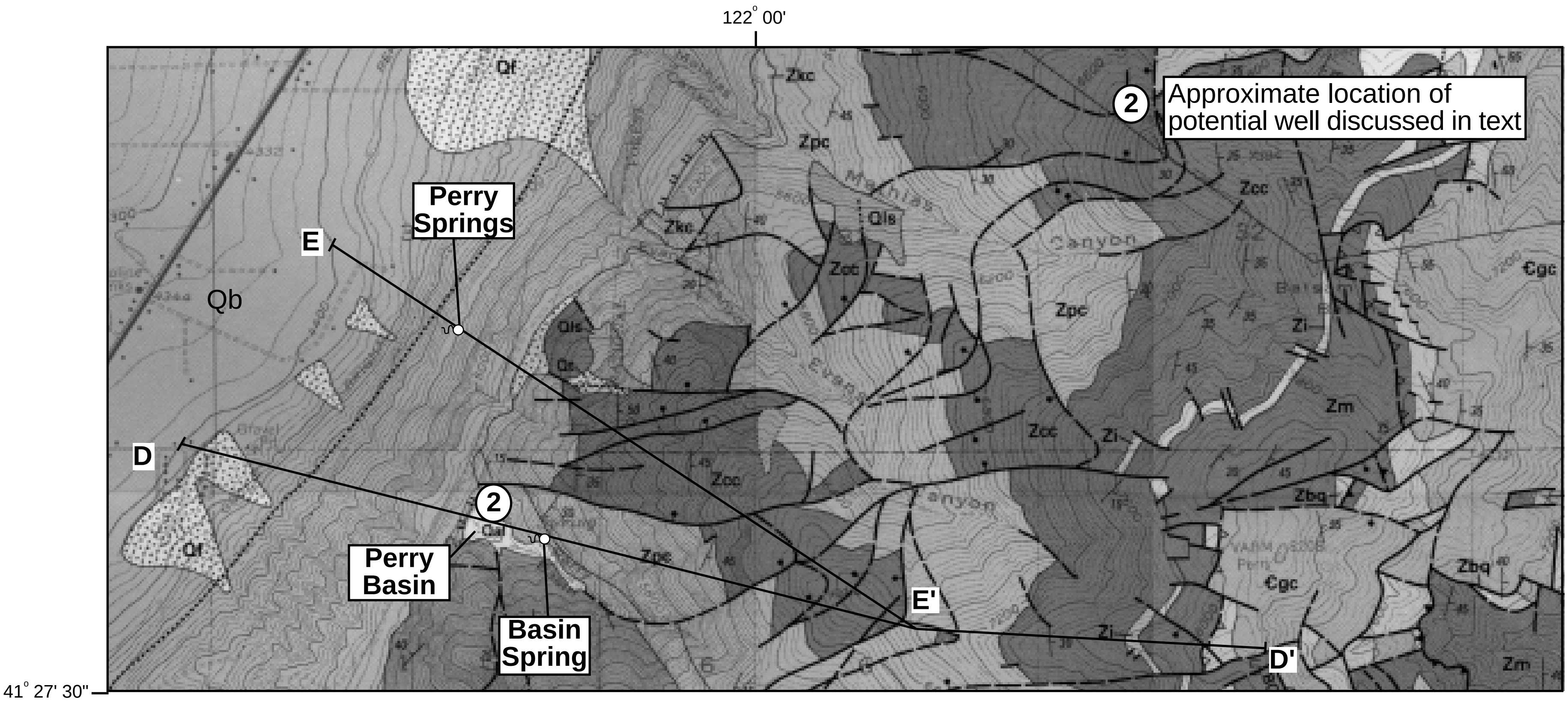


Figure A.6. *Cross section C-C'. Scale is 90% of 1:24,000.*



Topographic base from U.S. Geological Survey Mantua (1991) and Willard (1992) 7.5-minute quadrangles.
Geology from Crittenden and Sorensen (1985a).

1 ½ 0 1 MILE

1000 0 1000 2000 3000 4000 5000 6000 7000 FEET

1 .5 0 1 KILOMETER

SCALE 1:24,000 CONTOUR INTERVAL 40 FEET

Figure A.7. *Locations of cross sections D-D' and E-E'.*

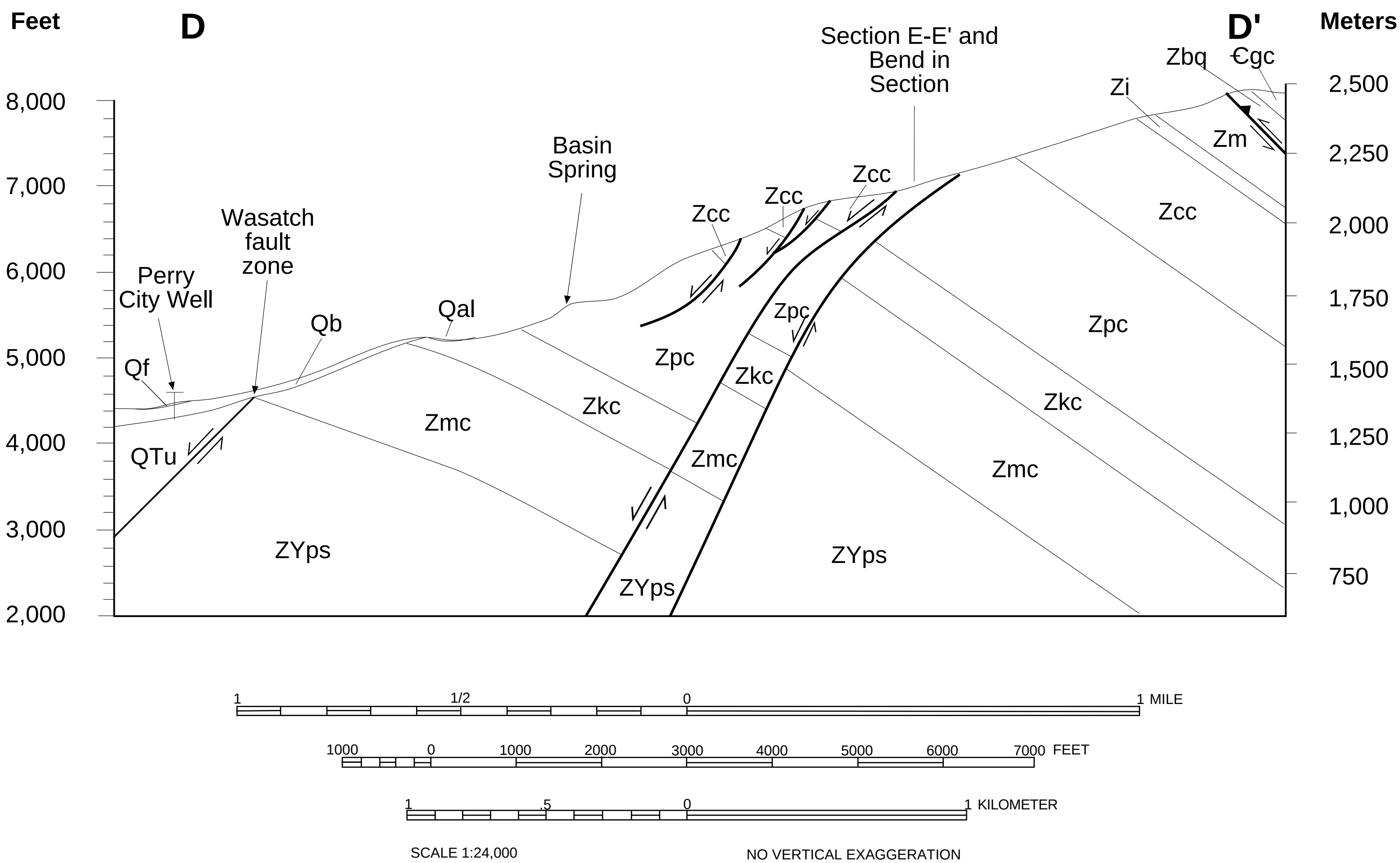


Figure A.8. *Cross section D-D'.*

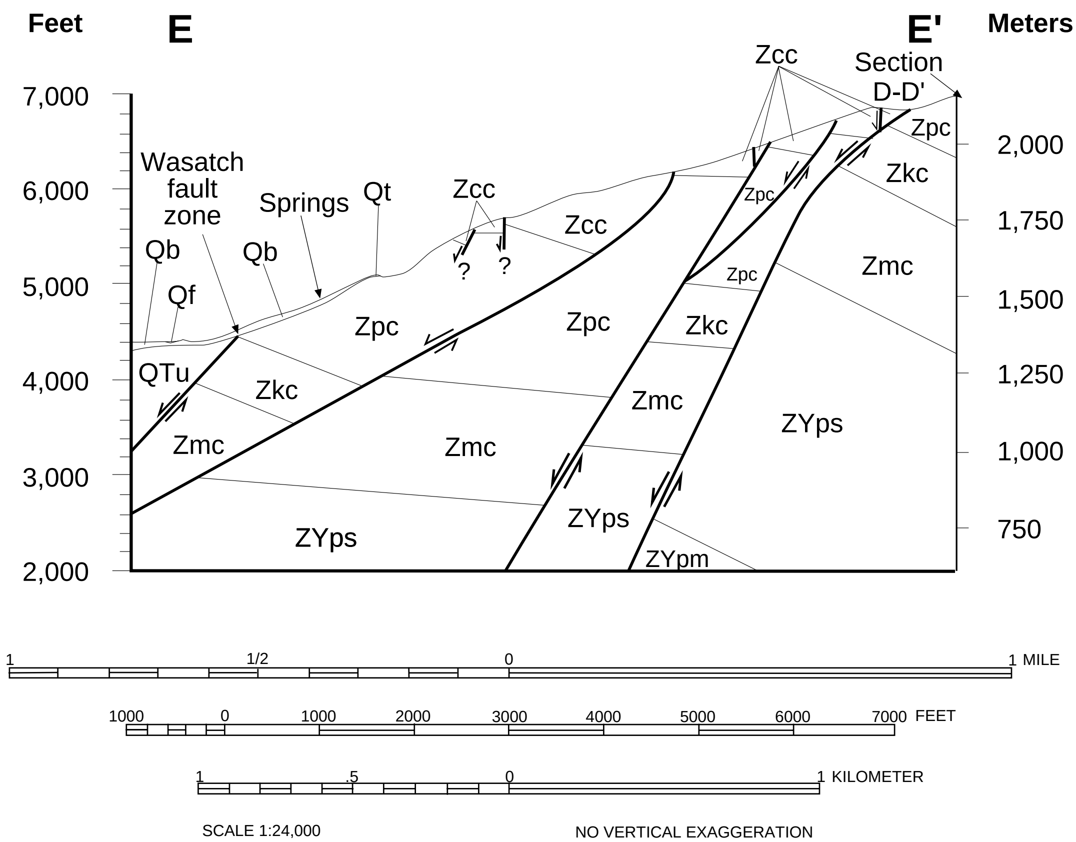
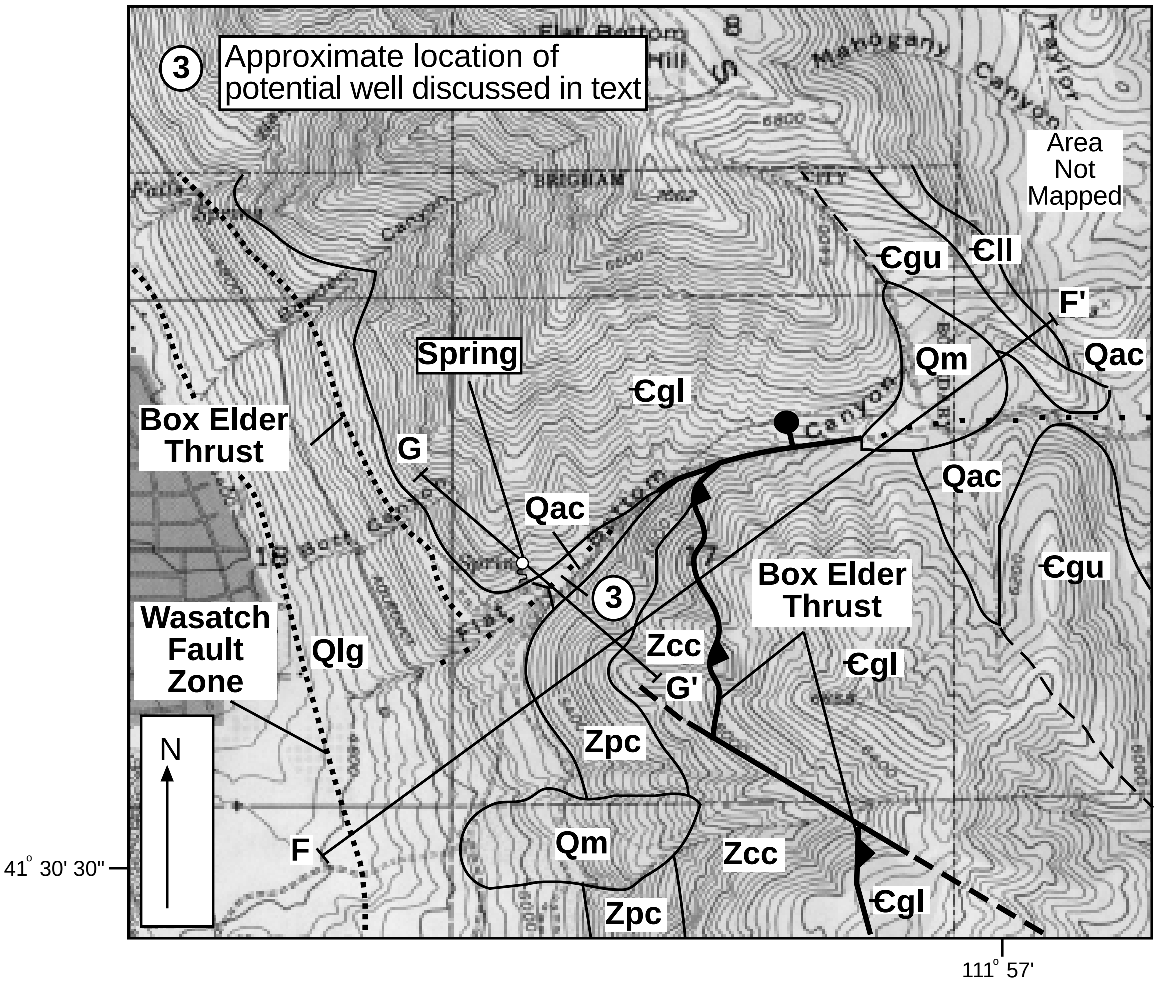
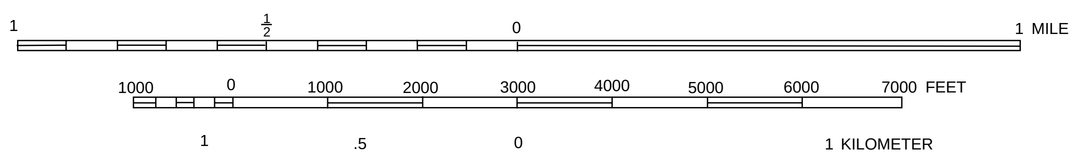


Figure A.9. *Cross section E-E'.*



Topographic base from U.S. Geological Survey Mount Pisgah (1986) 7.5-minute quadrangle.
Geology by Sorensen and Crittenden (1976), Jensen and King (1995), and H. A. Hurlow (unpublished mapping,1997). Map symbols are the same as those in Jensen and King (1995).



