GEOLOGIC AND HYDROGEOLOGIC SETTING OF THE UPPER EMIGRATION CANYON AREA

By W. Adolph Yonkee and Don A. Barnett

Prepared for:
Emigration Improvement District
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Executive Summary

Geologic mapping and structural analysis of the Upper Emigration Canyon study area were completed to provide a better understanding of the stratigraphy, structure, and spatial distribution of bedrock units, and the potential implications on the nature of ground-water flow. The area is located in a region of complexly folded and fractured bedrock with a varied stratigraphy and steep topography, resulting in potentially complex ground-water flow patterns. Partly because of these complexities, there is a need to carefully target and test new potential water resources, evaluate safe yields of existing and any new water resources, and protect all existing and potential new water resources from potential contaminants. Specific key points are summarized below.

- Stratigraphically, the study area exposes a thick sequence of overall steeply dipping Pennsylvanian to Early Cretaceous sedimentary rocks, including limestone, dolostone, sandstone, mudstone, and shale, which are locally capped by a gently dipping Late Cretaceous conglomerate unit. In general, thicker-bedded limestone, dolostone, and

sandstone intervals tend to have larger-scale fractures of a variety of orientations, whereas shale and mudstone intervals tend to have smaller-scale, bed-parallel partings.

- Structurally, Emigration Canyon is located along a major syncline (down warp), which has a northeast-trending, gently northeast-plunging hinge that roughly coincides with the bottom of the main canyon. The study area is located along the northwest limb of the syncline and exposes northeast-striking, overall steeply southeast-dipping beds, although in detail bedding varies from moderately southeast-dipping to overturned, northwest-dipping. No major faults are exposed at the surface in the study area, although faults are likely present at depth.

- Topographically, the study area has a series of second order drainage divides and basins (including Killyon Canyon, Jeep Creek Canyon, Burr Fork, Brigham Fork, and Freeze Creek) that trend northwest to southeast from greater to lower elevations toward the main canyon bottom, and thus are subperpendicular to the strike of bedding. Thus, successively higher stratigraphic levels are encountered going topographically downward within a single basin, and the elevation of a single stratigraphic unit systematically increases and decreases going along strike from drainage divides to drainage bottoms.

- Strong correlations exist between stratigraphy and the locations of springs and gaining sections of streams (e.g. a line of springs and gaining sections of streams occur near the top of the Nugget Sandstone). Based on these correlations, and following Ashland and others (1996) who studied a similar sequence of rock in the nearby Park City area, bedrock in the study area is provisionally divided into hydrostratigraphic units that contain more fractured layers of limestone, dolostone, and sandstone, and are potentially more permeable aquifers; and into confining intervals that contain less fractured shale and mudstone, and probably limit ground-water flow. From stratigraphic bottom to top, and exposed from northwest to southeast, hydrostratigraphic units include: the Weber, Upper Park City, Thaynes, Nugget, Lower Twin Creek, and Upper Twin Creek units.

- Hydrostratigraphic units are provisionally subdivided into topographic subunits based on second order drainage divides, which may crudely correspond to ground-water flow divides. However, ground-water divides are likely dynamic, changing with seasonal fluctuations in water levels and with drawdown from pumping of wells, and topographic and ground-water divides may not correspond to each other in areas of complex geology, complex topography, or gentle topography.

- Recharge to subunits is probably mostly from a combination of direct infiltration of precipitation where the subunit is exposed within a basin, leakage between subunits, and from leakage of surface waters from losing parts of streams that cross a subunit. Additional recharge may occur by leakage of ground water into subcrops of a unit that projects underneath the Late Cretaceous conglomerate and from flow of shallow ground water in thin unconsolidated deposits that overlie various parts of drainage basins.

- Although the area has been provisionally divided into hydrostratigraphic units and topographic subunits, there should not be an inference that water can not flow into, out of, or between units. Some leakage between hydrostratigraphic units is probable as ground water slowly percolates down gradient through less permeable layers. Also, flow between topographic subunits is likely in areas of more subdued topography, such as associated with the Upper Twin Creek unit, and significant amounts of surface waters leak into some subunits.

- Special considerations for developing, estimating safe yields, and protecting ground-water resources in the study area include:

  (a) Potential water resources are largely located within steeply dipping, fractured bedrock aquifers, which probably have complex, heterogeneous, anisotropic permeability structures.

(b) The ability of fractured bedrock aquifers to store water may be relatively low, resulting in potentially large seasonal fluctuations in water levels and relatively rapid lowering of water levels during periods of drought.

(c) Hydrostratigraphic units and topographic subunits are limited in areal extent. As wells completed into these subunits are pumped, their cones of depression may encounter aquifer boundaries or less fractured areas, resulting in increased rates of drawdown. Also, after prolonged or high rates of pumping such wells may recover at relatively slow rates. Also, the ability of a fractured bedrock aquifer to transmit water may be decreased over time by over pumping that causes excessive drawdown and closing of fractures.

(d) The combination of complex permeability structure and potentially low storage may make estimates of safe yield difficult.

(e) The combination of multiple recharge sources for aquifers and potentially rapid and complex fluid flow paths may make determination of source protection areas difficult. Because fluid flow may be rapid along fractures, contaminants may undergo relatively little filtration, indicating an important need to adequately protect recharge areas from potential contamination sources.

(f) Complications may be encountered in drilling wells in steeply dipping rocks.

(g) Currently available hydrogeologic data are limited.

- However, as steeply dipping, fractured bedrock aquifers are the only available ground-water resources in the area, consideration should be given to cautiously proceeding with an exploration program that includes: detailed hydrogeologic mapping of specific target sites; long-term monitoring of spring and stream discharges; seepage studies on streams to determine losing and gaining stretches; aquifer tests on existing domestic wells; and geochemical and isotopic analyses to constrain potential flow paths and residence times of ground water.

- Hydrogeologically, a number of possible targets exist for water resource development in the study area, but access, economic, and environmental factors that are beyond the scope of this study, will also need to be considered and may limit potential development. Possible targets include Secret, Thomas and the Pinecrest Pipeline Operating Company springs along upper Burr Fork, as well as potential well sites in the Thaynes, Nugget, Lower Twin Creek, and Upper Twin Creek hydrostratigraphic units where exposed along Burr Fork and Brigham Fork. Potential targets also occur along Jeep Creek Canyon and Killyon Canyon, but access would be very difficult.

- In any drilling program, particularly in steeply dipping bedrock, there is a risk that target stratigraphic units will be missed in whole or in part, long intervals of non-productive rock will be encountered, and difficulties may be encountered in maintaining a straight well bore during drilling. Thus test wells are strongly encouraged at any potential production well site.

INTRODUCTION

Scope of Work

This report summarizes results of geologic mapping and structural analysis of a study area in the upper part of Emigration Canyon (Figure 1). The study area is located within parts of sections 9, 10, 14, 15, 16, 17, 20, 21, 22, 23, 27, 28, and 29 of T.1N., R.2E. Field work in the area was completed during parts of June, July, August, September and October of 1997 using standard methods. Geologic mapping was conducted at a scale of 1:16,000 using a base map enlarged from the Mountain Dell 1:24,000 topographic map published by the U.S. Geological Survey and using color aerial photographs. General lithologic characteristics of geologic formations were determined by field observations of exposed rocks, and orientations of bedding were measured with a Brunton compass for structural analysis. Geologic data were then combined with available hydrologic data to help understand the hydrogeologic setting of the study area. Using this information, the following were completed: a general stratigraphic column (Figure 2); a geologic map illustrating the distribution of geologic formations (Figure 3); a map with representative bedding orientations (Figure 4); stereograms of bedding data for structural analysis (Figure 5); a series of cross sections illustrating interpreted subsurface distributions of geologic formations (Figure 6); a map summarizing main topographic features (Figure 7); a map showing distribution of potential hydrostratigraphic units and drainage basins (Figure 8), a series of cross sections illustrating interpreted subsurface distributions of potential hydrostratigraphic units (Figure 9), and graphs summarizing available pump test data for Freeze Creek Well #2 (Figure 10). Additionally, Appendix A presents of glossary of technical terms used in the report and Appendix B briefly explains important hydrology terms.

The upper Emigration Canyon study area lies within part of the Salt Lake City 30' by 60' sheet, which is covered by the U.S. Geologic Survey Map I-1944 at a scale of 1:100,000 (Bryant, 1990). The study area, however, has not been previously mapped at a detailed scale. Geologic mapping of the study area at a more detailed scale of 1:16,000 resulted in: revisions of some contacts on map I-1944; delineation and mapping of members within the Park City Formation, Thaynes Formation, and Twin Creek Limestone; addition of detailed bedding data for structural analysis; refined understanding of the structural and stratigraphic settings of springs; and interpretation of potential hydrostratigraphic units.

Regional Setting

Regionally, the upper Emigration Canyon study area lies within part of the Idaho-Utah-Wyoming thrust belt (Figure 1). This belt is characterized by a series of thrust faults and associated folds that transported a thick section of sedimentary rocks overall eastward to southeastward during the Cretaceous to Early Tertiary Sevier Orogeny (Royse and others, 1975). Most thrust faults have top-to-east to top-to-southeast slip and a stair-step geometry of very gently dipping flats and moderately dipping ramps that cut upwards toward the east in the direction of transport. Detachment faults that are subparallel to bedding and separate differently deformed packages of rocks, and backthrusts with top-to-west to top-to-northwest slip are also locally developed. Major faults exposed near the study area include the Crawford thrust, Mount Raymond thrust, and East Canyon fault zone (Figure 1). Large-scale folds are associated with transport of strata over thrust faults with stair-step geometries, propagation of thrust faults, concentrated shear near faults, and shortening along detachment faults. Major folds exposed within and near the study area include the Wasatch anticlinorium, Emigration Canyon syncline, Spring Creek anticline, and Parleys Canyon syncline (Figure 1). Locally developed cleavage, minor folds, and minor fault and fracture networks produce additional internal deformation. These structures are developed in a thick sequence of Cambrian to Jurassic sedimentary rocks (Granger, 1953), which are locally capped by Cretaceous to Early Tertiary synorogenic sediments that were derived by erosion of the growing thrust belt (Yonkee and others, 1997; Figure 1). Early Cretaceous strata comprise a lower synorogenic sequence derived by erosion of thrust sheets located to the west, Late Cretaceous strata comprise a middle synorogenic sequence deposited as the thrust belt propagated eastward, and latest Cretaceous to Early Tertiary strata comprise an upper synorogenic sequence deposited east of the progressively growing Wasatch anticlinorium. Normal faults, including the Wasatch normal fault, then developed during Late Tertiary extension, locally overprinting thrust structures and partly controlling development of current topography, including the Wasatch Range. Late Tertiary to Quaternary sediments and volcanic rocks partly filled corresponding basins that formed during extension.