SCALE 1:24,000 CONTOUR INTERVAL 40 FEET

Figure A.10. *Locations of cross sections F-F' and G-G'.*

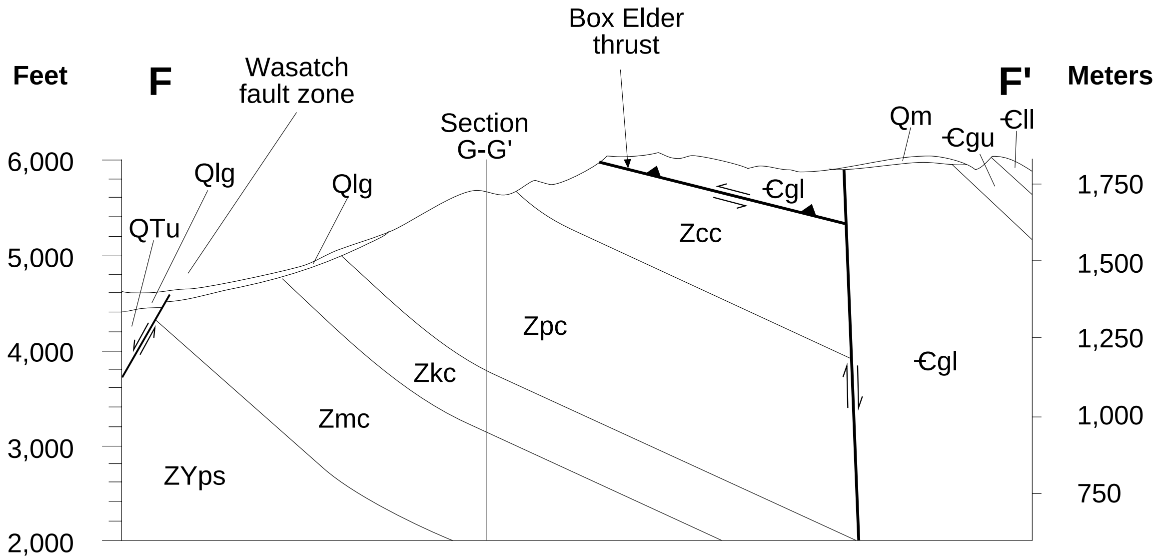
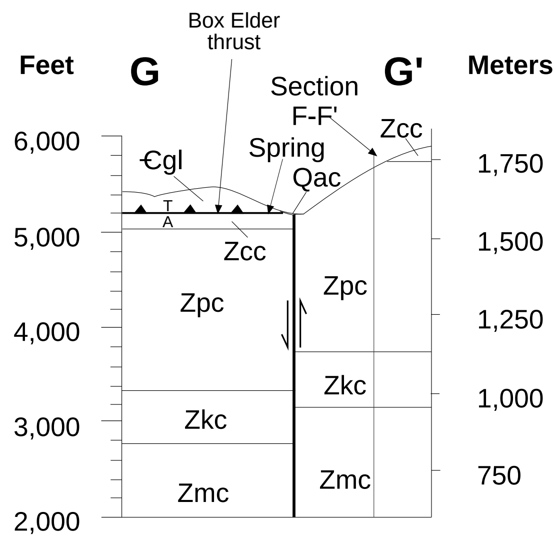
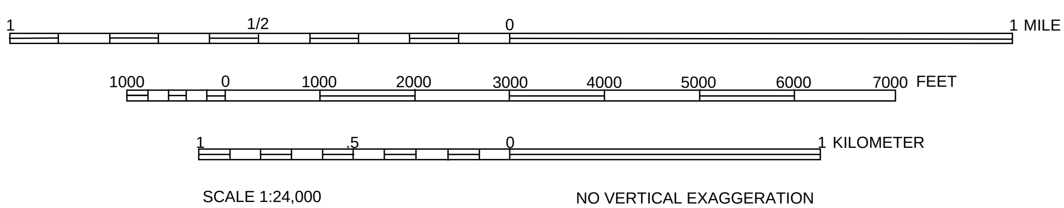


Figure A.11. *Cross section F-F'.*

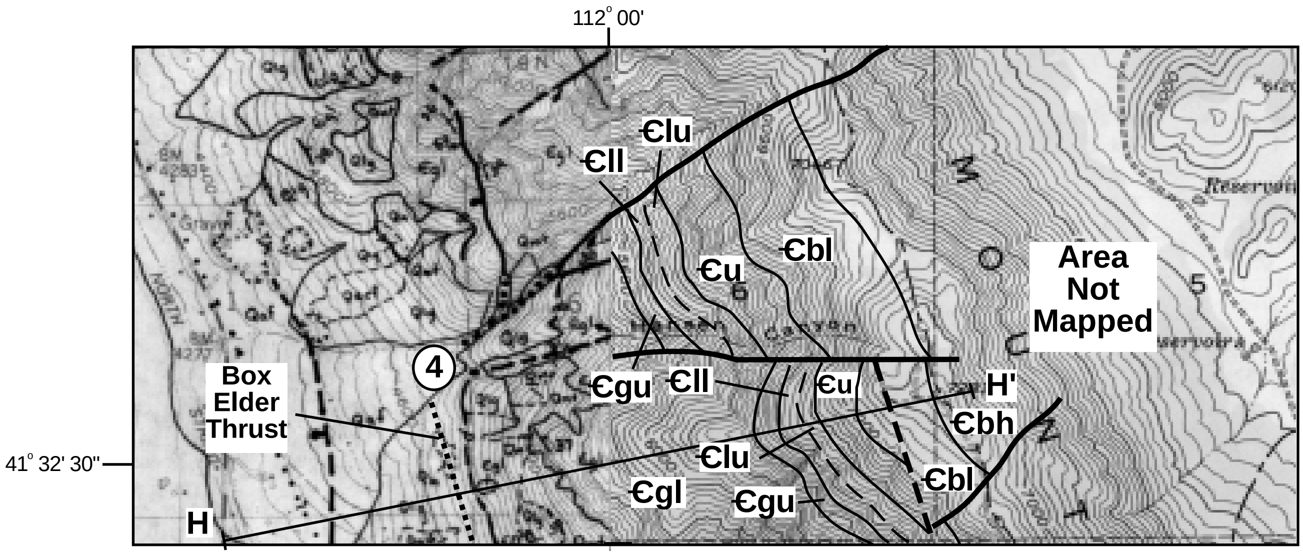


Note: Bedding strikes parallel to line of section and dips northeast.

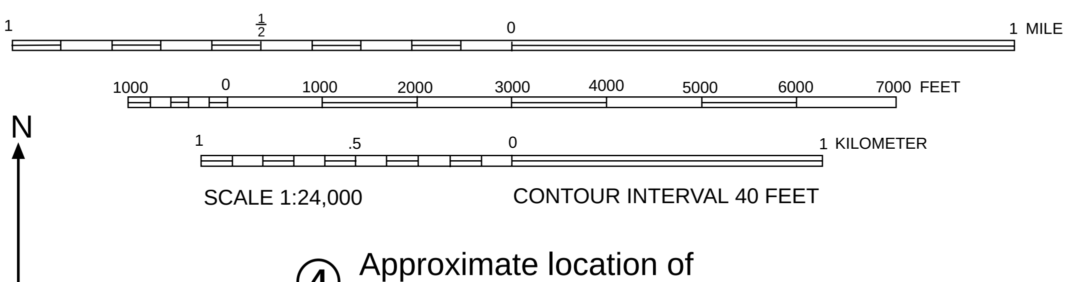
Figure A.12. *Cross section G-G'.*



This scale applies to both cross sections.



Topographic base from U.S. Geological Survey Mount Pisgah (1986) and Brigham City (1988) 7.5-minute quadrangles.
Geology of west half from Jensen and King (1995); geology of east half by M. Jensen (unpublished mapping) and H. Hurlow (unpublished mapping, 1997).