The stratigraphic nature of bedrock units, combined with structural geometry and topography, partly control the nature of regional ground water flow, and have important implications for local development and protection of ground water resources (Ashland and others, 1996). In the following sections the stratigraphic relations of the geologic units exposed in the study area are first described, next the structural geometry of the area is analyzed, and key topographic features are then discussed. These data are combined with available hydrologic data to develop a provisional model for the general hydrogeology of the area, and potential implications for general development and protection of ground water resources are then discussed.

STRATIGRAPHY OF GEOLOGIC UNITS

Geologic units in the study area comprise a thick bedrock sequence of moderately to steeply dipping, Pennsylvanian to Early Cretaceous sedimentary strata, which are locally capped with angular unconformity by a gently dipping Late Cretaceous conglomerate unit, and are locally covered by thin, Quaternary unconsolidated deposits. The thick bedrock sequence consists of complexly interlayered limestone, dolostone, mudstone, shale, siltstone, and sandstone, as illustrated in the general stratigraphic column in Figure 2 and described below.

Pennsylvanian Strata

Weber Sandstone

This formation consists mostly of fine- to medium-grained, well-sorted, quartz-rich sandstone. The sandstone is overall medium- to thick-bedded, tan to light gray weathering, and is moderately resistant, generally forming steeper slopes covered by scree. A few layers of light gray dolostone and limestone are locally interbedded with the sandstone. Sandstone in the formation is variably cemented with quartz and calcite and is cut by closely to widely spaced fractures. Total thickness of the formation is probably between 1200 and 1700 ft (300 and 500 m), based on thicknesses in nearby areas (Bryant, 1990), but the base of the formation is not exposed in the study area.

Permian Strata

Park City Formation

This formation has been divided into three informal members in the study area: a lower member; a middle shale member; and an upper member. The informal lower, middle, and upper members may correlate respectively with the Grandeur, Meade Peak, and Franson Members (Granger, 1953). Total thickness of this formation in the study area is about 1600 ft (480 m), based on outcrop patterns.

The lower member consists of interlayered sandstone, dolostone, and limestone. Sandstone is overall fine- to medium-grained, well-sorted, tan to gray weathering, quartz-rich, and variably friable, being overall less well cemented than similar rocks in the stratigraphically underlying Weber Sandstone. Limestone and dolostone are fine-grained, light to dark gray, variably fossiliferous, and overall thick-bedded. This member is resistant, and contains a distinctive ridge-forming dolostone interval near its top. Beds in this member are cut by closely to widely spaced fractures, some layers appear locally brecciated, and some fractures in carbonate layers may have undergone solution widening. Thickness of this member is about 450 ft (135 m).

The middle member consists mostly of black, phosphatic shale, with some interbedded platy, dark gray, fine-grained, cherty limestone and dolostone. This member is non-resistant and forms swales generally covered by soil. Small-scale partings and fractures occur mostly parallel to bedding. Thickness of this member is about 700 ft (210 m).

The upper member consists of complexly interbedded dolostone, limestone, shale, and sandstone. The carbonates are thin- to thick-bedded, gray, fine-grained, and variably fossiliferous and cherty. Some intervals of dark gray to black shale occur near the middle of the member. Sandstone is fine-grained, quartz-rich, and thin- to thick-bedded. The member is overall resistant and forms ledgy exposures that contrast with overlying, poorly exposed lower Triassic strata.

Fractures are variably developed in this member, with longer fractures in thicker bedded intervals. Thickness of this member is about 450 ft (135 m).

Triassic Strata

Dinwoody Formation

This formation consists of tan to yellow-brown weathering, thin-bedded, calcareous siltstone, green-yellow shale, and gray to tan, thin-bedded, silty limestone. This unit is non-resistant and very poorly exposed, being generally covered by mass wasting deposits, making analysis of rock and fracture characteristics difficult. Small-scale partings occur parallel to bedding, but large-scale fracturing appears limited where the unit is exposed. Total thickness of the formation is about 400 ft (120 m), but is difficult to estimate due to poor exposure. This formation was previously combined with the Woodside Shale in mapping by Bryant (1990).

Woodside Shale

This formation consists of interbedded red to purplish red siltstone, shale, and some fine-grained, micaceous sandstone. An interval of gypsum occurs in this unit in the nearby Park City area (Ashland and others, 1996). Siltstone and sandstone are very-thin- to medium-bedded, and ripple marks are widespread. This unit is also non-resistant and very poorly exposed, being generally covered by mass wasting deposits with reddish soil. Large-scale fracturing appears limited where the unit is exposed, although small-scale fractures and bed-parallel partings are locally developed. Total thickness of the formation is about 700 ft (210 m), but is difficult to estimate due to poor exposure.

Thaynes Formation

This formation has been divided into four informal members in the study area: the basal Meekoceras limestone member; lower siltstone member, ridge limestone member, and upper siltstone member. Fracturing is variable through this lithologically complex and thick formation. Total thickness of this formation is about 2100 ft (630 m), based on outcrop patterns.

The Meekoceras limestone member consists of thin- to thick-bedded, variably silty, gray to tan weathering limestone. Parts of the limestone are highly fossiliferous with abundant remains of Meekoseras, a marine mollusc. This unit is overall resistant and generally forms ledgy outcrops. This member is cut by closely to widely spaced fractures. Thickness of this member is about 300 ft (90 m).

The lower siltstone member consists mostly of tan to yellow-gray weathering, thin-bedded, calcareous siltstone, with interlayered gray limestone and minor green shale. Limestone is mostly thin- to medium-bedded, fine-grained, and locally fossiliferous. The member is overall non-resistant and forms slopes with limestone ledges. The unit is variably fractured, with longer fractures in some limestone layers. Thickness of this member is about 500 ft (150 m).

The ridge limestone member consists of thick-bedded, slightly fossiliferous to oolitic, gray limestone. This unit is resistant and forms a distinct ridge. The limestone is moderately fractured in most exposures. Thickness of this member is about 50 to 100 ft (15 to 30 m).

The upper siltstone member consists mostly of tan to yellow-gray weathering, thin-bedded, calcareous siltstone, with some interlayered gray to tan weathering limestone, green shale, and rare red shale, similar in lithology to the lower siltstone member. Limestone is mostly thin-bedded, fine-grained, variably silty, and locally fossiliferous. The unit is overall non-resistant and forms slopes with limestone ledges. The upper part of the member is very poorly exposed and may include more abundant shale. The unit is variably fractured, with longer fractures in some limestone layers. Thickness of this member is about 1200 ft (360 m).

Ankareh Formation

This formation is locally divided into three members, a lower member, the Gartra Grit Member, and an upper member. However, in some locations the Gartra Grit is not apparent and the formation is not divided into members. Total thickness of the formation is about 1400 ft (430 m).

The lower member consists of interbedded red to purple-red siltstone, sandstone, and shale. Siltstone is thin-bedded, generally micaceous, and displays widespread ripple marks. Sandstone is thin- to medium-bedded, quartz-rich to micaceous, and fine- to medium-grained.

This member is overall non-resistant and poorly exposed, forming slopes with reddish soil and a few sandstone ribs. Where exposed, bed-parallel partings are widespread and some larger fractures at various angles to bedding are developed in sandstone layers.

The Gartra Grit Member consists of lenses of white to light-purple conglomerate and pebbly sandstone. Conglomerate and sandstone are overall thick-bedded, moderately sorted, moderately to well cemented, and contain quartz and chert pebbles. Lenses are laterally discontinuous, such that the member is not apparent everywhere. Where present, the member is overall resistant and forms discontinuous ledges. Fracturing is variable, with larger fractures in thicker-bedded layers. The member is about 20 to 80 ft (6 to 25 m) thick where present.

The upper member is lithologically similar to the lower member, consisting mostly of thin-bedded, red to purple-red siltstone, sandstone, and shale. This member is overall non-resistant, forming slopes with reddish soil and some sandstone ribs. Fracturing is variable, with mainly bed-parallel partings in siltstone intervals and some larger fractures in sandstone beds.

Jurassic Strata

Nugget Sandstone

This formation consists of tan- to salmon-colored, fine- to medium-grained, well-sorted, quartz-rich sandstone. The sandstone displays widespread, large-scale, high-angle cross bedding, making accurate determination of true bedding difficult. This unit is overall resistant and generally forms sandstone ledges, but is locally covered by mass wasting deposits on some north-facing exposures. Sandstone beds are variably cemented with quartz and calcite and are cut by widely to moderately spaced, large-scale fractures. Total thickness of the formation is about 1400 to 1500 ft (430 to 460 m).

Twin Creek Limestone

This formation consists mostly of fine-grained limestone, with lesser amounts of oolitic limestone, fossiliferous limestone, sandy limestone, siltstone, and claystone. The formation is divided into seven members, which are from bottom to top: the Gypsum Spring, Sliderock, Rich, Boundary Ridge, Watton Canyon, Leeds Creek, and Giraffe Creek Members (Imlay, 1967). The total thickness of the formation in the study area increases slightly westward from about 3200 to 3600 ft (970 to 1100 m). Thicknesses given below for individual members are general and may vary in areas of complex deformation.

The Gypsum Spring Member consists of red to red-brown mudstone and shale, but is very poorly exposed, forming covered slopes with distinctive reddish soil. Anhydrite layers have been reported locally in the subsurface in north-central Utah and southeastern Idaho (Peterson, 1957). Fracture characteristics are difficult to determine due to very poor exposure. Thickness of the member is about 80 to 120 ft (25 to 35 m). The contact with the underlying Nugget Sandstone is sharp and distinct.

The Sliderock Member consists of a lower interval of thick-bedded, variably fossiliferous to oolitic, gray limestone, overlain by an upper interval of thin- to medium-bedded, fine-grained, gray limestone. The lower interval is resistant and forms blocky ledges; the upper interval is moderately resistant and forms ribs and scree covered slopes. Limestone in the upper interval is slightly clayey and cut by widely spaced tectonic stylolites parallel to and subperpendicular to bedding. Widely to closely spaced fractures of varying orientation cut the lower interval, and partings occur parallel to the tectonic stylolites in the upper interval. Thickness of the member is about 100 to 150 ft (30 to 45 m).