SCALE 1:24,000 CONTOUR INTERVAL 40 FEET

(4) Approximate location of potential well discussed in text

Figure A.13. *Location of cross section H-H'.*

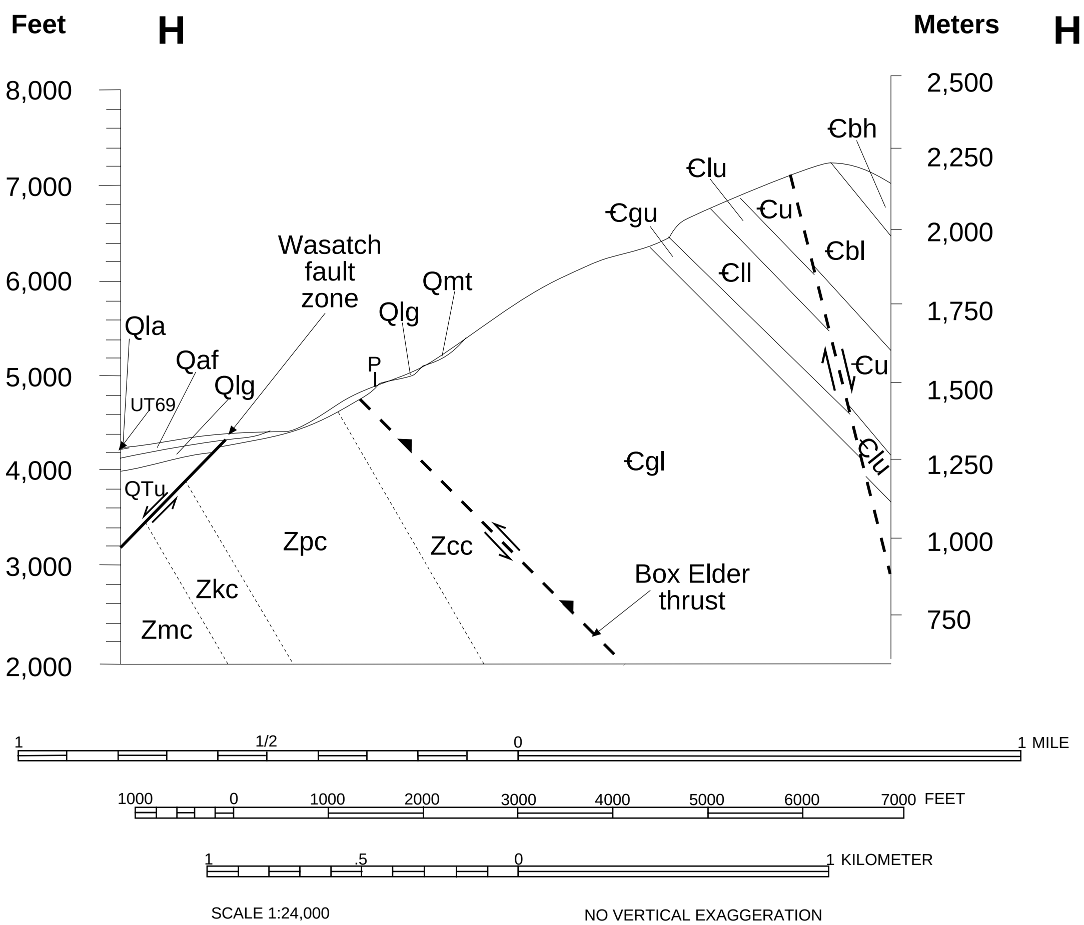


Figure A.14. *Cross section H-H'.*

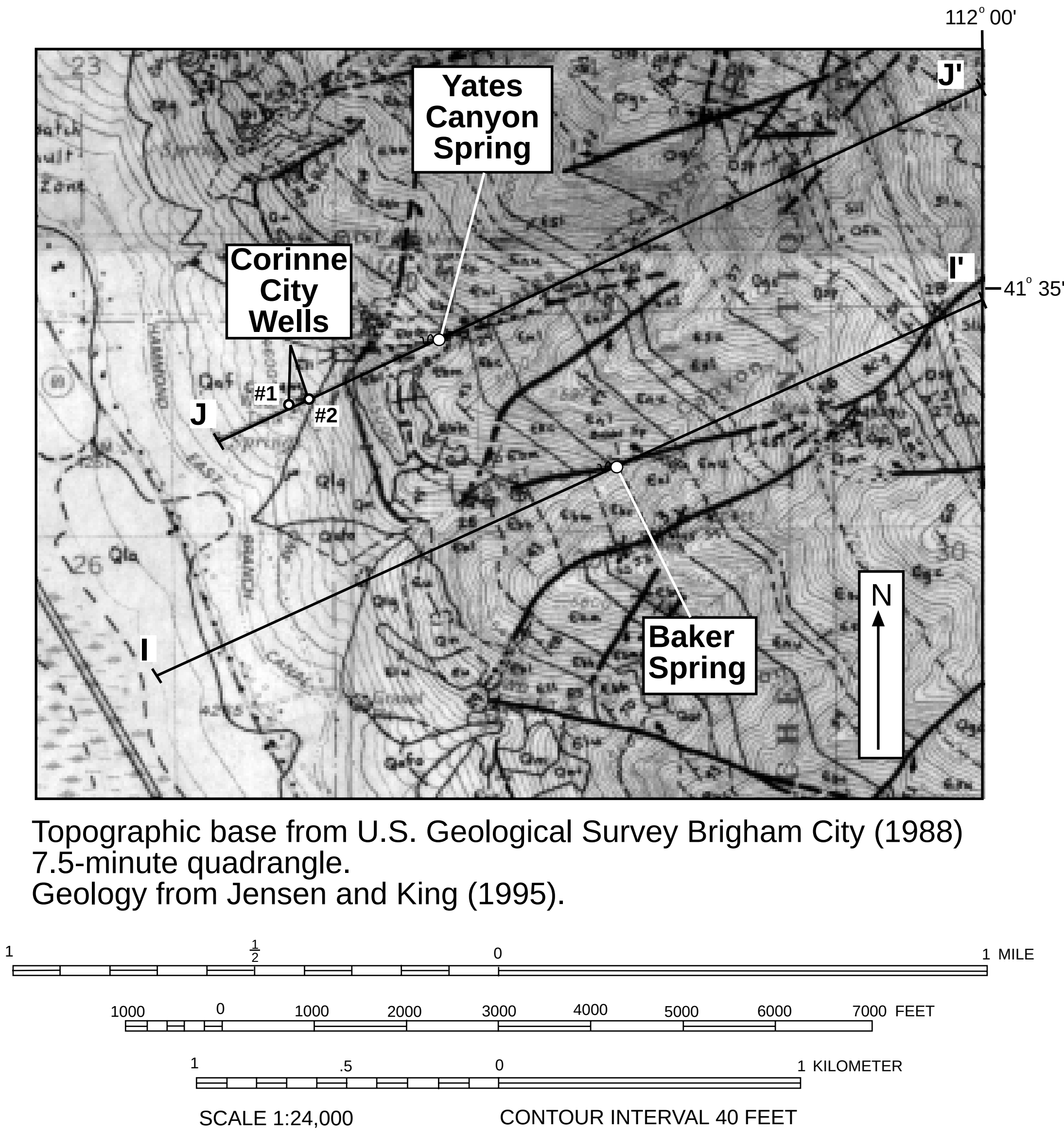


Figure A.15. *Locations of cross sections I-I' and J-J'.*

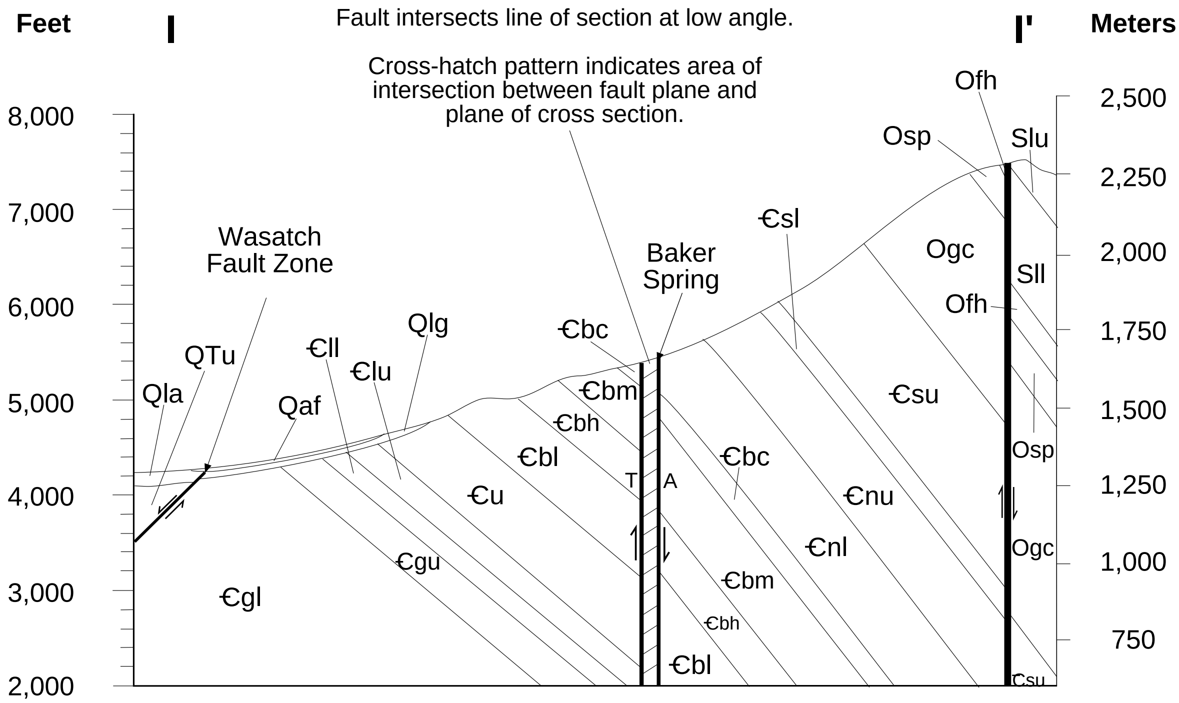


Figure A.16. *Cross section I-I'.*

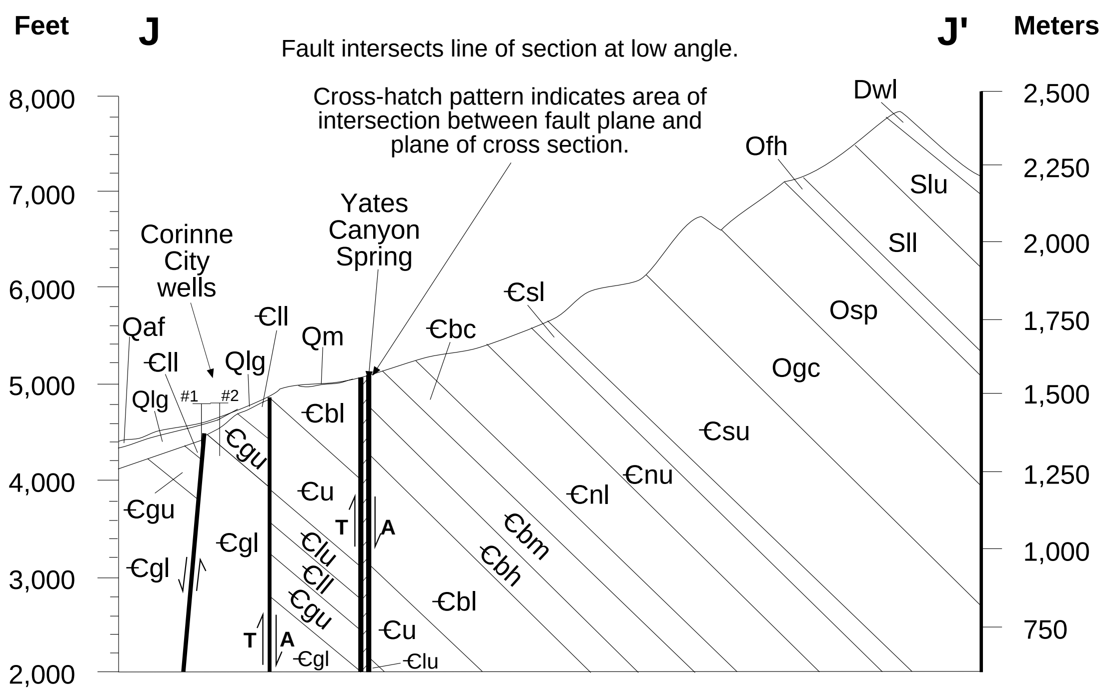
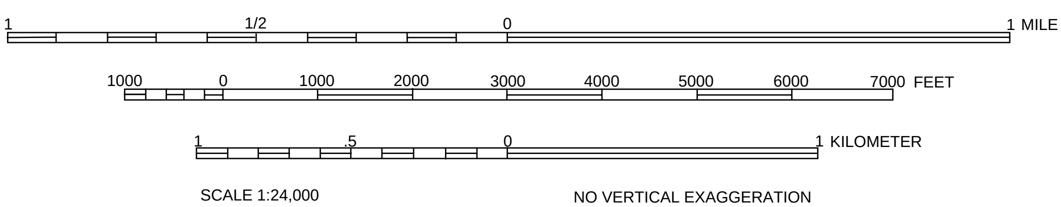
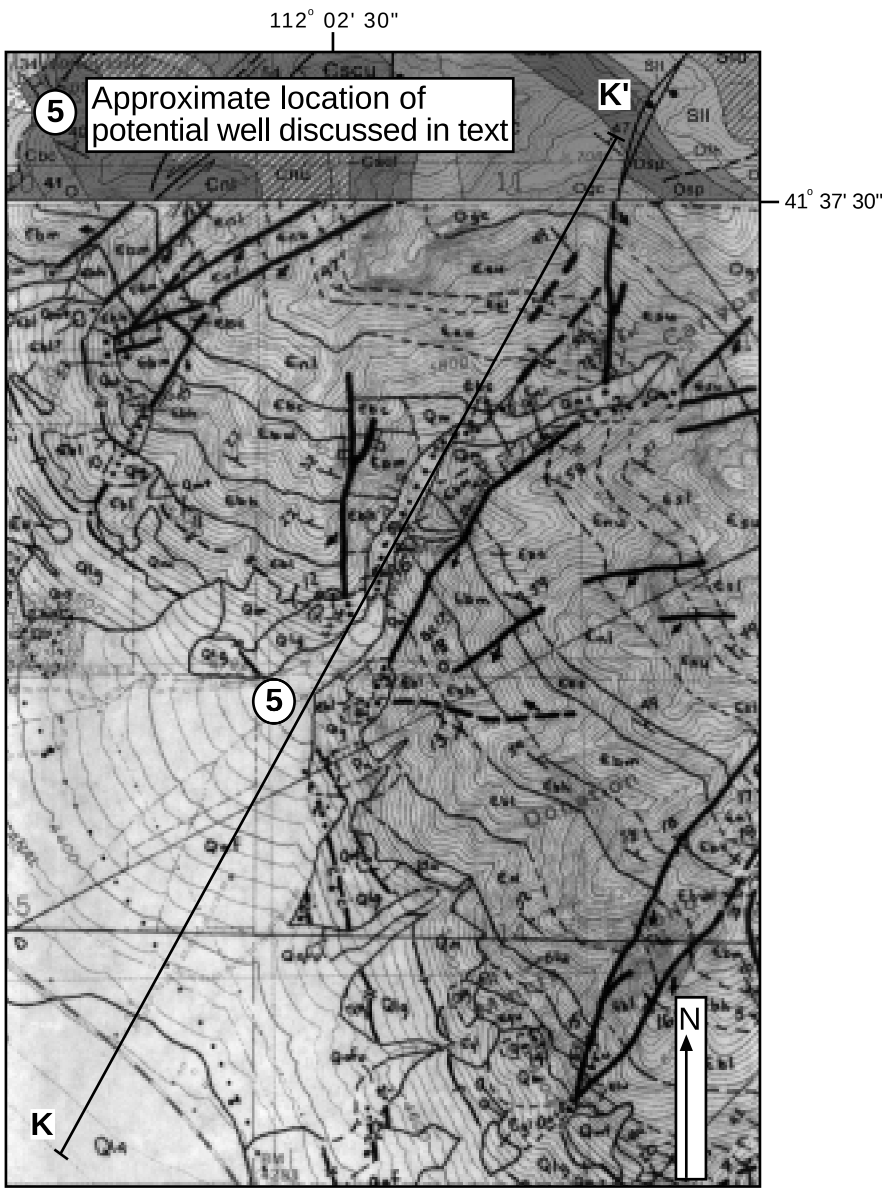


Figure A.17. *Cross section J-J'.*



This scale applies to both cross sections.



Topographic base from U.S. Geological Survey Honeyville (1961) and Brigham City (1988) 7.5-minute quadrangles. Geology from Jensen and King (1995) and Oviatt (1986).

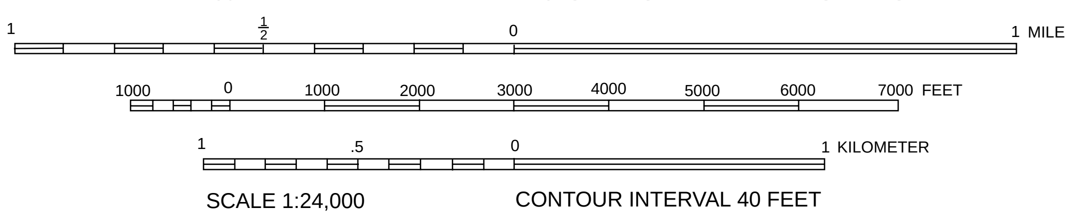
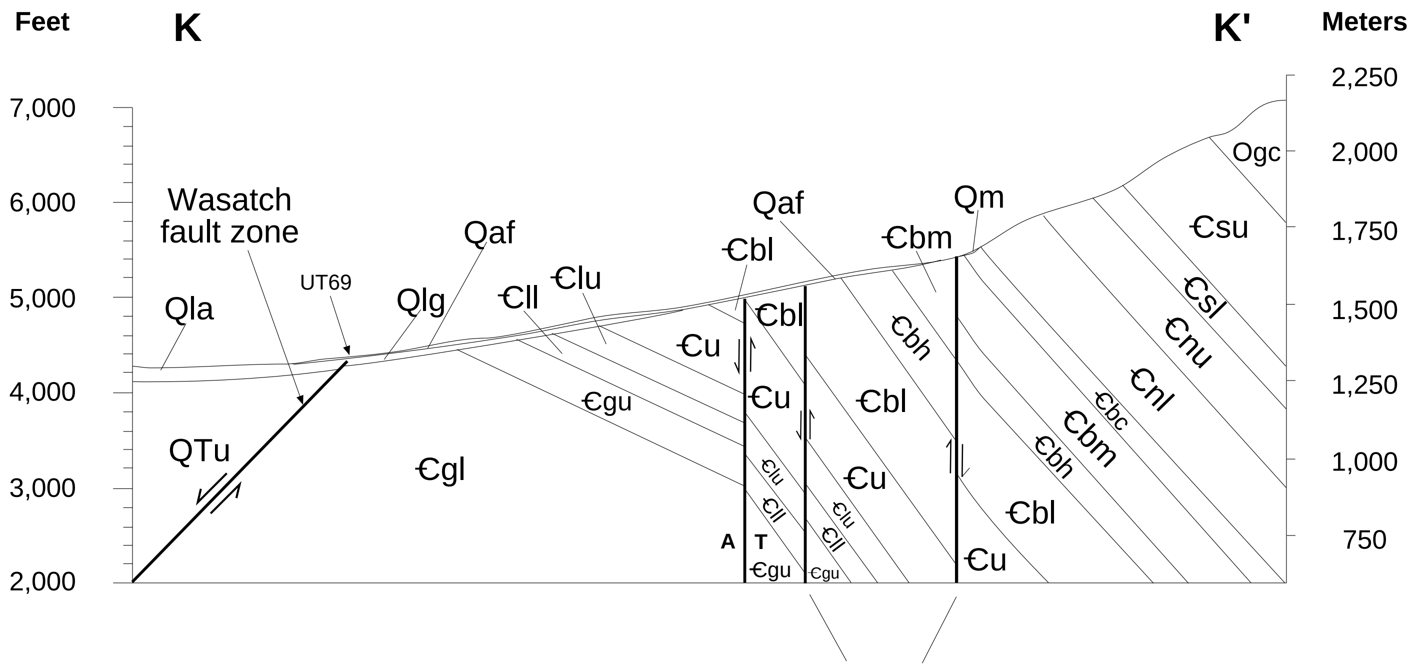


Figure A.18. *Location of cross section K-K'.*



Note: These fault strands are part of a single fault that underlies the canyon bottom, is slightly curved, and intersects the line of section in two places.

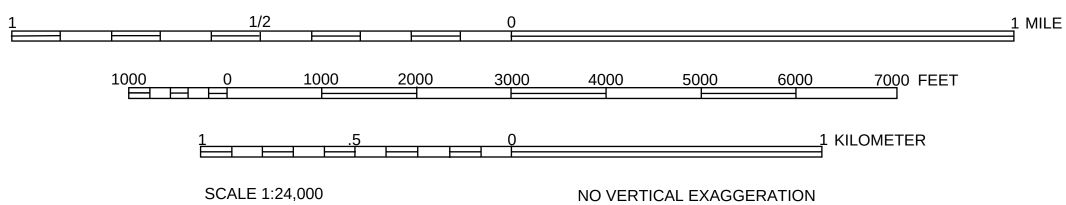
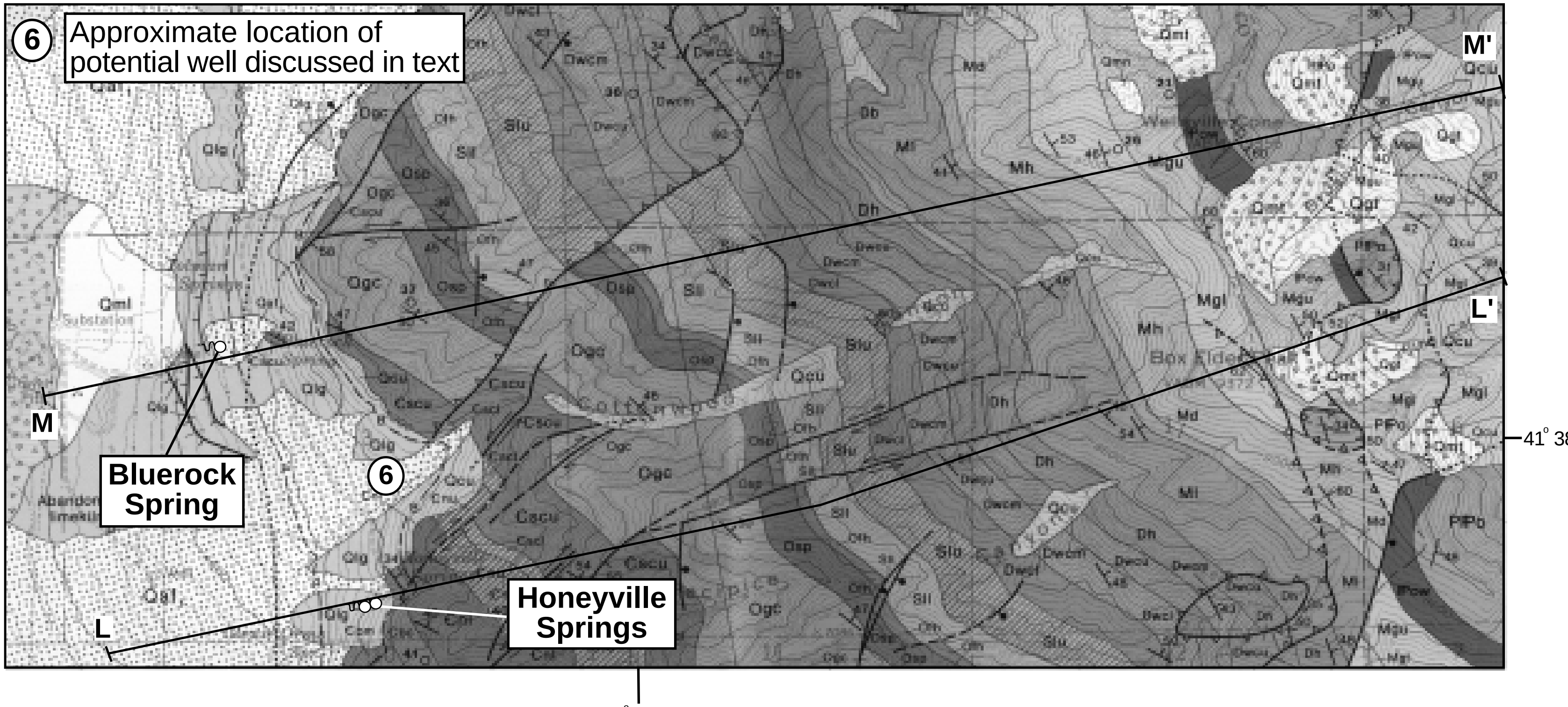


Figure A.19. *Cross section K-K'.*



Topographic base from U.S. Geological Survey Honeyville (1961) 7.5-minute quadrangle.
Geology from Oviatt (1986).

N

1 ½ 0 1 MILE

1000 0 1000 2000 3000 4000 5000 6000 7000 FEET

1 .5 0 1 KILOMETER

SCALE 1:28,235 CONTOUR INTERVAL 40 FEET

Figure A.20. *Locations of cross sections L-L' and M-M'. Scale is 85% of 1:24,000.*

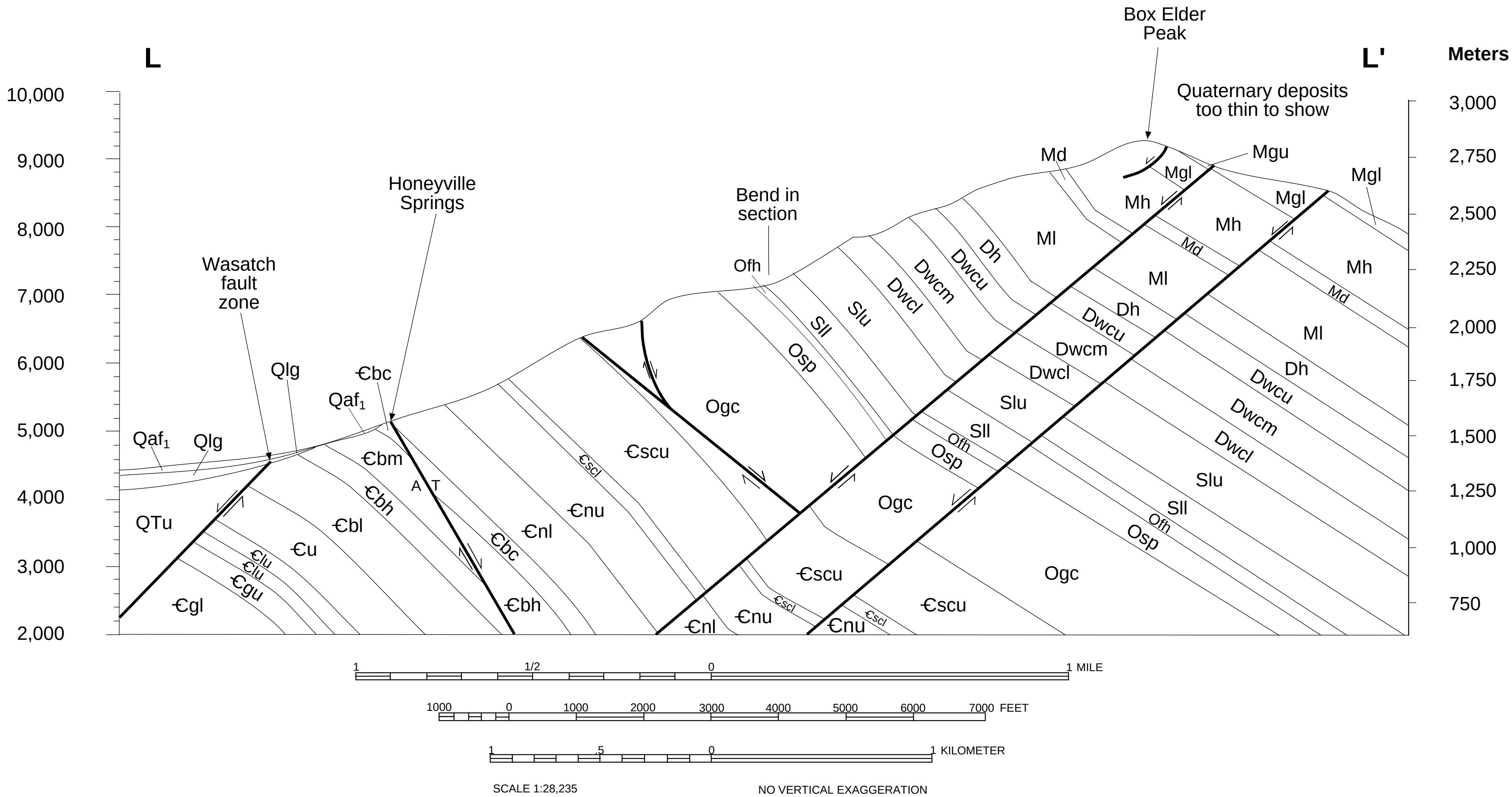


Figure A.21. *Cross section L-L'. Scale is 85% of 1:24,000.*

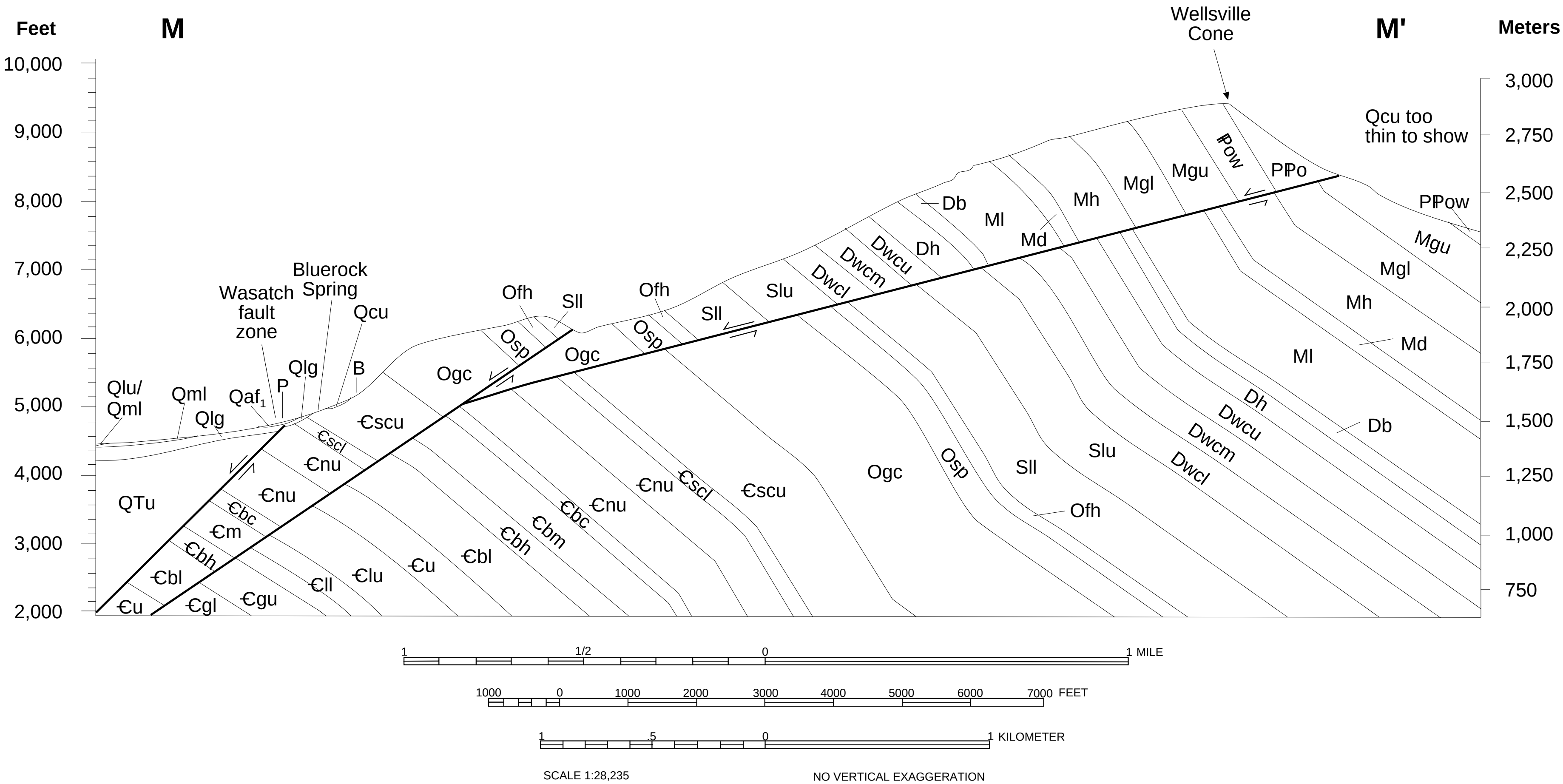
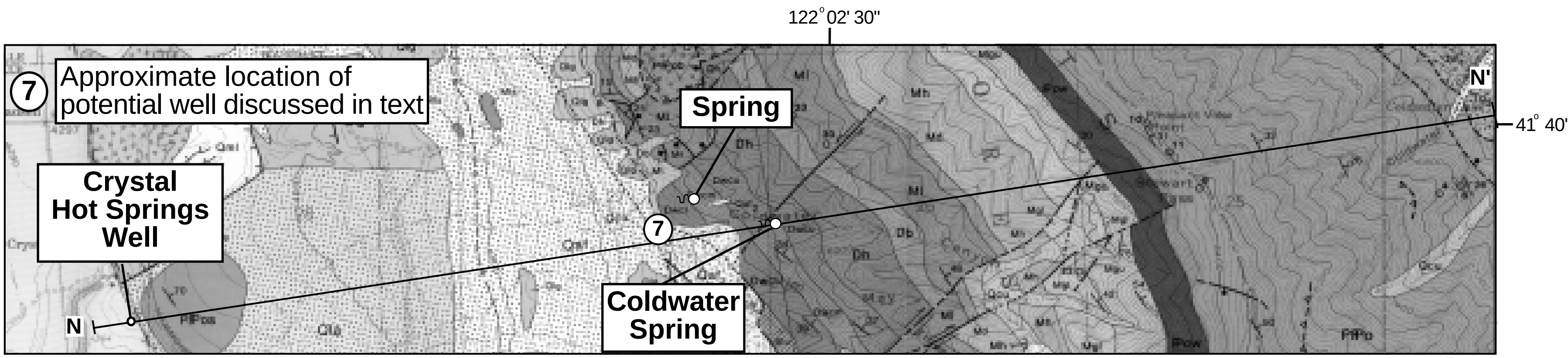


Figure A.22. *Cross section M-M'. Scale is 85% of 1:24,000.*



Base from U.S. Geological Survey Honeyville (1961) 7.5-minute quadrangle.
Geology from Oviatt (1986).