The Rich Member consists of moderately clayey to silty, fine-grained, gray limestone. The member is non-resistant and generally forms swales. Limestone in the member displays weakly to strongly developed tectonic cleavage subperpendicular to bedding. The cleavage is defined by spaced seams of clay-rich material that give a "shaley" parting in some outcrops, but bedding is generally recognizable and defined by thin silty layers. Thickness of the member is about 350 to 450 ft (105 to 135 m).

The Boundary Ridge Member consists of a lower interval of thick-bedded, oolitic, gray limestone, overlain by an upper interval of red mudstone and shale. The lower interval forms a resistant ledge, whereas the upper interval is non-resistant and forms a distinct swale partly covered with reddish soil. Thickness of the member is probably about 100 to 150 ft (30 to 45 m), but varies locally due to internal deformation.

The Watton Canyon Member consists of thin- to thick-bedded, slightly clayey to silty, fine-grained, gray limestone, with a few layers of oolitic limestone. This unit is moderately resistant and forms steeper slopes with ledgy exposures. Some limestone beds display widely spaced tectonic stylolites subperpendicular to and subparallel to bedding, and partings along these stylolites give a characteristic blocky outcrop pattern. Fractures and partings are overall longer and wider than in other members of the Twin Creek Limestone. Thickness of this member is about 450 to 550 ft (135 to 165 m).

The Leeds Creek Member consists mostly of thin-bedded, moderately clayey to silty, fine-grained, gray limestone, with some interbedded silty limestone, claystone, siltstone, and fine-grained sandstone Beds of silty limestone and siltstone increase in abundance upward in the member, and several thin intervals of sandstone occur near the top of the member. Imlay (1967) also reports several intervals of claystone or shale, but this is difficult to verify due to poor exposure. The member is non-resistant and overall poorly exposed, forming gentle slopes covered with gray soil and float. Some clayey limestone beds display weakly developed tectonic cleavage subperpendicular to bedding, and small-scale partings along both cleavage and bedding produce local "pencil fracturing". The contact with the underlying Watton Canyon Member is transitional with a gradual decrease in clay content and increase in resistance stratigraphically downward. The thickness of the member increases from about 1700 to 2000 ft (about 500 to 600 m) going southwest across the study area, possibly reflecting primary stratigraphic variation or secondary tectonic thickening.

The Giraffe Creek Member consists mostly of thin- to thick-bedded, gray to tan, sandy limestone and calcareous sandstone, with lesser amounts of silty limestone, siltstone, and shale. Limestone is slightly fossiliferous and sandstone is fine- to medium-grained. The member is moderately resistant and forms blocky ledges. Variably spaced and oriented fractures cut limestone and sandstone beds. Thickness of the member is about 120 to 180 ft (35 to 55 m).

Preuss Formation

This formation consists of thin- to medium-bedded, red-brown to red siltstone, shale, and sandstone. Sandstone is fine- to medium-grained, contains some chert fragments, and is overall moderately sorted. The unit is non-resistant and generally forms a covered swale with reddish soil. This formation locally contains salt-bearing intervals in the subsurface in northern Utah and surrounding areas (Yonkee and others, 1997). Where exposed the unit displays variably spaced fractures, some minor faults, and bed-parallel partings. Thickness of the formation is about 1000 ft (300 m).

Early Cretaceous Strata

Kelvin Formation

The Kelvin Formation is divided into two members, the basal Parleys Canyon Member and the main body of the formation. This formation marks initial influx of large amounts of synorogenic debris that were eroded from a growing thrust belt to the west during the Early Cretaceous.

The Parleys Canyon Member consists of interlayered: red to white siltstone with calcareous concretions; white, fine-grained limestone; and lenses of pink to white, gritty sandstone and conglomerate. Limestone layers are resistant and form ledgy exposures. Conglomerate is moderately sorted and contains clasts to several inches in size. Thickness of this member is about 200 ft (60 m).

The main body of the Kelvin Formation appears to consist mostly of poorly exposed red mudstone, with beds and lenses of sandstone and conglomerate. Sandstone is thin- to thick-bedded, fine- to coarse-grained, contains chert and rock fragments, and is overall moderately sorted. Conglomerate lenses contain clasts to 12 inches (30 cm) in size. Clast types include dolostone, limestone, sandstone, and siltstone. Most of this unit is non-resistant and forms slopes covered by mass wasting deposits, but more resistant conglomerate and sandstone beds form local ledges. The top of the formation is not exposed in the study area, so only a minimum thickness of about 2000 ft (600 m) can be estimated.

Late Cretaceous Strata

Conglomerate Unit

A sequence of gently dipping conglomerate that overlies steeply dipping strata with angular unconformity in the northeast part of the study area is referred to herein as the "Conglomerate Unit". This unit represents synorogenic deposits shed off the Wasatch anticlinorium, and may correlate with the Late Cretaceous Weber Canyon Conglomerate to the north (Peter DeCelles, personal communication, 1997). The Conglomerate Unit consists of very-thick-bedded, moderately to poorly sorted, overall orange to gray-red conglomerate, which is clast-supported with some sandy matrix. Clasts in the conglomerate vary from pebble to boulder size, with larger clasts up to 24 inches (60 cm) across. Clast types include dolostone, limestone, sandstone, and some siltstone derived by erosion of Paleozoic to Jurassic strata. The unit is cut by overall long, but widely spaced fractures. Thickness of the unit is uncertain as the top is not exposed in the study area.

Quaternary Unconsolidated Deposits

Alluvial Deposits

Alluvial deposits occur along perennial and intermittent streams and consist mostly of clast-supported gravel with some sand, silt, and clay matrix. These deposits are overall moderately sorted and layered. Clast are mostly subrounded to rounded fragments of sandstone, limestone, dolostone, siltstone, and conglomerate derived from source areas along the streams. This unit also includes some debris flow deposits that are overall poorly sorted with abundant clayey matrix, are weakly to non-layered, and contain larger, angular clasts. Thicknesses of alluvial deposits are probably less than 20 ft (6 m) in most areas, and small exposures of bedrock locally protrude through alluvial deposits along some stream channels.

Mass Wasting Deposits

This unit includes hill-slope colluvium and landslide deposits, which are most abundant on north-facing slopes and overlying non-resistant units, including the Dinwoody, Woodside, Ankareh, Preuss, and Kelvin Formations. Deposits generally have thicker soil and denser vegetation compared to other units. Mass wasting deposits consist mostly of non-layered to weakly layered, non-sorted to poorly sorted, mixtures of gravel, sand, silt, and clay. Larger clasts are mostly angular, and clast types and nature of the matrix reflect source local source areas. Deposits derived from siltstone and mudstone have abundant clayey matrix, deposits derived from limestone and dolostone have angular carbonate clasts with some clayey matrix, and deposits derived from sandstone have sandstone clasts sitting in a sandy matrix. Landslide deposits have hummocky surfaces. Thickness of mass wasting deposits is probably less than 30 ft (9 m) in most areas, but some landslide deposits may be thicker.

STRUCTURAL GEOMETRY OF STUDY AREA

Structural Setting

The upper Emigration Canyon and surrounding areas were affected by several phases of thrust-related deformation including: an early phase of folding and cleavage development associated with detachment faulting; and a later phase of folding and limited cleavage development associated with slip on the Crawford-Mount Raymond-Absaroka thrust systems (Yonkee and others, 1992, 1997). The early phase probably occurred during the Early Cretaceous (between about 140 to 100 m.y.) and the later phase had a protracted history mostly during the Late Cretaceous (from about 100 to 65 m.y.). These thrust-related structures were then overprinted by younger extensional structures during the later Tertiary to Quaternary (from about 40 m.y. to recent).

Early-phase folds (referred to as F1 folds) consist of a series of north-trending anticlines and synclines that are best developed near Parleys Canyon (Figure 1). These folds formed between a fault within Permian strata, referred to as the "Lower detachment", and a probable fault in the Jurassic Preuss Formation, referred to as the "Upper detachment". An early-phase cleavage (defined by spaced seams of clay-rich material and referred to as S1) locally developed within the Twin Creek Limestone. This S1 cleavage is generally north-striking subparallel to F1 fold axes and about perpendicular to bedding. Only local, small-scale F1 folds and limited S1 cleavage development are, however, observed in the upper Emigration Canyon area.

Later-phase folds (referred to as F2 folds) consist of a series of northeast-trending anticlines and synclines, including the Parleys Canyon syncline, Spring Creek anticline, and Emigration Canyon syncline (Figure 1). These folds probably represent the southwestward continuation of a fold system associated with propagation and slip along the frontal parts of the Crawford and Mount Raymond thrust systems (Yonkee and others, 1997). These folds lie southeast of the Wasatch anticlinorium, a major basement-cored fold that formed synchronously with slip on the Crawford and Mount Raymond thrust systems. The anticlinorium has a steeply dipping southeastern limb that is shared with the steeply dipping northwestern limb of the Emigration Canyon syncline. In the Emigration Canyon area, the Crawford thrust is interpreted to be a "blind" fault in the subsurface that cores the Spring Creek anticline. A complex fault zone, referred to as the East Canyon fault zone, parallels the hinge of the Emigration Canyon syncline and is interpreted to have initiated as a backthrust (Figure 1; Yonkee and others, 1997). The Mount Raymond thrust system consists of several faults that ramp up and merge eastward with the Upper detachment, which forms a regional flat within the Absaroka thrust system further east. A later-phase cleavage (defined by widely spaced clay-rich seams and referred to as S2) is locally developed along with some small-scale F2 folds. The S2 cleavage is generally northeast-striking, subparallel to F2 fold axes, and subperpendicular to bedding. S2 cleavage is weakly developed in parts of the Twin Creek Limestone and Thaynes Formation in the upper Emigration Canyon area.

An early phase of extension started soon after cessation of thrusting about 40 m.y. ago, synchronous with localized volcanic activity. During this early phase the East Canyon fault zone was reactivated as a normal fault. A later phase of extension began about 15 m.y. ago and continues today. Large-scale normal faults, including the Wasatch normal fault, and smaller normal faults within parts of the Wasatch Range, developed during this later extension. The present day Wasatch Range was uplifted and gently tilted eastward due to slip along the Wasatch normal fault.