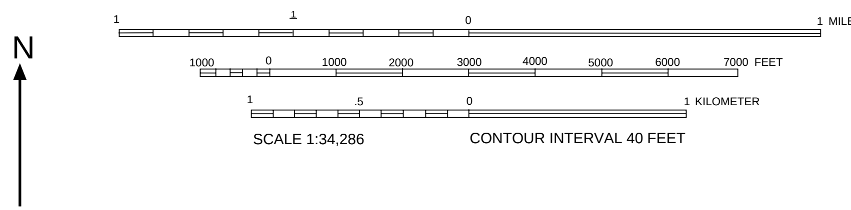


Figure A.23. *Location of cross section N-N'. Scale is 70% of 1:24,000.*

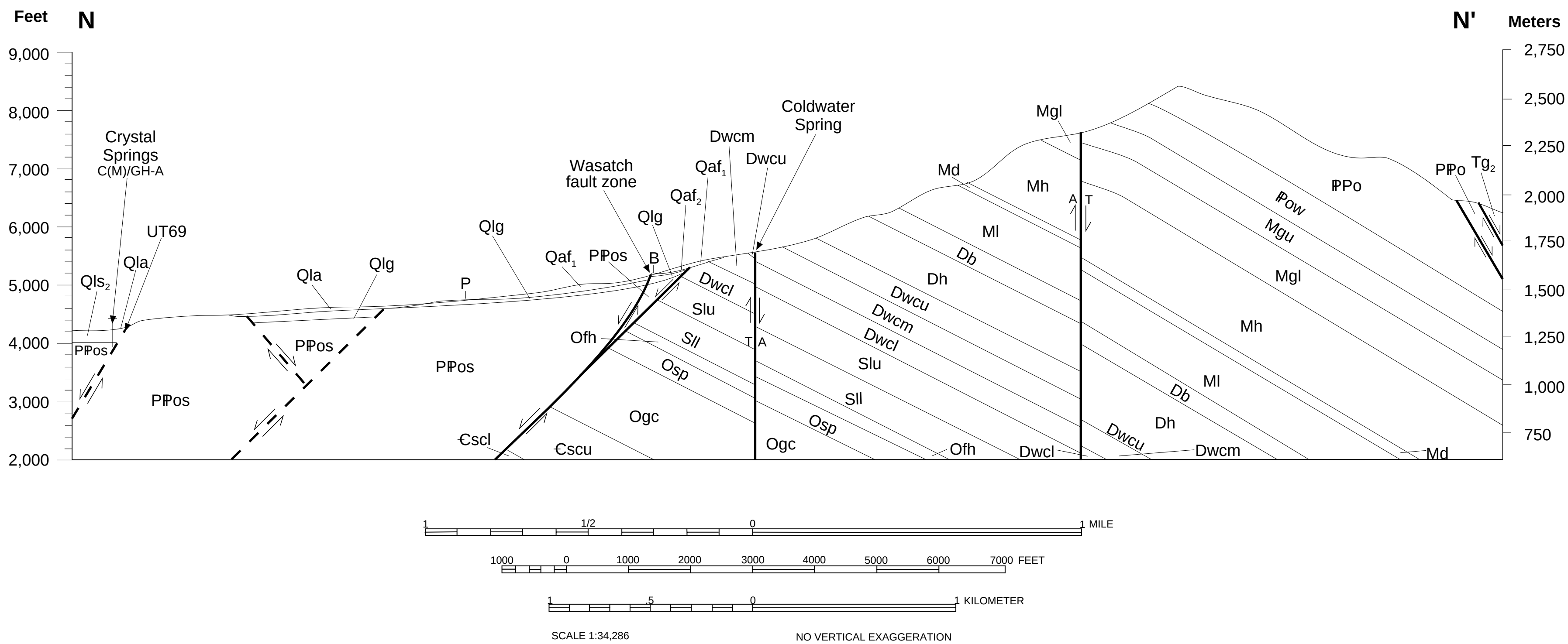
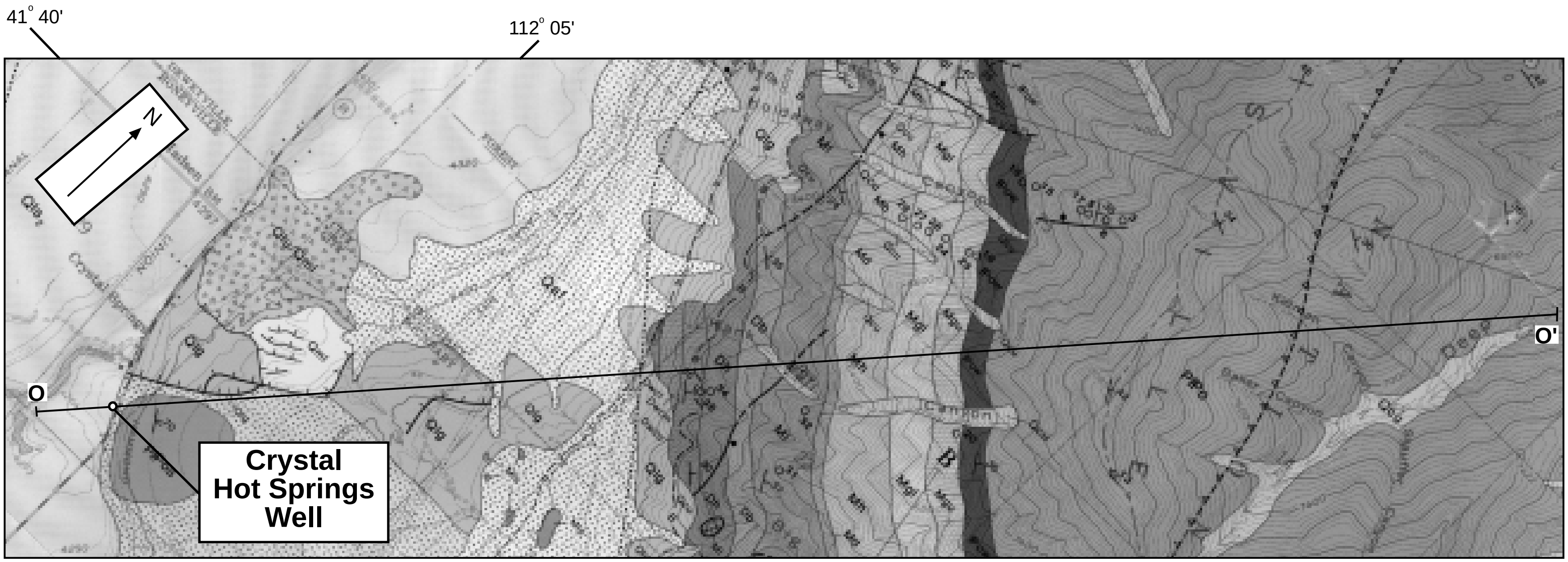
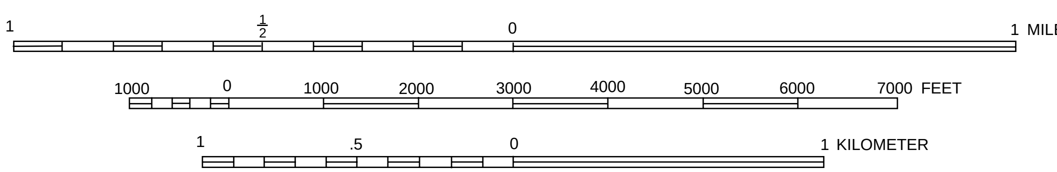


Figure A.24. *Cross section N-N'. Scale is 70% of 1:24,000.*



Base from U.S. Geological Survey Honeyville (1961) 7.5-minute quadrangle.
Geology from Oviatt (1986).



SCALE 1:32,000 CONTOUR INTERVAL 40 FEET

Figure A.25. *Location of cross section O-O'. Scale is 75% of 1:24,000.*

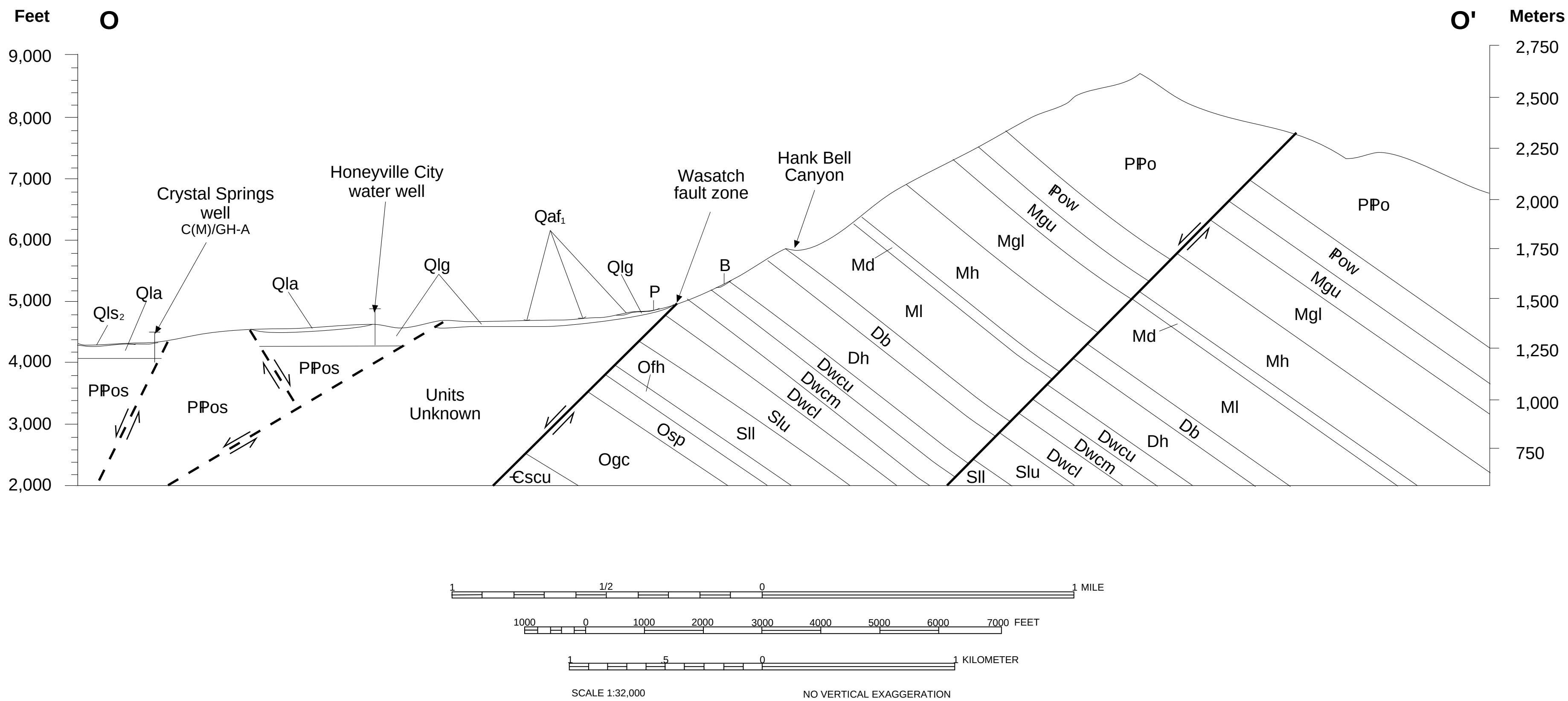
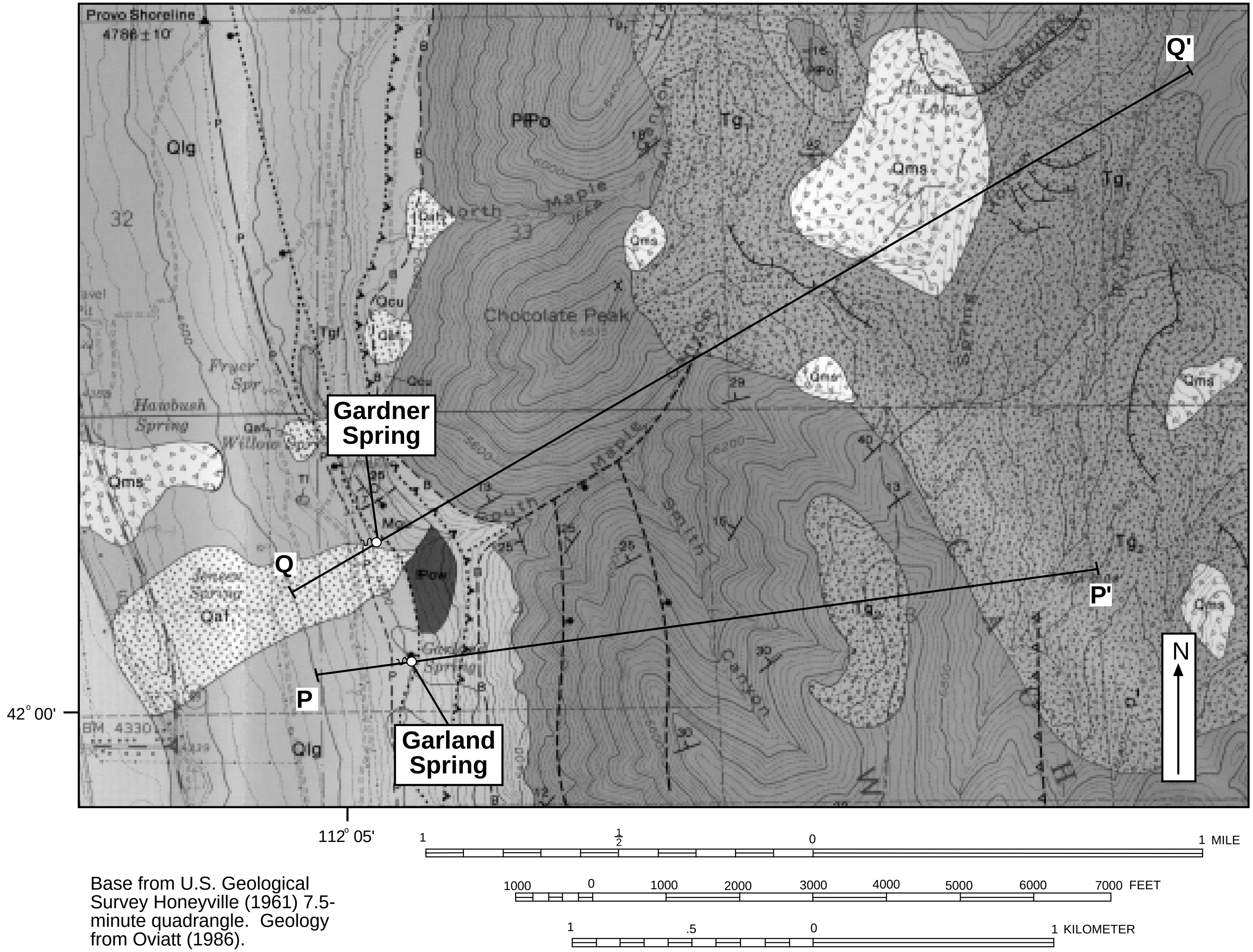


Figure A.26. *Cross section O-O'. Scale is 75% of 1:24,000.*



Base from U.S. Geological Survey Honeyville (1961) 7.5-minute quadrangle. Geology from Oviatt (1986).

SCALE 1:24,000 CONTOUR INTERVAL 40 FEET

Figure A.27. *Locations of cross sections P-P' and Q-Q'.*

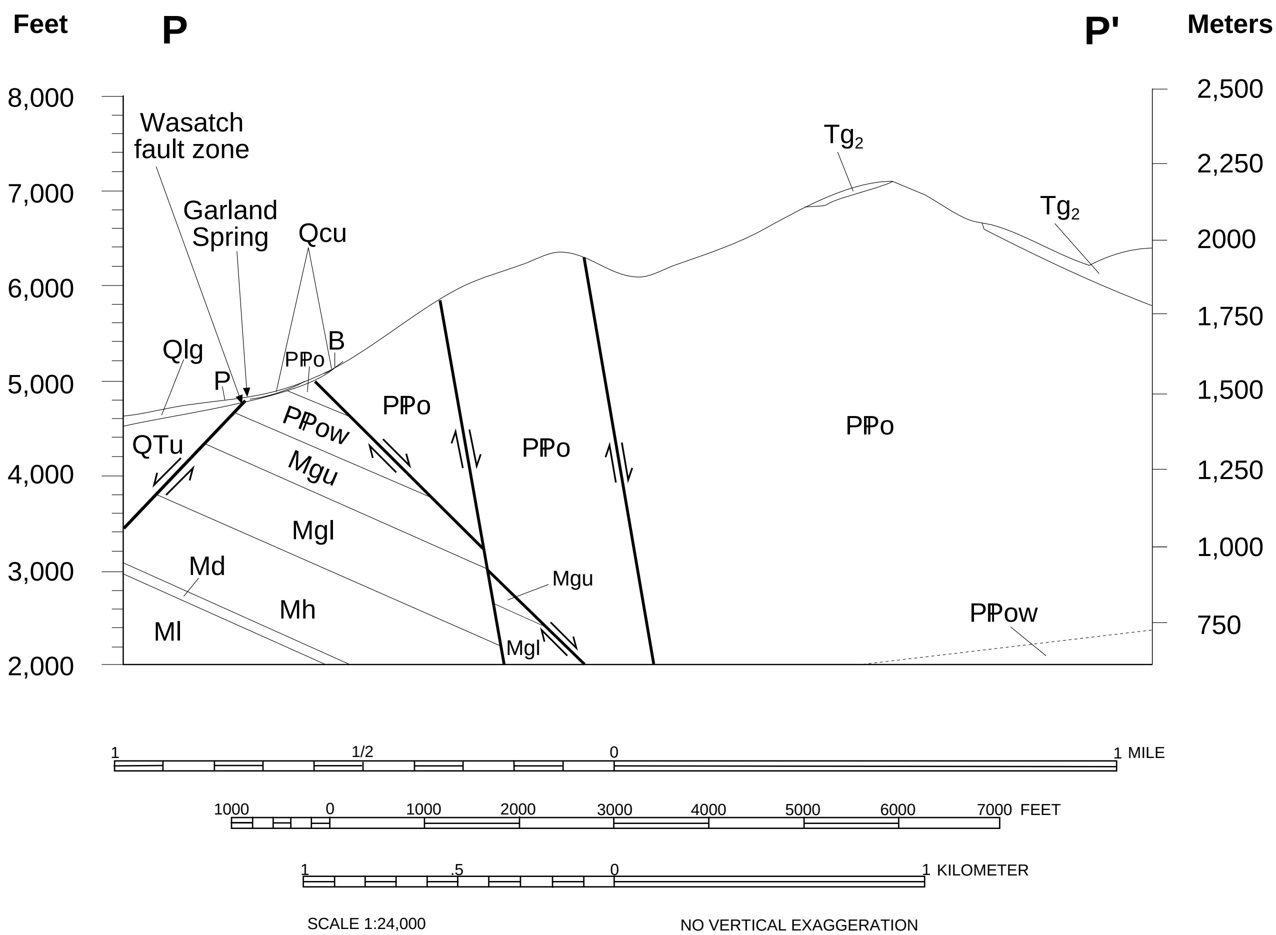


Figure A.28. *Cross section P-P'.*

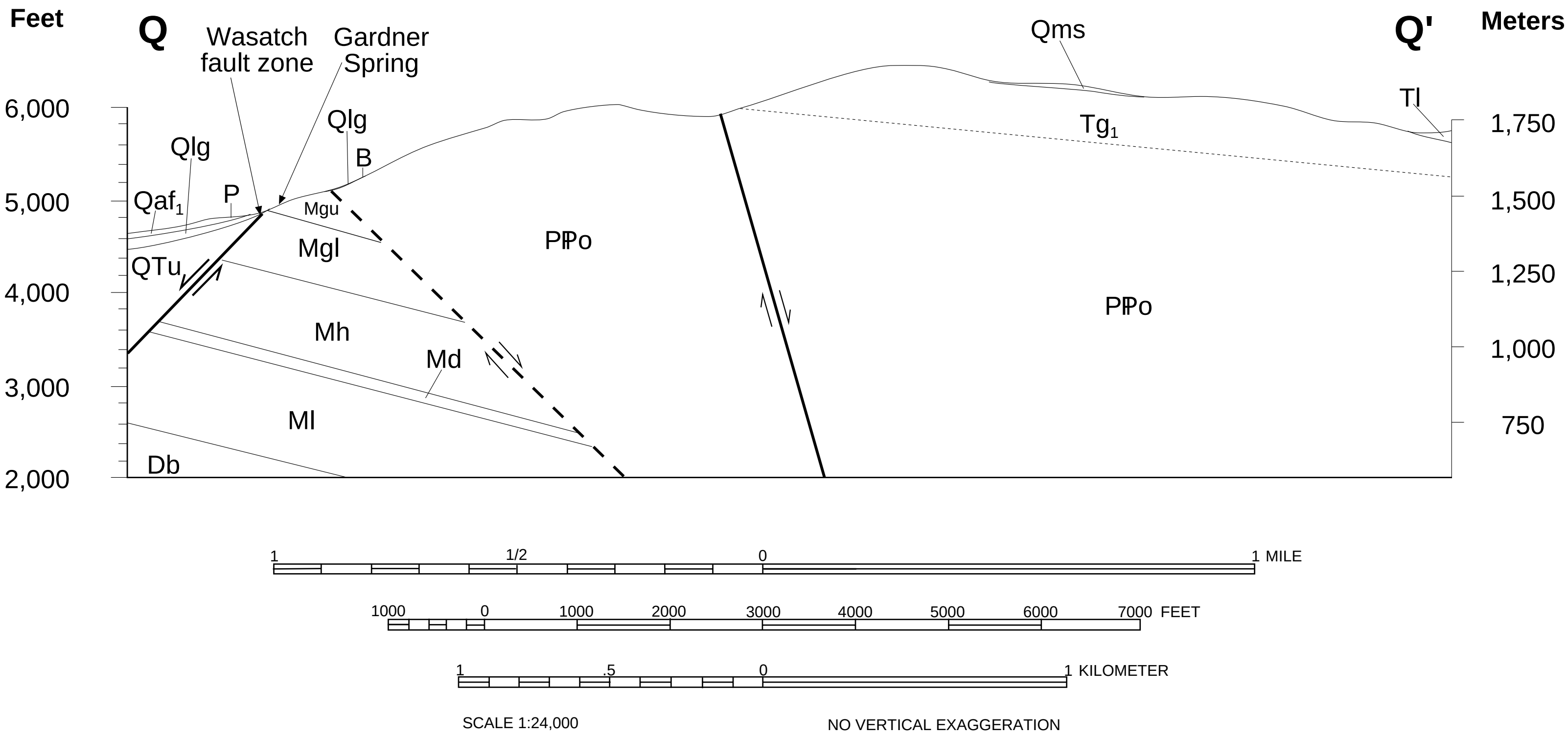


Figure A.29. *Cross section Q-Q'.*

APPENDIX B

Description of Map Units

(modified from Crittenden and Sorensen, 1985a and 1985b; Oviatt, 1986; and Jensen and King, 1995)

Quaternary

Qal Alluvium - Fine grained to gravelly; deposits in floodplains and channels.

Qaf, Qaf$_1$, Qaf$_2$, Qf Alluvial-fan deposits - Poorly sorted boulders, cobbles, pebbles, sand, silt, and clay. Deposited in alluvial fans at the base of the mountain front. Qaf$_1$ deposits are post-Lake Bonneville in age, and Qaf$_2$ deposits are pre-Lake Bonneville in age (Oviatt, 1986).

Qla Mixed lacustrine and alluvial gravel deposits - Sand, silt, clay, and gravel.

Qlg Lacustrine gravel and sand - Subrounded to well-rounded pebbles, cobbles, and rare boulders mixed with sand.

Qls$_2$ Lacustrine sand, silt, and clay - Very fine-grained, subrounded to rounded, moderately sorted sand, mixed with variable amounts of silt and clay.

Qlu, Qb Undifferentiated lacustrine deposits.

Qlu/Qml Thin lacustrine deposits overlying lateral-spread mass-movement deposits.

Qml Lateral-spread mass-movement deposits - Composed of Qlg, stabilized and inactive.

Qms Landslide deposits - Derived from Qlg or from Tertiary gravel or lacustrine deposits.

Qmt Talus - Thick rock-fall accumulations below cliffs.

Qm Mass-movement deposits, undivided.

Qcu, Qac Colluvial and alluvial deposits, undivided - Locally includes talus, alluvium, debris-flow, and avalanche-debris deposits.

Qu Surficial deposits, undivided.

Quaternary-Tertiary

QTu Quaternary-Tertiary sediments, undivided - Likely includes lacustrine, alluvial, and alluvial-fan sediments. This unit is not exposed, and is shown in the hanging wall of the Wasatch fault zone. May include the Miocene Salt Lake Formation.

PIPos Oquirrh Formation - In gravity slide mass (Oviatt, 1986) east of Crystal Springs.

Tertiary

Tg$_1$ Gravel deposits - Includes both locally derived clasts of Paleozoic rocks and exotic clasts of silicic volcanic rocks.

Tg$_2$ Gravel deposits - Clasts locally derived and generally finer grained and more angular than Tg$_1$.

Tl Lacustrine deposits - Marl and oolitic limestone, interbedded with locally thick layers of volcanic ash in lower part.

Appendix B (continued)

Permian-Pennsylvanian

PIPo — Oquirrh Group - Sandstone with interbedded sandy limestone and limestone; fusulinids common in some lower beds; approximately 5,000 feet (1,524 m) thick.

Pennsylvanian

IPow — West Canyon Limestone - Medium-gray cherty limestone, sandy limestone, and minor shale; 400-450 feet (122-137 m) thick.

Mississippian

Great Blue Formation

Mgu — Upper member -Cherty gray, fossiliferous limestone in upper part, interbedded olive-gray shale and limestone in lower part; 430-740 feet (131-226 m) thick.

Mgl — Lower member - Medium- to dark-gray, fossiliferous limestone; 550-800 feet (168-224 m) thick.

Mh — Humbug Formation - Brown sandstone with interbedded sandy limestone or limestone; 800-850 feet (244-259 m) thick.

Md — Deseret Limestone - Cherty limestone and minor sandstone; thin phosphatic shale and black chert in lower part; 90-175 feet (27-53 m) thick.

Ml — Lodgepole Limestone - Medium- to dark-gray, fossiliferous limestone; 950-1,000 feet (290-305 m) thick.

Devonian

Db — Beirdneau Formation - Medium- to light-gray dolomite, and orange dolomitic sandstone and siltstone; 0-346 feet (0-105 m) thick.

Dh — Hyrum Formation - Dark- to medium-gray dolomite, includes two or three thin local quartzite beds; 450-700 feet (137-213 m) thick.

Water Canyon Formation

Dwcu — Upper member - Light-gray to white dolomite containing fish-bone fragments; 350-450 feet (107-137 m) thick.