Structural Analysis of Study Area

The study area lies within the northwest limb of the Emigration Canyon syncline, which displays overall northeast to east-northeast striking, steeply southeast to south-southeast dipping bedding. Steeply dipping beds in this limb are capped with angular unconformity by gently dipping beds of the Late Cretaceous Conglomerate Unit. The hinge of the syncline trends roughly along the topographic bottom of upper Emigration Canyon just southeast of the study area; smaller-scale, complex F2 folds become well developed southwest of the study area along a broad hinge zone in the lower part of Emigration Canyon. No major thrusts are exposed in the study area, although the East Canyon fault zone is exposed just to the southeast near the hinge of the Emigration Canyon syncline (Figure 1).

In detail, bedding in the northwest limb of the Emigration Canyon syncline displays minor variations in strike and dip at various scales in the study area. Three general domains can be defined based on changes in average orientation of bedding (Figures 4 and 5). Within the western domain bedding generally strikes from 070° to 055° and dips from 40° to 70° southeast. The average orientation of bedding in the western domain, excluding areas of localized minor folding, has a strike of 062° and a dip of 58° southeast (Figure 5). Going eastward bedding steepens overall. Within the central domain bedding generally strikes from 065° to 050° and dips from 60° to 90° southeast. The average orientation of bedding in the central domain, excluding areas of localized minor folding, has a strike and dip of 057° and a dip of 71° southeast (Figure 5). Within the eastern domain bedding generally strikes from 060° to 045° and dips from 70° southeast to 80° northwest and overturned. The average orientation of bedding in the eastern domain, excluding areas of localized minor folding, has a strike of 052° and a dip of 90° southeast (Figure 5). Minor folds, from inches to tens of feet in scale, are also locally developed. These minor folds are disharmonic and best developed in well-bedded intervals, such as parts of the Twin Creek Limestone. Minor folds include: an open anticline developed in the lower Twin Creek Limestone just northeast end of Killyon Canyon with a fold axis plunging gently northeast; and an anticline-syncline pair developed in the middle Twin Creek Limestone just east for Freeze Creek with a fold axis plunging moderately east-northeast. The orientation of a best fit fold axis for all bedding data in the study area has a plunge of 15° and a trend of 060°, subparallel to orientations of F2 folds in this general area.

A series of cross sections further illustrate the structural geometry of the study area (Figure 6). Section A-A’ along Freeze Creek in the western domain displays moderately southeast-dipping beds with some minor warps, and mostly Jurassic to Early Cretaceous strata are exposed in this area. Sections B-B’ and C-C’ along Brigham Fork and Burr Fork in the central domain display overall steeply southeast-dipping beds with some minor warps, including a narrow band of moderately dipping beds near the northwest end of section B-B’. Mostly Pennsylvanian to Early Cretaceous strata are exposed along sections B-B’ and C-C’. Section D-D’ along Jeep Creek in the eastern domain displays subvertical to locally overturned beds, and Triassic to Early Cretaceous strata are exposed, capped by the gently dipping Late Cretaceous Conglomerate Unit at the northwest end of the section.

TOPOGRAPHIC FEATURES OF STUDY AREA

The study area displays relatively rugged topography, which may partly influence the nature of recharge and ground water flow. Regionally, the study area lies within the upper, northeastern part of the first-order (large-scale) Emigration Canyon drainage basin. The bottom of this basin slopes gently from northeast toward the southwest, about parallel to the hinge of the Emigration Canyon syncline and is drained by Emigration Creek. A number of second-order (smaller-scale) drainage basins occur on both the southeast and northwest sides of the canyon. Second-order basins in the study area are from northeast to southwest: Killyon Canyon basin, Jeep Creek basin, Middle Fork basin, Burr Fork basin, Brigham Fork basin, Freeze Creek basin, and an unnamed basin referred to as the “western” basin (Figure 7). The characteristics of these drainage basins are partly controlled by the structural geometry of bedrock layers. The bottoms of these basins slope moderately to gently, overall from northwest toward southeast, about perpendicular to the average strike of bedding. Streams that drain each of these basins thus transverse a number of geologic units, crossing from stratigraphically older units in the upper, northwestern parts of the basins to stratigraphically younger units in the lower, southeastern parts of the basins. Drainage divides for these basins correspond to intervening ridges, which slope overall moderately, but irregularly, from northwest toward southeast, with elevations of ridges generally being about 400 to 1000 ft above corresponding parts of the drainage bottoms. Thus outcrops of an individual stratigraphic unit systematically increase and decreases in elevation across drainage divides and bottoms (Figure 7). However, ridges are locally less than 400 ft above drainage bottoms in the southeastern part of the area where less resistant rocks of the upper Twin Creek to Kelvin Formations are exposed. There is also a slight overall decrease in the elevations of drainage bottoms progressively from northeast to southwest along outcrops of an individual stratigraphic unit. For example, the stratigraphic top of the Nugget Sandstone, along which a series of springs occur, decreases in elevation from about 6700 ft along the bottom of Killyon Canyon in the northeastern part of the area, to about 6400 ft along the bottom of Freeze Creek in the southwestern part of the area (Figure 7).

Elevations range from about 5800 ft along streams at the southwestern boundary of the study area to over 8900 ft at Lookout Peak along the ridge at the northeastern boundary of the area (Figure 7). Precipitation, as well as combined runoff and recharge by direct infiltration, are probably greater at higher elevations. Regions with elevations above 7000 ft comprise the upper parts of all second-order basins except for the western basin, and regions with elevations above 8000 ft occur in the uppermost parts of the Burr Fork, Jeep Creek, and Killyon Canyon basins. Although all parts of these basins are potential recharge areas, the upper parts of the basins are particularly important for recharge by direct infiltration and for runoff to streams. Leakage of surface waters from these streams may also help recharge other aquifers along the lower parts of the drainage basins, requiring consideration of a watershed approach to protecting ground water sources.

GENERAL HYDROGEOLOGIC SETTING OF STUDY AREA

Introduction

Observed characteristics of bedrock units in the study area, combined with comparison to the previous work of Ashland and others (1996) in the nearby Park City area, allow preliminary interpretation of the hydrostratigraphy of the upper Emigration Canyon area. Ashland and others (1996) proposed that fractured sandstone and carbonate intervals generally have higher permeabilities and may form what we refer to as hydrostratigraphic units (HSUs), whereas shale and mudstone intervals generally have much lower permeabilities and may act as confining intervals that limit short-term fluid flow between HSUs. Evidence for HSUs in the Park City area includes well aquifer test data and historical accounts of water flow in mine workings. The study area contains a similar stratigraphy as the Park City area, and relations of springs to stratigraphy provide limited evidence for similar HSUs in the upper Emigration Canyon area. Based on the observed stratigraphy, locations of springs, and units identified by Ashland and others (1996) in a similar sequence of rocks, provisional HSUs and confining intervals in the study area are indicated in Figure 2. Although fluid flow may be favored within a HSU, some fluid may also percolate across confining intervals between units.

Faults also partly control fluid flow, acting as complex conduit-barrier systems that may further subdivide fluid flow in HSUs into individual structural subunits (Caine and others, 1996). Ashland and others (1996) interpreted HSUs in the Park City area to be locally subdivided into individual fault-bounded subunits, which have different flow and recharge systems. Geologic mapping, however, indicates that large-scale surface faulting is limited in the study area, although major faults may exist at depth.

Topography also partly controls fluid flow, and topographic divides may roughly correspond to ground-water flow divides that further subdivide HSUs into individual topographic subunits in different basins, which may have different fluid flow and recharge systems. However, in areas of complex geology and anisotropic permeability, ground-water flow divides may not correspond to topographic divides, depending partly on relations between structural geometry, stratigraphy, and topography. In the study area, strata are overall northeast-striking and steeply dipping. Interlayering of relatively permeable and impermeable intervals, and presence of bed-parallel fractures, probably produce overall anisotropic permeability that would favor northeast-southwest fluid flow. Second-order drainage basins and divides in the study area trend from northwest to southeast, subperpendicular to the strike of bedding. Thus exposures of individual stratigraphic layers systematically increase and decrease in elevation going across the second-order drainage basin divides and bottoms, which may also favor northeast-southwest fluid flow from divides toward stream bottoms. However, where topographic divides are oblique to bedding, such as in the heads of the second order drainage basins, or where other structural complications occur, ground water and topographic divides may not coincide. Additionally, ground water divides are dynamic, and may change with seasonal variations in depths to the water table and with drawdown from pumping of water wells. Patterns may be particularly complex and dynamic where topographic divides are less pronounced and streams are losing water, such as in the southern part of the area along exposures of the Twin Creek Limestone. Elevations of different drainage bottoms along a single stratigraphic layer tend to decrease slightly going from northeast to southwest, such that a component of large-scale, northeast to southwest fluid flow could occur across some topographic divides and thus between some topographic subunits. Thus, boundaries between topographic subunits may be only weakly defined and dynamic, with the potential for significant ground water flow between some subunits, as well as for leakage of surface waters into some subunits along losing parts of streams.

Figure 9 illustrates relations between surface exposures of potential HSUs and drainage basins, which may have implications for recharge and flow systems of topographic subunits in the study area. For example, if topographic and ground water divides approximately coincide, then areas for direct recharge by infiltration of precipitation for individual subunits may correspond approximately with surface exposures of a hydrostratigraphic unit within a drainage basin. It is also extremely important to note that subunits may have significant indirect recharge by leakage of surface water from losing parts of streams, as well as from leakage of shallow ground water that flows through unconsolidated deposits overlying parts of a subunit, leakage between hydrostratigraphic units and across drainage divides between subunits, and leakage of ground water through the Cretaceous Conglomerate Unit into underlying subcrops of a hydrostratigraphic unit. Importantly, because of possible recharge from losing parts of streams, the entire drainage basin above a particular subunit may need to be considered for protection of ground water sources. Even along normally gaining parts of streams, pumping water from a well could locally lower the water table below stream level and result in leakage of surface waters into a subunit.

Although detailed hydrologic data are currently limited, the following section gives a provisional model for overall HSUs and topographic subunits that serves as a general guide for better understanding the general hydrogeology of the area, realizing that complications are likely. Complications include: drainage divides may not correspond to ground water divides in some areas; deep ground water may leak into hydrostratigraphic units at depth in the Emigration Canyon syncline over long time intervals; additional local confining intervals may be present in some units that further subdivide fluid flow patterns, and confining intervals may be locally breached by fractures and minor faults that allow some flow between HSUs. Importantly, interpretations of HSUs, subunits, and potential recharge areas should be tested with additional hydrologic data, such as long-term monitoring of spring discharges and stream flows, conducting additional well aquifer tests, long-term monitoring of water well levels and production, and conducting geochemical and isotopic studies to determine paths and average residence times of water in various subunits.