Dwcm — Middle member - Grayish-orange dolomitic sandstone and sandy dolomite, some thin limestone beds near middle of unit; 350-400 feet (107-122 m) thick.

Dwcl Dwl — Lower member - Light-gray laminated, nonfossiliferous dolomite; 400-430 feet (122-131 m) thick.

Silurian

Laketown Dolomite

Slu — Upper member - Light- to medium-gray, coarsely crystalline dolomite containing colonial corals; 550 feet (168 m) thick.

Sll — Lower member - Medium- to dark-gray dolomite containing colonial corals; 560 feet (171 m) thick.

Appendix B (continued)

Ordovician

Ofh — Fish Haven Dolomite - Dark-gray to medium-gray, fossiliferous dolomite; 180-200 feet (55-61 m) thick.

Osp — Swan Peak Formation - Dark olive-gray shale in lower part and white to purple quartzite in upper part; shale is fossiliferous; 260-380 feet (79-116 m) thick.

Ogc — Garden City Formation - Fossiliferous limestone, silty limestone, intraformational limestone conglomerate; chert is common in upper part; 1,330-1,390 feet (405-424 m) thick.

Cambrian

St. Charles Formation

Ꞓscu / Ꞓsu — Upper member - Dark- to light-gray, thick-bedded dolomite; some silty dolomite in upper part; 980-990 feet (299-302 m) thick.

Ꞓscl / Ꞓsl — Lower member - Thin interbedded quartzite, limestone, and shale in lower part; silty limestone in upper part; fossiliferous; 170-180 feet (52-55 m) thick.

Nounan Formation

Ꞓsu — Upper member - Interbedded dolomite, sandy dolomite, dolomitic sandstone, and thin, fossiliferous limestone; 545 feet (166 m) thick.

Ꞓnl — Lower member - Medium- to dark-gray dolomite; 650-730 feet (198-222 m) thick.

Bloomington Formation

Ꞓbc — Calls Fort Shale Member - Olive-gray shale, medium- to light-gray silty limestone, intraformational limestone conglomerate; fossiliferous; 235-306 feet (72-93 m) thick.

Ꞓbm — Middle limestone member - Medium-gray, argillaceous, crystalline limestone; 650 feet (198 m) thick.

Ꞓbh — Hodges Shale Member - Light-olive- to light-brown shale interbedded with light- to dark-gray, silty limestone; 335 feet (102 m) thick.

Ꞓbl — Blacksmith Formation - Very fine to coarsely crystalline, very light to medium gray, thick-bedded dolomite and dolomitic limestone; 810 feet (247 m) thick.

Ꞓu — Ute Formation - Interbedded gray, sandy limestone and shale in lower part; gray limestone in upper part; 690 feet (210 m) thick.

Ꞓlu — Langston Formation

Upper member - Medium to coarsely crystalline, light brown to light gray dolomite and limestone; 250 feet (76 m) thick.

Ꞓll — Lower member - Medium-gray, crystalline, brown-weathering limestone, dolomite, yellowish- to reddish-brown- and gray-weathering silty shale interbedded with silty limestone, and minor sandstone; 230 feet (70 m) thick.

Ꞓm — Maxfield Limestone - Thin- to medium-bedded, finely crystalline, medium- to dark-gray and medium- to dark-blue-gray limestone and dolomite; 900 feet (274 m) thick.

Ꞓo — Ophir Formation - Light-brown to greenish-brown and olive-drab micaceous shale and siltstone; 98-130 feet (30-40 m) thick, but structural thickness locally varies due to ductile deformation.

Ꞓt — Tintic Quartzite - Coarse- to medium-grained, medium- to thick-bedded quartzite with locally abundant cross-bedding. Upper part is generally white or tan; lower part is more darkly colored with purplish to reddish-brown hues. Base of unit contains a deep-purplish-red, quartzite-pebble conglomerate. Thickness 1,200-1,400 feet (366-427 m).

Appendix B (continued)

Geertsen Canyon Quartzite

Ꞓgu — Upper member - Medium- to coarse-grained, cross-bedded, medium- to thick-bedded quartzite interbedded with dark purplish- to greenish-gray argillite; 360 feet (110 m) thick.

Ꞓgl Ꞓgc — Lower member - Pale pinkish-gray to white, medium- to very thick-bedded, cross-bedded quartzite with lenses and layers of pebble conglomerate. Pebbles are rounded, light-colored quartzite. Thickness 3,900-4,500 feet (1,189-1,372 m).

Proterozoic

Zbq — Browns Hole Formation

Quartzite Member - White, medium- to fine-grained, medium-bedded, vitreous quartzite. A lower member of basaltic to andesitic, purplish- to reddish-gray volcanic breccia is locally present. Thickness 115-280 feet (35-85 m).

Zm — Mutual Formation - Medium- to coarse-grained, locally pebbly, gray to purplish-gray feldspathic quartzite interbedded with greenish- to purplish-gray argillite; 2,215-2,625 feet (675-800 m) thick.

Zi — Inkom Formation - Laminated, green-weathering siltstone with lenses of tuff, and dark-green, fine-grained sandstone; 16-197 feet (5-60 m) thick.

Zcc — Caddy Canyon Quartzite - Light-gray and greenish-gray, medium- to thick-bedded, fine-grained quartzite with minor interbedded dark gray argillite; 984-1,640 feet (300-500 m) thick.

Zpc — Papoose Creek Formation - Gray, brown, and greenish-brown siltstone, interbedded with fine-grained quartzitic sandstone and medium- to coarse-grained quartzite; 755-1,509 feet (230-460 m) thick.

Zkc — Kelley Canyon Formation - Thin-bedded, dark-gray to olive-drab argillite; 590 feet (180 m) thick.

Zmc — Maple Canyon Formation - Coarse-grained, pale-green to greenish-gray arkosic quartzite, locally grading to pebble conglomerate, interbedded with olive-drab and green laminated siltstone; 984-1,476 feet (300-450 m) thick.

ZYp — Formation of Perry Canyon, undivided. Also divided into:

ZYps — Sandstone member - Olive-drab to brown siltstone and fine-grained quartzitic sandstone, with minor dark-gray shale and mudstone; 2,952 feet (900 m) thick.

ZYpd — Diamictite member - Gray to black diamictite with boulder- to pebble-size quartzitic and granitoid clasts set in a black, medium- to fine-grained, sandy mudstone matrix; 0-1,640 feet (0-500 m) thick.

ZYpm — Mudstone member - Massive black mudstone and sandy mudstone grading laterally into slate; 1,640-3,280 feet (500-1,000 m) thick.

Xf — Facer Formation, undivided. Also divided into:

Xfq — Quartzite member - Medium- to thick-bedded, white to pale-gray, vitreous quartzite, intercalated with muscovite-chlorite schist; 1,312 feet (400 m) thick.

Xfs — Schist and phyllite member - Grayish-green and grayish-purple siltstone and mudstone; 1,312 feet (400 m) thick.

XAfc — Farmington Canyon Complex - Medium- to coarse-grained quartz monzonite gneiss composed of quartz, plagioclase, alkali feldspars, and minor biotite. hornblende. May include lenses of gneiss and schist derived from sedimentary rocks of Archean age. Thickness is greater than 5,000 feet (1,524 m).

APPENDIX C

Correlation Charts

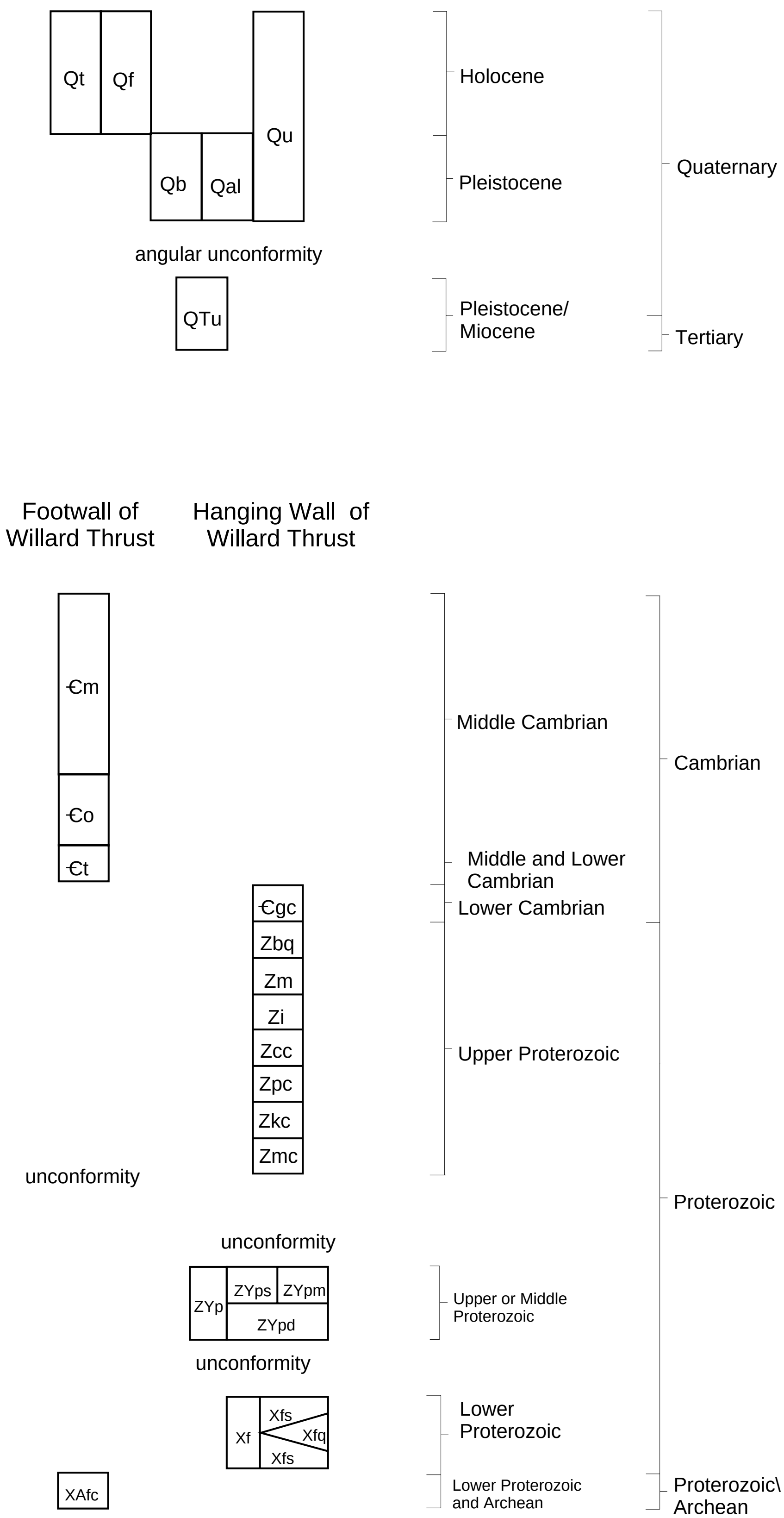


***Figure C.1.** Correlation chart for cross sections A-A' through E-E', appendix A (modified from Crittenden and Sorensen, 1985a and 1985b).*

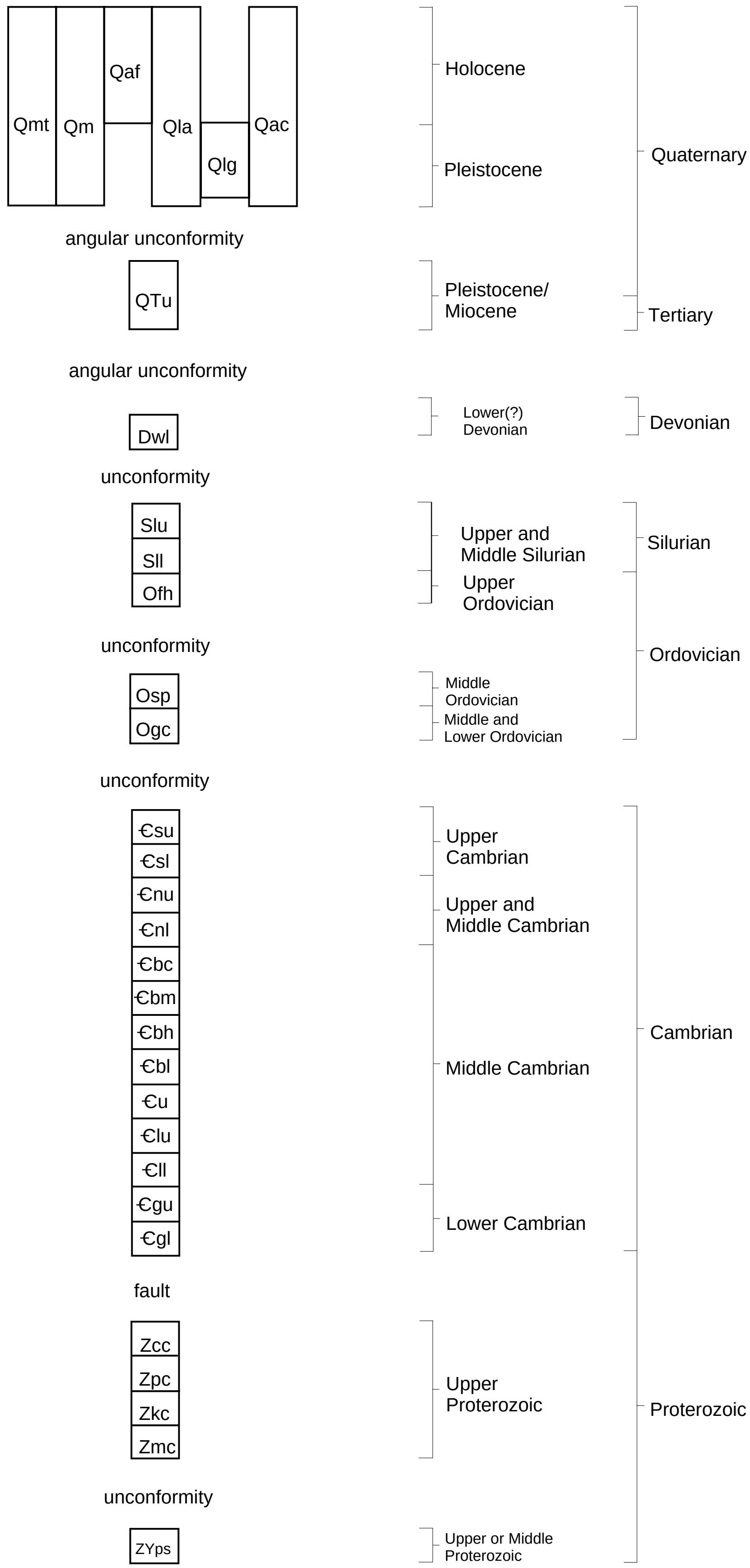


Figure C.2. *Correlation chart for cross sections F-F' through K-K'; appendix A (modified from Sorensen and Crittenden, 1976, and Jensen and King, 1995).*