Potential Hydrostratigraphic Units and Confining Intervals

Weber HSU

The Weber HSU, following the nomenclature of Ashland and others (1996), is interpreted to consist of the Weber Sandstone and the lower member of the Park City Formation (Figure 2). The Weber Sandstone in the study area is variably fractured, probably producing heterogeneous permeability partly related to fracture intensity. The lower member of the Park City Formation contains variably cemented to brecciated sandstone and thick-bedded carbonates with some long fractures having possible solution widening, probably resulting in enhanced fracture and grain-scale permeability.

The Weber HSU is exposed in the upper part of the Burr Fork drainage basin (subunit W4 in Figure 8), which appears to be the source of Secret and Thomas springs (springs S1 and S2 in Figures 8 and 9). Periodic discharge measurements of these two springs have been made since the summer of 1993 (Table 1). Discharge has varied over time, with peak discharges occurring during late spring to early summer periods and low discharges during fall and winter periods of a given year. Average discharge also varied between years, with greater average discharge during 1995 to 1997, which had greater snowpacks. Overall, discharge has varied from about 35 to greater than 80 gpm for Secret Spring and from about 30 to 80 gpm for Thomas Spring. These springs are located along topographic lows and near the contact with a stratigraphically overlying, but topographically lower confining interval of shale to the southeast. Recharge areas for this subunit and associated springs probably include exposures of the Weber Sandstone and lower member of the Park City Formation in the upper part of Burr Fork drainage basin, with additional possible recharge from subcrops of these formations where they project beneath the Cretaceous Conglomerate Unit (Figure 8).

No wells have been completed in this interval in the upper Emigration Canyon area, so data on local aquifer characteristics are unavailable. Holmes and others (1996) reported apparent transmissivities (which is a measure of the ability of an aquifer to provide water to a well and is equal to the hydraulic conductivity times the thickness of an aquifer, Appendix B) of about 400 to 1000 ft^2 per day for one well and several mine workings completed in the Weber Sandstone in the nearby Park City area. The variation in values probably reflects significant variations in fracture intensity and connectivity that depend critically on structural setting, which is typical of most fractured bedrock aquifers.

Note, apparent transmissivity values reported by Holmes and others (1996) for this and other units are estimated from aquifer test data using the method described by Theis (1935) as modified by Jacob (1940), which has simplifying assumptions that include: the aquifer is homogeneous, isotropic, horizontal, and of large aerial extent; flow to the well is laminar and radial; the well fully penetrates the aquifer; and the well was pumped at a constant rate. These simplifying assumptions are violated in most cases, and values estimated from test data should be used with extreme caution, although they provide guidance on general aquifer properties. Further note that apparent transmissivity values determined in fractured bedrock aquifers may pertain more to fracture permeability than to grain-scale (or primary) permeability of the rock, and that fracture characteristics may vary greatly with structural setting and stress state, in addition to lithology and bed thickness (Keighly and others, 1997). Hence, reported transmissivity values are only directly applicable to the structural settings of the specific wells tested, and values for the same

Table 1 — Spring Discharge Measurements

Date of Measurement	Discharge of Secret Spring[1] (gpm)	Discharge of: Thomas Spring[2] (gpm)
July 15, 1993	49 gpm	84 gpm
November 11, 1993	46 gpm	43 gpm
June 1, 1994	65 gpm	--
June 16, 1994	52 gpm	82 gpm
June 30, 1994	44 gpm	54 gpm
July 12, 1994	44 gpm	49 gpm
August 2, 1994	40 gpm	43 gpm
August 18, 1994	40 gpm	30 gpm
September 6, 1994	37 gpm	37 gpm
September 20, 1994	39 gpm	33 gpm
October 12, 1994	37 gpm	38 gpm
November 11, 1994	37 gpm	37 gpm
July 1, 1995	82 gpm+	--
August 4, 1995	82 gpm+	81 gpm
September 11, 1995	82 gpm+	69 gpm
October 20, 1995	82 gpm	55 gpm
July 18, 1996	82 gpm+	75 gpm
September 5, 1997	82 gpm+	--

Notes:

[1] Measurement of discharge from Secret Spring is by a 90^0 V-notch weir with a capacity of 82 gpm.

[2] Measurement of discharge from Thomas Spring is by vessel method of both the flow in the stream below Thomas Spring as well as discharge from the "Geyser" pipe.

stratigraphic units in the Emigration Canyon area may be different and show large variations, depending on structural setting and local fracture characteristics.

Confining Interval

A confining interval is interpreted to correspond to the middle member of the Park City Formation, which separates the Weber HSU from the Upper Park City HSU (Figure 2). This member contains abundant shale with very small grain size, very thin bedding, and limited large-scale fracturing, probably producing low permeability and limiting fluid flow across this interval.

Upper Park City HSU

The Upper Park City HSU, following the nomenclature of Ashland and others (1996), is interpreted to correspond to the upper member of the Park City Formation (Figure 2). This member is lithologically complex, containing some thick-bedded intervals of dolostone, limestone, and sandstone with longer fractures that may enhance permeability.

The Upper Park City HSU is exposed along a narrow band in the upper part of Burr Fork drainage basin (subunit UP4 in Figure 8), which appears to the source of several seeps and one unnamed spring (spring S3 in Figures 8 and 9). This spring had a flow of less than 50 gpm during September, 1997, and is located along a low point in topography, near the contact with a confining interval of lower Triassic strata. Recharge areas for direct infiltration of precipitation for the subunit and associated spring probably include the narrow band of the upper member of the Park City Formation exposed along the upper part of Burr Fork basin, with some possible recharge from subcrops of the upper member that project beneath the Cretaceous Conglomerate Unit (Figure 8). Additionally, some recharge could come from leakage of surface stream water along the branches of Burr Fork where they cross the subunit. No wells have been completed in this interval in the study area, and thus its hydrologic properties are uncertain.

Confining Interval

An overall confining interval is interpreted to consist of the lower Triassic Dinwoody Formation and Woodside Shale (Figure 2), similar to the thick confining interval in lower

Triassic strata reported by Ashland and others (1996). These formations contain abundant siltstone and shale with fine grain size, thin bedding, and limited large-scale fracturing, probably producing overall low permeabilities, especially perpendicular to bedding. However, some thicker-bedded sandstone layers in this interval may have locally higher permeabilities, possibly giving rise to some thin, local aquifers. No wells have been completed in this interval in the study area. Holmes and others (1996) reported a relatively low apparent transmissivity of about 100 ft^2 per day based on production from a sandstone-bearing interval in the Woodside Shale, which is probably higher than values for shale-bearing intervals.

Thaynes HSU

The Thaynes Formation is lithologically complex and heterogeneously fractured, making interpretation of HSUs and confining intervals difficult (Figure 2). Ashland and others (1996) defined a Lower Thaynes HSU and an Upper Thaynes HSU, separated by a relatively thick confining interval of red shale in the Park City area. Thick red shale, however, is not observed in the study area, although several thin green and red shale intervals are present. Lacking detailed hydrologic data and information on the continuity of the shale intervals, a single, undivided Thaynes HSU is provisionally interpreted to correspond to most of the Thaynes Formation in the study area. Fluid flow, however, is likely complex in this unit, with local intervals of much lower and higher permeability. The basal Meekoceras limestone and middle Ridge limestone members contain thicker-bedded sequences of limestone with longer fractures and may have overall higher permeabilities. The lower siltstone and upper siltstone members probably have overall lower, but variable, permeabilities, with more fractured intervals having moderate permeabilities, and shale intervals that may form local confining layers having low permeabilities.

The Thaynes HSU is exposed within parts of the Jeep Creek, Burr Fork, and Brigham Fork drainage basins, respectively forming subunits T2, T4, and T5 in Figure 8. Several springs are located in these subunits within or close to topographic lows along exposures of the ridge limestone member (springs S4, S5, and S6 in Figures 8 and 9). Spring S5 located along Burr Fork is used as a public water supply and is reported to display seasonal and long term variations in discharge. Burr Fork and Brigham Fork appear to be overall gaining streams where they cross the Thaynes Formation, whereas some sections of Jeep Creek that cross the formation are non flowing for parts of the year. However, quantitative data on variations in stream flows are lacking. Direct recharge areas for these potentially complex subunits probably include exposures of the Thaynes Formation in the Jeep Creek, Burr Fork, and Brigham Fork drainage basins (Figure 8). Additional recharge to subunits may include local leakage of surface water from losing intervals of streams, leakage of shallow ground water that flows through unconsolidated deposits that overly parts of the Thaynes Formation, and leakage of ground water into subcrops of the Thaynes Formation that project northeastward beneath the Cretaceous Conglomerate Unit.

No wells have been completed in the Thaynes Formation in the study area. Holmes and others (1996) report overall high, but widely ranging, apparent transmissivities from about 2,000 to 7,000 ft^2 per day for more productive wells completed in the Thaynes Formation in the nearby Park City area. However, less productive wells located in less intensely fractured areas have much lower transmissivities. Future hydrologic studies in the Emigration Canyon area, including detailed long term monitoring of spring and stream discharge and pump test data, may be needed for better understanding local details of the Thaynes HSU.

Confining Interval

An overall confining interval is interpreted to consist of the Ankareh Formation, and possibly the more shaley uppermost part of the Thaynes Formation (Figure 2). Siltstone and shale with fine grain size, thin bedding, and limited fracturing, probably produce overall lower permeabilities. However, thin sandstone layers in this interval may have higher permeabilities, and form local aquifers. The Gartra Grit Member of the Ankareh Formation may form a local HSU (Ashland and others, 1996), but this member is laterally discontinuous and relatively thin in the study area. No wells have been completed in this interval in the study area.

Nugget HSU

The Nugget HSU, following the nomenclature of Ashland and others (1996), is interpreted to correspond directly with the Nugget Sandstone. This formation consists of well-sorted sandstone having variable grain-scale and fracture-related porosity and permeability, depending on degree of cementation and intensity of fracturing. Drilling logs for several small home-water-supply wells along Burr Fork indicate that fractured intervals preferentially transmit water.

The Nugget HSU is exposed within parts of the Killyon Canyon, Jeep Creek, Middle Fork, Burr Fork, Brigham Fork, and Freeze Creek drainage basins, respectively forming subunits N1 to N6 shown in Figure 8. A series of springs are located within these subunits along topographic lows in the Killyon Canyon, Jeep Canyon, and Freeze Creek basins (springs S7 to S10 in Figures 8 and 9), and these springs appear to be the main sources for stream flow in these basins. These springs occur near the contact with a stratigraphically overlying but topographically lower confining interval at the base of the Twin Creek Limestone to the southeast. Visually estimated flows for these springs during September, 1997, varied from greater than 80 gpm for a series of springs along Killyon Canyon to less than 5 gpm for the small spring along Middle Fork. Burr Fork and Brigham Fork appear to be overall gaining streams where they cross the Nugget Formation, but detailed stream flow measurements are lacking. Direct recharge areas for the Nugget subunits include exposures of the Nugget Formation in all the basins (Figure 8). Additional recharge may occur from: leakage of surface waters from losing parts of streams; ground water leaking into subcrops of the Nugget that project northeastward beneath the Cretaceous Conglomerate Unit, enhancing the flow of the Killyon Canyon springs; and leakage of shallow ground water that flows through unconsolidated deposits that overly both the Ankareh Formation and Nugget Sandstone.

Holmes and others (1996) reported apparent transmissivities of about 200 to 300 ft^2 per day for wells completed in the Nugget Sandstone in the nearby Park City area, and pump test data for a recently completed well in the Summit Park area give an apparent transmissivity of about 300 ft^2 per day (Weston Engineering, 1997). Several small home-water-supply wells completed in the Nugget Sandstone along Burr Fork have apparent transmissivities of about 400 to 1000 ft^2 per day for more fractured intervals, crudely estimated from limited data for short-term pump tests reported on drilling logs, which often overestimate well performance. These crude estimates in the study area should be used with extreme caution, and values may vary greatly depending on local fracture and grain-scale permeability.

Confining Interval

A thin, but widespread confining interval is interpreted to correspond to the Gypsum Spring Member of the Twin Creek Limestone, based on patterns observed in the Park City area (Ashland and others, 1996). This member contains mudstone and shale that probably have low permeability perpendicular to bedding, limiting fluid flow across this unit. The presence of a confining interval may be partly responsible for the line of springs observed at the stratigraphic top of the Nugget Sandstone in the study area.

Lower Twin Creek and Upper Twin Creek HSUs

The remainder of the Twin Creek Limestone is lithologically complex and thick (Figure 2). Ashland and others (1996) defined a Lower Twin Creek HSU and an Upper Twin Creek HSU, separated by a confining interval of red shale in the Boundary Ridge Member. Red shale is also observed in the study area and the formation is provisionally divided into an overall Lower Twin Creek HSU and an overall Upper Twin Creek HSU. Fluid flow, however, is likely to be complex within both HSUs, both of which may contain intervals with lower and higher permeabilities. Within the Lower Twin Creek HSU, the Sliderock and lower part of the Rich Members contain thicker-bedded limestones that tend to have longer fractures and may have relatively higher permeability, whereas thin claystone intervals in the upper part of the Rich Member may form local confining layers with low permeabilities. Within the Upper Twin Creek HSU, the Watton Canyon Member contains thicker-bedded limestone that tends to have overall longer fractures and may have overall higher permeabilities. The thick Leeds Creek Member may have overall lower, but highly variable permeabilities, with more fractured intervals having moderate permeabilities, and shaley and claystone intervals forming local confining layers with low permeabilities. The Giraffe Creek Member contains some thicker-bedded sandstone and sandy limestone that may have overall moderate permeabilities, as well as some thin shaley intervals that may have low permeabilities.

The Lower Twin Creek and Upper Twin Creek HSUs are exposed within parts of the Killyon Canyon, Jeep Creek, Middle Fork, Burr Fork, Brigham Fork, Freeze Creek, and western drainage basins, respectively forming subunits LT1 to LT 7 and UT1 to UT7 in Figure 8. Middle

Fork, Burr Fork, and Brigham Fork appear to be overall losing streams where they cross the Twin Creek Limestone, but detailed stream flow measurements are lacking. Recharge for the potentially complex Lower Twin Creek and Upper Twin Creek subunits may include: direct infiltration into exposures of the Twin Creek Limestone in all drainage basins; widespread leakage of surface water downward along losing parts of streams where they cross the subunits; and leakage into subcrops of the Twin Creek Limestone where it projects northeastward beneath the Cretaceous Conglomerate Unit. Because of the widespread presence of losing streams associated with the Twin Creek subunits, a significant part of the recharge may come indirectly from surface waters that drain out of the respective basins. Future hydrologic studies, including additional aquifer tests on wells, long term monitoring of water levels and production in wells, tracer tests and Microscopic Particulate Analyses to evaluate surface water influence, and detailed monitoring of stream discharge, will probably be needed to better understand variations in hydrologic characteristics of the Twin Creek Limestone.

Two public-water-supply wells have been completed within parts of the Upper Twin Creek HSU in the Freeze Creek and Western drainage basins (Figures 8 and 9). Freeze Creek Well 1 starts near the base of the Preuss Formation, is open through parts of the Giraffe Creek Member and uppermost part of the Leeds Creek Member of the Twin Creek Limestone, and has a total depth of 500 ft; whereas Freeze Creek Well 2 is perforated through the middle part of the Leeds Creek Member and has a total depth of 802 ft (Figures 2, 6, and 9). Freeze Creek Wells 1 & 2 have been reported to have flowed under artesian pressure each spring from their respective completions in 1984 and1994 until 1998 (Moffat, personal communication), indicating that a local confining layer may be present within the Leeds Creek Member and that large seasonal fluctuations in water levels occur (however the wells did not flow under artesian conditions during the spring of 2000).

A 5-day, constant-rate pumping (drawdown) test was conducted on Well 2 during March, 1998, to better understand the hydrologic setting of the wells, and results are briefly summarized here (see Barnett, 1998, for a more complete analysis). Water levels in Wells 1 and 2 were rising at average rates of about 1.5 ft/day and 0.8 ft/day respectively prior to the drawdown test, and had "static" water levels of about 5940 and 6000 ft respectively just prior to onset of the test (Figure

10A). During the test Well 2 was pumped at a rate of about 280 gpm and changes in water levels were recorded in both wells. A drawdown of about 400 ft was observed in Well 2 during the test, whereas the water level in Well 1 continued to rise slowly, indicating that significant hydraulic communication did not occur between the two wells over the time of the test. This apparent lack of communication could be related to: presence of complex fracture systems that limited connectivity between the wells; presence of confining claystone layers in the Leeds Creek Member between the wells, and the wells being in different drainage basins. However, outside temperatures were rising during the test, leading to increased snow melt and potential recharge during the test, which may be responsible for the rise in water levels prior to and during the test in Well 1, and which may have masked minor communication between the wells. Following the drawdown test, Well 2 was left idle for several days and water levels were measured during recovery.

Drawdown and recovery data from Well 2 were analyzed using the method developed by Theis (1935) and modified by Jacob (1940), which describes the flow of ground water to wells under simplifying assumptions as previously discussed. Although most of these simplifying assumptions are violated in the study area, a review of drawdown and recovery data may still provide guidance on general aquifer performance and properties. According to the theory, drawdown should increase linearly with the logarithm of time, with the slope of the line related to the transmissivity of the aquifer (i.e. for a given constant pumping rate a steeper line indicates a lower transmissivity). Drawdown data plot as a fairly straight trend for times from about 20 minutes to 6 hours (Figure 10B, note earlier drawdown data are affected by higher initial pumping rates). However, for times from about 6 hours to 5 days the slope of the drawdown curve increases. This type of change may reflect some combination of: the cone of depression reaching less permeable hydrologic boundaries, such as claystone layers; the cone of depression tapping progressively less fractured material, smaller fractures at deeper levels, or less connected fractures during the test; and anisotropic permeability. Fitting a straight line to the late-time data gives an apparent transmissivity of about 50 ft^2 per day (Figure 10B). However, because the slope of the drawdown curve increased during later times in the test, extreme caution is needed in extrapolating results, and apparent transmissivity will likely decrease further as drawdown increases and the cone of depression increases in size. Recovery data should also plot as a straight line for an ideal aquifer, but actual data show more complicated patterns with an initially more rapid rate of recovery, followed by a slower rate, followed by an accelerated rate that may indicate increased recharge from increased snow melt (Figure 10C). Fitting a straight line to the middle-time recovery data gives an average transmissivity of about 230 ft^2 per day (Figure 10C). Importantly, for an ideal aquifer, recovery data should project toward 0 drawdown for longer recovery times, but the middle-time data project to a drawdown of about 80 ft, which is indicative of an aquifer with limited aerial extent and having less permeable hydrologic boundaries. The late-time acceleration of recovery may reflect rapid response of the aquifer to increased recharge associated with increased snow melt. Note that these apparent transmissivity values are only given to serve as a general guide and should be used with extreme caution, as fracture characteristics may vary substantially with location and less permeable intervals are likely to be present.

Confining Interval

An overall confining interval is interpreted to consist of the Preuss and Kelvin Formations, similar to the interpretation of Ashland and others (1996). This thick interval contains abundant fine-grained, thin-bedded mudstone and shale that probably have low permeabilities, particularly perpendicular to bedding. However, both formations also contain local sandstone layers, and the Kelvin Formation contains a few conglomerate lenses, which may have varying grain-scale and fracture permeability, such that thin aquifers may be locally present in this interval. A number of single-family water supply wells produce from these formations in the Emigration Canyon area. The Preuss Formation also locally contains discontinuous layers of salt (Yonkee and others, 1997), which could result in saline waters. Saline waters have been encountered in several, home-water-supply wells within the southern part of the study area that were apparently drilled into the adjacent to Kelvin Formation; however the exact source of the salinity is unknown.

Aquifers in Unconsolidated Materials

Ground water also occurs locally in perched aquifers within some Quaternary unconsolidated deposits. For example, small seeps occur locally in relatively thick landslide and hillslope colluvium deposits that formed from parts of Preuss and Kelvin Formations and contain abundant clays, which serve as local confining layers above which shallow ground water is discharged. These local aquifers are of limited thickness and subject to recharge by local surface waters.

IMPLICATIONS FOR GROUND WATER SOURCE DEVELOPMENT AND PROTECTION

General Considerations

Several partly related factors should be considered in future development and protection of ground water sources in the upper Emigration Canyon area. (1) Potential water sources are largely located within fractured bedrock aquifers that probably have complex permeability structures. (2) Fractured bedrock aquifers may have relatively low storage capacities. (3) Bedding is steeply dipping throughout the area, which may cause complications for locating and drilling wells. (4) A combination of complex permeability structure and low storage may make it difficult to estimate safe yields. (5) A combination of multiple recharge sources for aquifers, including potentially significant leakage of waters from streams, and complex permeability structure may make determination of source protection areas difficult. (6) Currently available hydrologic data are limited. These various considerations are briefly addressed below.