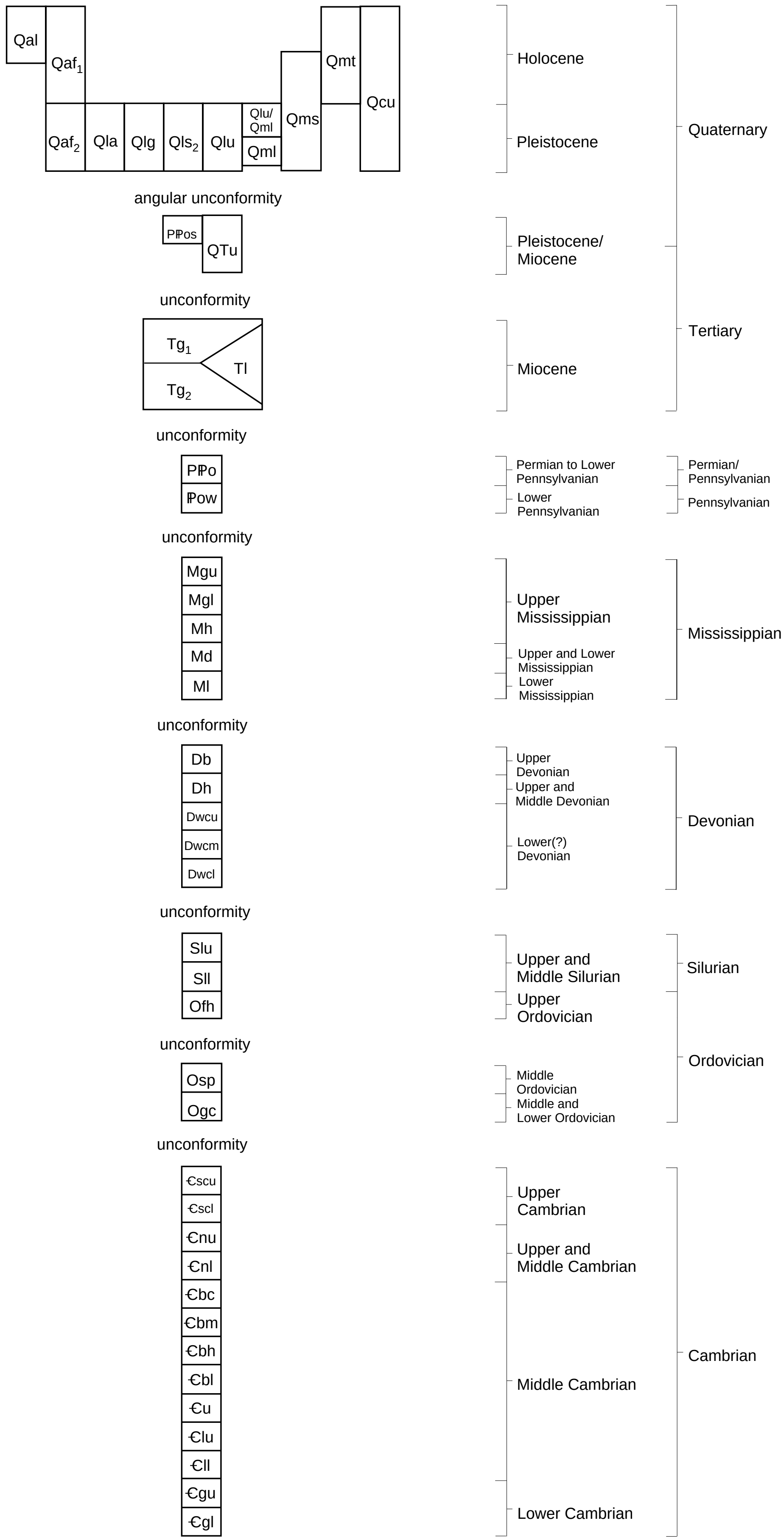


Figure C.3. *Correlation chart for cross sections L-L' through Q-Q', appendix A (modified from Oviatt, 1986).*

APPENDIX D

Summary of lithostratigraphy and fracture characteristics of bedrock units in study area

Map Symbol	Formation Name	Age	Lithology	Thickness in feet (m)	Fracture Characteristics
PIPo	Oquirrh Group	Permian to Early Pennsylvanian	Interbedded limestone and sandstone	5,000 (1,524)	Moderate density; some calcite filling; moderate connectivity
IPow	West Canyon Limestone	Early Pennsylvanian	Bioclastic limestone	400-450 (122-137)	Moderate density; some calcite filling; moderate connectivity
Mmc[1]	Manning Canyon Shale	Late Mississippian	Interbedded shale and limestone	900 (274)	Outcrops not observed
Mgu	Great Blue Limestone- upper member	Late Mississippian	Bioclastic limestone	430-740 (131-226)	Moderate to low density; calcite filling common; moderate to low connectivity
Mgm[1]	Great Blue Limestone- middle member	Late Mississippian	Interbedded limestone and siltstone	600 (183)	Outcrops not observed
Mgl	Great Blue Limestone - lower member	Late Mississippian	Bioclastic limestone	550-800 (168-244)	Moderate to low density; calcite filling common; moderate to low connectivity
Mh	Humbug Formation	Late Mississippian	Interbedded sandstone and limestone	800-850 (244-259)	Moderate to low density; mostly clean surfaces; moderate to low connectivity
Mlf[1]	Little Flat Formation	Mississippian	Sandstone with interbedded limestone	900 (274)	Outcrops not observed
Md	Deseret Limestone	Late and Early Mississippian	Cherty bioclastic limestone	90-175 (27-53)	Moderate to low density; calcite filling common; moderate to low connectivity
Ml	Lodgepole Limestone	Early Mississippian	Well-bedded bioclastic limestone	950-1,000 (290-305)	Moderate to high density; mostly clean surfaces; high connectivity
Db[2]	Beirdneau Formation	Late Devonian	Dolomite, sandstone, and siltstone	0-346 (0-105)	Outcrops not observed
Dh	Hyrum Formation	Late and Middle Devonian	Algal and bioclastic limestone and dolomite	450-700 (137-213)	Low to moderate density; some calcite filling; low connectivity
Dwu Dwcu[3]	Water Canyon Formation - upper member	Early(?) Devonian	Dolomite	350-450 (107-137)	Moderate to high density; some calcite filling; moderate to high connectivity
Dwm Dwcm[3]	Water Canyon Formation - middle member	Early(?) Devonian	Interbedded sandstone and limestone	350-400 (107-122)	Moderate density; mostly clean surfaces; moderate connectivity
Dwl Dwcl[3]	Water Canyon Formation - lower member	Early(?) Devonian	Dolomite	400-430 (122-131)	Moderate to high density; some calcite filling; moderate connectivity

Map Symbol	Formation Name	Age	Lithology	Thickness in feet (m)	Fracture Characteristics
Slu	Laketown Dolomite - upper member	Late or Middle Silurian	Medium- to coarse-grained dolomite	550 (168)	Moderate density; some calcite filling; moderate connectivity
Sll	Laketown Dolomite - lower member	Late or Middle Silurian	Medium- to coarse-grained dolomite	560 (171)	Moderate to high density; some calcite filling; moderate connectivity
Ofh	Fish Haven Dolomite	Late Ordovician	Medium- to fine-grained dolomite	180-200 (55-61)	Moderate to low density; some calcite filling; low connectivity
Osp	Swan Peak Formation	Middle Ordovician	Quartzite and shale	260-380 (79-116)	Moderate to high density; clean surfaces; high connectivity
Ogc	Garden City Formation	Middle and Early Ordovician	Well-bedded, silty to clayey limestone	1,330-1,390 (405-424)	Moderate to low density; calcite filling common; moderate connectivity
Ꞓsu Ꞓscu[3]	St. Charles Formation - upper member	Late Cambrian	Thick-bedded limestone and dolomite, locally cherty	980-990 (299-302)	Moderate density; some calcite filling; moderate to low connectivity
Ꞓsl Ꞓscl[3]	St. Charles Formation - lower member	Late Cambrian	Interbedded shale and limestone	170-180 (52-55)	Low to moderate density; mostly clean surfaces; moderate connectivity
Ꞓnu	Nounan Formation - upper member	Late and Middle Cambrian	Dolomite and sandy dolomite	545 (166)	Moderate to high density; mostly clean surfaces; moderate to high connectivity
Ꞓnl	Nounan Formation - lower member	Late and Middle Cambrian	Dolomite	650-730 (198-222)	Moderate to high density; mostly clean surfaces; moderate to high connectivity
Ꞓbc	Bloomington Formation - Calls Fort Shale Mbr.	Middle Cambrian	Interbedded shale and limestone	235-306 (72-93)	Moderate to low density; mostly clean surfaces; moderate to high connectivity
Ꞓbm	Bloomington Formation - middle limestone member	Middle Cambrian	Thick-bedded limestone	650 (198)	Moderate density; some solution widening along bedding plane-joint inter-sections
Ꞓbh	Bloomington Formation - Hodges Shale Mbr.	Middle Cambrian	Interbedded shale and limestone	335 (102)	Moderate to low density; mostly clean surfaces; moderate connectivity
Ꞓbl	Blacksmith Formation	Middle Cambrian	Hard, fine-grained dolomite	810 (247)	Very high density; clean surfaces; very high connectivity
Ꞓu	Ute Formation	Middle Cambrian	Thin-bedded limestone with sandy to silty interbeds	690 (210)	Moderate density; mostly clean surfaces; moderate connectivity
Ꞓlu	Langston Formation - upper member	Middle Cambrian	Interbedded limestone and dolomite	250 (76)	Moderate density; some calcite fill; moderate to low connectivity
Ꞓll	Langston Formation - lower member	Middle Cambrian	Interbedded limestone and shale	230 (70)	Moderate to low density; some calcite filling; moderate to low connectivity

Map Symbol	Formation Name	Age	Lithology	Thickness in feet (m)	Fracture Characteristics
Ꞓm[4]	Maxfield Limestone	Middle Cambrian	Interbedded limestone, dolomite, and shale	900 (274)	Low to moderate density; calcite veins common; moderate connectivity
Ꞓo[4]	Ophir Formation	Middle Cambrian	Dark, micaceous shale	98-130 (30-40)	Low to moderate density; clean surfaces; low connectivity
Ꞓt[4]	Tintic Quartzite	Middle and Early Cambrian	Orthoquartzite and conglomerate	1,200-1,400 (366-427)	Very high density; clean surfaces; high connectivity
Ꞓgu	Geertsen Canyon Quartzite - upper member	Early Cambrian	Interbedded orthoquartzite, siltstone, and shale	360 (110)	Moderate to high density; clean surfaces; high connectivity
Ꞓgl Ꞓgc[3]	Geertsen Canyon Quartzite - lower member	Early Cambrian	Ortho-quartzite and conglomerate	3,900 - 4,500 (1,189-1,372)	Moderate to very high density; clean surfaces; high connectivity
Zbq	Browns Hole Formation - quartzite member	Late Proterozoic	Hard, vitreous orthoquartzite	115-280 (35-85)	High density; clean surfaces; high connectivity
Zm	Mutual Formation	Late Proterozoic	Quartzite, siltstone, and shale	2,215-2,625 (675-800)	High density; clean surfaces; high connectivity
Zi	Inkom Formation	Late Proterozoic	Volcaniclastic sandstone, siltstone, and shale; tuff	16-197 (5-60)	Moderate density; clean surfaces; low to moderate connectivity
Zcc	Caddy Canyon Quartzite	Late Proterozoic	Orthoquartzite and minor shale	984-1,640 (300-500)	High to very high density; clean surfaces; high connectivity
Zpc	Papoose Creek Formation	Late Proterozoic	Siltstone, shale, and quartzite	755-1,509 (230-460)	High to moderate density; clean surfaces; moderate connectivity
Zkc	Kelley Canyon Formation	Late Proterozoic	Shale	590 (180)	Outcrops not observed
Zmc	Maple Canyon Formation	Late Proterozoic	Quartzite and conglomerate	984-1,476 (300-450)	High to very high density; some mineralization on surfaces; high connectivity
ZYps	Formation of Perry Canyon - sandstone member	Late or Middle Proterozoic	Interbedded sandstone and siltstone	2,952 (900)	Moderate to low density; clean surfaces; moderate to low connectivity
ZYpd	Formation of Perry Canyon - diamictite member	Late or Middle Proterozoic	Black shale with quartzite pebbles	0-1,640 (0-500)	Low to moderate density; some mineralization; low connectivity
ZYpm	Formation of Perry Canyon - mudstone member	Late or Middle Proterozoic	Mudstone to sandy mudstone	1,640-3,280 (500-1,000)	Outcrops not observed
Xfq	Facer Formation - quartzite member	Early Proterozoic orthoquartzite	Hard, vitreous	1,312 (400)	High to very high density; clean surfaces; very high connectivity

Map Symbol	Formation Name	Age	Lithology	Thickness in feet (m)	Fracture Characteristics
Xfs	Facer Formation - schist and phyllite member	Early Proterozoic	Micaceous schist	1,312 (400)	Moderate to low density; some calcite filling; moderate connectivity
XAfc[4]	Farmington Canyon Complex	Early Proterozoic and Archean	Granitic gneiss	5,000+ (1,524+)	Moderate to high density; clean surfaces; moderate connectivity

[1] *Mapped only in Brigham City quadrangle (Jensen and King, 1995). Units Mmc, Mgm, and Mlf of Jensen and King (1995) are not depicted in appendix A because they do not appear on the cross sections in this report.*
[2] *Mapped only in Honeyville quadrangle (Oviatt, 1986).*
[3] *Some units have slightly different map symbols in different published quadrangles.*
[4] *Mapped only in Mantua, Willard, and North Ogden quadrangles (Crittenden and Sorensen, 1985a and 1985b).*