Complex Permeability Structure

Aquifers in bedrock typically display large spatial variations in permeability, with fluid flow partly controlled by variably developed fracture systems. For example, apparent transmissivities reported for the nearby Park City area show large variations (Holmes and others, 1996), and drawdown and recovery data from Well 2 in the study area show complex patterns that may be related to variable fracture characteristics and associated permeability. Keighley and others (1997) reported significant local variations in fracture intensities, lengths, and connectivities based on detailed fracture studies in parts of the Park City area, which produced complex, heterogeneous, and anisotropic permeability. Although detailed fracture studies have not been completed in the study area, similarly complex patterns are expected. Such studies could help with understanding the permeability structure of the area, but completion of fracture studies may be difficult due to limited exposures, large amounts of work involved, and potential for small-scale spatial variations of fracture characteristics. Fractured bedrock aquifers in the study area are also located in steeply dipping rock layers, with alternating intervals of more and less fractured and permeable rock. Thin to thick intervals of claystone and mudstone that are thin-bedded and contain shorter fractures may be relatively impermeable and act as hydrologic boundaries at a variety of scales. Presence of bed-parallel fractures and alternating more and less permeable layers may also produce overall anisotropic permeability that favors overall northeast-southwest fluid flow in the study area. However, quantitative data on permeability structure and controls on detailed fluid flow patterns are unknown. Complex flow patterns are expected along variably spaced fractures of different sizes and connectivity, such that simple models of homogeneous, isotropic aquifers may be inappropriate, requiring more sophisticated analysis of discrete fracture systems to understand details of fluid flow.

Potentially Low Storage Capacity

The ability of bedrock aquifers to store water may be low, depending on porosity and the detailed nature of fracture systems. Porosity associated with fracturing is typically low (less than several percent for most rocks), such that the volume available for storing water is limited. Additionally some subunits have limited aerial extent, which further limits potential storage of ground water. Because the volume available to store and transmit water may be relatively small, fluid flow may be rapid along individual fractures. Low storage and rapid fluid flow may result in relatively large and rapid seasonal fluctuations in ground water levels and spring discharges, as observed in the study area, and in the nearby Park City area, particularly for the Twin Creek Limestone (Ashland and others, 1996; Todd Jarvis, personal communications, 2000).

Importantly, over pumping of wells within fractured bedrock aquifers with limited storage may result in mining of ground water. Additionally, some fractures that close down as water pressures decrease during over pumping, with large drawdowns, may not completely reopen when water levels recover, permanently damaging the ability of the aquifer to deliver water to a well. Water levels and production of wells should be carefully monitored over the long term to carefully evaluate potential ground water mining and decline in aquifer efficiency.

Steeply Dipping Rock Layers

Bedding dips generally between 40 and 70° in the western domain to mostly greater than 80° in the eastern domain of the area, which presents problems for locating and drilling wells. A well drilled within steeply dipping strata would be at low angles to bedding, and would only sample across a limited stratigraphic interval, resulting in lower probabilities of intersecting bed-parallel fractures and bed-parallel permeable intervals. A well could also encounter and remain within relatively impermeable strata over long vertical distances, especially if the well is not carefully located or if hidden warps in the subsurface place impermeable strata beneath the well. A well completed in steeply dipping strata may also be located near hydrologic boundaries, and thus as water is pumped from a well the cone of depression may intersect steeply dipping impermeable layers at relatively short distances. Additionally, maintaining a vertical hole during drilling in steeply dipping strata may require special methods.

Estimates of Safe Yield

A major concern in developing a well or spring in steeply dipping, fractured bedrock aquifers as found in the study area, is estimating the long-term safe yield of the aquifer. The combination of variable permeability, low storage, presence of hydrologic boundaries, and small sizes of some subunits may make it particularly difficult to estimate safe yields. For example: fracture characteristics are likely to vary down to small scales, such that rock near a well that initially supplies water during pumping may have higher permeability, whereas rock further away that supplies water as the cone of depression expands during pumping may have lower permeability; impermeable hydrologic boundaries, such as claystone layers, may be present at various distances from a well and encountered at various times as a well is pumped; and progressively smaller or less connected fractures may provide fluid during continued pumping of a well. Such factors tend to increase actual drawdown compared to expected drawdown for a homogeneous aquifer of large aerial extent, such that extreme care is required in interpreting and extrapolating aquifer tests to estimate safe yield. For example, aquifer test data for Well 2 define a drawdown curve that increases in slope with the logarithm of time, such that standard linear projection of short-time data to longer time intervals would underestimate actual drawdown and overestimate the safe yield. Spring discharge and "static" water levels in wells also show large seasonal and long-term fluctuations, reflecting variations in precipitation and snow melt patterns, rapid fluid flow, and potentially low storage capacity. Periods of drought may thus significantly decrease abilities of springs and wells to provide adequate yields of water. For example, during the overall dry period from 1987 to 1994 (and particularly 1992), a number of smaller domestic wells in Emigration Canyon needed to deepened or replaced due to lowering of the water table in many aquifers. Sufficient historical data are not available for Well 1 to track static and pumping water levels during this period, and Well 2 was not completed until 1994. However, a review of 1998 data on water levels for Well 2 indicates that summer-time demand for water exceeded natural recharge to the aquifer in this relatively good water year. Thus if the aquifer does not recharge each spring, then mining of water from the aquifer is likely to occur, and similar considerations may apply to other potential aquifers in the study area. Over pumping of a well that repeatedly produces excessive drawdown may also damage an aquifer as some fractures that close down during over pumping may not completely reopen once water levels recover.

Protection of Drinking Water Sources

A major concern for long-term water use from wells and springs in fractured bedrock aquifers as found in the study area, is protection of sources from surface contaminants. For more "typical" aquifers in flat-lying, relatively porous, unconsolidated alluvial deposits, water molecules tend to travel more slowly over longer distances, resulting in longer times for filtration of contaminants. However, in bedrock aquifers much of the water may be transmitted along fractures, and the aquifer will tend to have low porosity, contain locally fractured zones with higher permeability, and display dispersion effects due to preferential flow along longer, connected fractures. Thus water molecules in fractured bedrock aquifers will tend to travel more quickly with less time for filtration of contaminants. A flat-lying bedrock aquifer may still be protected by an overlying confining interval, such as an aerially extensive claystone layer, which slows recharge of surface water directly downward into the aquifer. However, due to the steeply dipping beds found in the study area, a claystone layer may be present but still not protect the aquifer. For example, Well 2 apparently penetrates a local confining layer, but the aquifer encountered at depth is exposed only several hundred feet northwest of the well. If water flow occurs preferentially along fractures down the dip of bedding, then surface waters and potential contaminants could move relatively quickly into the aquifer at depth, with only limited filtration. Additionally, waters in an aquifer could move relatively quickly northeast-southwest along the strike of bedding, reflecting anisotropic permeability related to stratigraphic layering and presence of bed-parallel fractures. Overall, significant dangers may exist in extending standard computer models for contaminant transport in porous media to steeply dipping, fractured bedrock aquifers, especially without adequate data on spatial variations in fracture characteristics and anisotropy, and discrete fracture-system models may be required in some cases.

Protection of drinking water sources should also consider hydrologic connections between ground water and surface water, including delineation that integrates both the zones of surface-water and ground-water contribution to a water supply. Importantly, recharge to some units in the Upper Emigration Canyon area may include significant leakage of surface waters from losing parts of streams, especially if the cone of depression from a pumping well lowers the water table significantly below the stream level, such as appears to occur at times for Freeze Creek Wells 1 & 2. Thus, potential contaminants found in the drainage basin above the losing part of a stream could enter an aquifer with only limited filtration.

Based on geologic and hydrologic considerations in the study area, much of the recharge to the various subunits appears to occur from a combination of infiltration of snow melt and precipitation at surface exposures of the aquifer, and leakage of surface water along losing parts of streams. Response of aquifers to recharge appears to be relatively rapid, potentially reflecting rapid fluid flow and limited filtration. Hence, there is a great need to properly delineate and protect areas of recharge. Because much of the various drainage basins, particularly the higher parts, form recharge areas for one or more of the aquifers, a watershed protection approach is warranted. Although this study has provided important information on potential recharge areas, remaining problems include: determining relations between topographic and ground water divides; estimating effects of pumping on shifting positions of ground water divides; and quantifying recharge mechanisms in this geologically complex area.

Limited Hydrologic Data

Another major consideration is general lack of detailed hydrologic data in the study area. Although some data on general apparent transmissivities of aquifers are available from the Park City area, quantitative data on permeabilities, porosities, and storage characteristics of rock units in the study area are lacking. Additional data, such as long-term monitoring of spring and stream discharge, seepage studies along streams, long-term monitoring of well water levels and production, long-term monitoring of water quality, additional well aquifer tests, tracer tests, and geochemical and isotopic studies of ground water residence times may be useful in better understanding fluid flow patterns, estimating safe yields, and protecting water sources in the study area.

Implications for Potential Sources

The following section briefly summarizes implications of the geologic setting to potential development and protection of various possible general ground water sources. Possible general sources in the Upper Emigration Canyon area are described for the various HSUs and associated topographic subunits. Although some confining intervals may also contain local aquifers, such aquifers are likely to have relatively small yields and are not discussed here. Identification of specific sources to be developed and completion of specific source protection plans will require additional site-specific studies, as well as consideration of other factors beyond the scope of this report, including water rights issues, environmental factors, and engineering costs. Additionally, other potential source areas may exist outside the study area, such as the Upper and Lower Twin Creek HSUs along the lower part of Emigration Canyon to the southwest.

Weber HSU

The Weber HSU is exposed in the upper part of Burr Fork basin, where two springs that are potential sources are located. Thomas spring, which had a flow from about 30 to 80 gpm during 1993 to 1997, is already partly developed, and Secret Spring, which had a flow from about 35 to more than 80 gpm during 1993 to 1997 (Table 1), could be potentially developed. Access to Thomas Spring would require improvement to a currently impassable road, and access to Secret Spring would require construction of a new road; access to either spring would be difficult in winter. Development of the springs would probably decrease stream flow along upper Burr Fork, but part of the spring flow could be reserved to maintain a component of stream flow. Recharge areas for these springs include exposures of the Weber Sandstone and lower member of the Park City Formation in the upper part of Burr Fork drainage basin and subcrops of these formations beneath the Cretaceous Conglomerate Unit (Figure 8), which currently have no development, potentially making source protection easier compared to some other sources. Overall, the upper part of Burr Fork drainage basin is an important recharge area, directly for this HSU and indirectly for stream flow that may partly recharge some other HSUs, and special consideration should be given to source protection of this area.

Upper Park City HSU

The Upper Park City HSU is exposed in the upper part of Burr Fork basin, where an unnamed, currently undeveloped spring is located. This spring has not been monitored but appeared to have a discharge less than 50 gpm during the summer of 1997. This spring could be potentially developed, or a well could also be potentially drilled where this interval crosses Burr Fork. Access to the spring or a well would require some construction, and would be difficult in winter. Development of the spring would probably decrease stream flow in upper Burr Fork, and development of a well could decrease both spring and stream flow. The recharge areas for this HSU and spring include outcrops of the upper member of the Park City Formation in Burr Fork Basin and subcrops of this interval beneath the Cretaceous Conglomerate Unit, which currently have no development, potentially making source protection relatively easy. However, the recharge area is smaller compared to the Weber HSU, and thus the long-term safe yield may be relatively low.

Thaynes HSU

The Thaynes HSU is exposed along the upper parts of the Jeep Creek, middle parts of the Burr Fork, and upper parts of the Brigham Fork basins, and is the source for several unnamed springs, including one that is currently used as a public water source for the Pinecrest area. In general, some of these springs could be developed or a well(s) could be drilled. However, the Thaynes Formation is lithologically complex and the overall HSU may contain impermeable layers that act as local confining intervals, as well as more permeable layers. The ridge limestone member, which contains thick-bedded limestone with overall longer fractures and appears to be the source for several springs, may be more permeable and a relatively better target within the formation. Detailed hydrologic characteristics in the study area are, however, uncertain, and wells drilled in steeply dipping strata may encounter relatively permeable or impermeable layers over significant depths. Thus, general consideration should be given to drilling test wells before considering development of any larger public-water-supply well(s). Additionally, water quality from test wells should be checked, as some wells completed in the Thaynes Formation in the Park City area have had problems with turbidity (Keighley and others, 1997). Factors pertinent to each subunit are now briefly listed.

A spring or well could be developed in the Burr Fork subunit. Access would be relatively easy along an existing road. Burr Fork appears to be overall gaining through this interval, but pumping of a water well could decrease spring flow and ground water recharge to the stream, and significant pumping could lower the local water table below stream level, resulting in leakage of stream water into the aquifer. The direct recharge area for this subunit, which includes exposures of the Thaynes Formation in Burr Fork Basin, is relatively large (Figure 8), and additional recharge could potentially come from leakage of stream water. Thus, source protection would probably require protecting the entire upper part of the Burr Fork drainage basin along and northwest of exposures of the Thaynes Formation. The overall yield of this subunit may be relatively large, but a well drilled in steeply dipping strata containing local confining layers may only be able to effectively tap water from a small portion of the subunit.

A well could be drilled into the Jeep Creek subunit, but access would be very difficult and require significant construction. The direct recharge area for this subunit appears to be moderately sized with no human structures, so source protection may be relatively easier, but safe yields from this subunit are uncertain. A well could also be drilled into the Brigham Fork subunit or an unnamed spring, which has a relatively small flow, could be developed. Access would again be very difficult and require significant construction. The direct recharge area for this subunit also appears to be moderately sized with no human structures, so source protection may be relatively easier, but safe yields are also uncertain.

Nugget HSU

The Nugget HSU is exposed along the upper parts of the Killyon Canyon and Freeze Creek basins, and along the middle parts of the Jeep Creek, Middle Fork, Burr Fork, Brigham Fork basins (Figure 8). This HSU is the source for several unnamed springs, and streams along Burr Fork and Brigham Fork appear to be gaining where they cross this interval. In general, some of these springs could be developed or a well(s) could be drilled. The Nugget Sandstone is more lithologically uniform and may contain some grain-scale permeability, as well as spatially variable fracture permeability. Very limited hydrologic data for two domestic wells appear to indicate moderate apparent transmissivities, but longer term aquifer tests of these wells and/or test wells should be completed to better understand general aquifer performance, before development of any larger public-water-supply well(s). Factors pertinent to each subunit are now briefly listed.

The springs along Killyon Canyon and Jeep Canyon could be potentially developed. However, access would be very difficult and require significant construction. Development of the springs would also probably decrease stream flow, although a portion of the spring discharge could be reserved to maintain some component of stream flow. Direct recharge areas for the springs, which include exposures of the Nugget Sandstone in the respective basins and possibly subcrops of the formation beneath the Cretaceous Conglomerate Unit, appear to be moderate in size and at relatively high elevations, and some recharge could come from flow of shallow groundwater through unconsolidated deposits that cover parts of bedrock in the upper parts of these basins. These springs appear to have relatively large flows, but quantitative measures are lacking and thus long-term safe yields are uncertain. No human development currently exists in these basins, and so source protection would be potentially easier. A small spring along Middle Fork would be very difficult to access and would probably have a limited yield.

A well could potentially be developed along Burr Fork. Access would be easy along an existing road, but source protection would likely be very difficult. Although Burr Fork appears to be overall gaining through this interval, pumping of a water well could lower the local water table below stream level, resulting in leakage of stream water into the aquifer. The direct recharge area for this subunit includes relatively small exposures of the Nugget Sandstone in Burr Fork basin (Figure 8), with additional recharge potentially from leakage of stream water. Thus, source protection would probably require protecting the middle and upper parts of the Burr Fork drainage basin along and northwest of exposures of the Nugget Sandstone, including the Pinecrest area, which may be difficult. Water quality would need to be carefully monitored, and safe yield would need to be carefully evaluated by long-term pump test data.

A well could also potentially be developed along Brigham Fork. Access would be more difficult, requiring improvement of a currently impassable road, but source protection would be easier compared to Burr Fork. Brigham Fork appears to be overall gaining through this interval, but pumping of a water well could decrease ground water recharge to the stream, and significant pumping could lower the local water table below stream level, resulting in leakage of stream water into the aquifer. The direct recharge area for this subunit, which includes exposures of the Nugget Sandstone in the Brigham Fork basin, is moderately sized (Figure 8), and additional recharge could come from leakage of stream water. Thus, source protection would probably require protecting the middle and upper parts of the Brigham Fork drainage basin along and northwest of exposures of the Nugget Sandstone. Human development is currently lacking in this part of the basin, making potential source protection relatively easier. The hydrologic characteristics and safe yield of this subunit are unknown and should be carefully evaluated, possibly by drilling a test well and conducting long-term pump tests before development of a public-water-supply well.

An unnamed spring along Freeze Creek could also be potentially developed. However, access would be very difficult and require significant construction, and development of the spring would decrease stream flow.

Lower and Upper Twin Creek HSUs

The Lower Twin Creek and Upper Twin Creek HSUs are exposed along the lower parts of all the basins (Figure 8). The Twin Creek Limestone is lithologically complex and overall HSUs may contain impermeable layers that act as local confining intervals, as well as more permeable layers. The Watton Canyon Member contains some thicker-bedded limestone with overall longer fractures, and thus may be more permeable and a relatively better target within the formation. Detailed hydrologic characteristics of the formation are, however, uncertain in most areas, and are likely to be complex based on aquifer test data from Well 2 (Figure 10). Thus, general consideration should be given to drilling test wells and conducting additional long-term aquifer tests before developing any additional public-water-supply wells in this formation. Recharge for the various subunits comes from direct infiltration into surface exposures of the Twin Creek Limestone, and from leakage of surface water along losing parts of streams. Because most streams appear to be losing where they cross Upper and Lower Twin Creek HSUs, source protection areas for all subunits would potentially include the respective drainage basin areas located upstream and northwest from outcrops of the Twin Creek Limestone. Flow may be relatively rapid with limited filtration, storage capacity may be low, and permeability structure may be complex, indicating a need to carefully consider uncertainties in estimating safe yields. Also, apparent transmissivities estimated from aquifer test data for Well 2 are fairly low, such that a new public-water-supply well would probably need to be relatively deep with the pump also set relatively deep, due to the possibility of significant drawdown during pumping and to significant seasonal fluctuation in water levels. Long term monitoring of water levels and production in current wells and detailed monitoring of stream discharge, in addition to drilling test wells, would help with understanding water flow in this thick, lithologically complex formation. Factors pertinent to each subunit are now briefly listed.

The Freeze Creek and Western basin subunits of the Upper Twin Creek HSU are the sources of Wells 1 and 2, which produce respectively from the Giraffe Creek Member and middle part of the Leeds Creek Member (Figure 6). Development of additional wells in these members could cause well interference and is not recommended. However, the Watton Canyon Member is a potential target for development of a well. Access would be fairly easy, and beds are moderately dipping in this area. The potential source protection area for such a well would likely include that part of the Freeze Creek basin located northwest and above exposures of the Watton Canyon Member.

A well(s) could potentially be developed along Brigham Fork, near the ridge between Brigham Fork and Burr Fork, or along Burr Fork, possibly into the Watton Canyon Member. Access along Brigham Fork or the ridge would be moderately difficult, requiring improvement of a currently impassable road, whereas access would be easy along Burr Fork. Brigham Fork and Burr Fork appear to be losing where they cross the Twin Creek Limestone, indicating a potential for significant leakage of stream water into the aquifer and raising concerns about source protection. The overall recharge areas for these subunits would potentially consist of much of the Brigham Fork and Burr Fork drainage basins, with potential for leakage from streams and between subunits. A well located nearer the ridge would allow for greater filtration of stream waters that entered the aquifer, but depending on the shape of the water table, water levels could be significantly below the ground surface. The Brigham Fork area is currently undeveloped, potentially making source protection of this area easier, but the possibility of future development in the area may need to be considered. The Burr Fork basin includes the Pinecrest area, making source protection more difficult. The hydrologic parameters and safe yields of all these subunits are unknown and should be carefully evaluated, possibly by drilling test wells and conducting long-term aquifer tests before developing a public-water-supply well in this area.

The Upper Twin Creek and Lower Twin Creek HSUs are also exposed along Killyon Canyon, Jeep Creek, and Middle Fork drainage basins. A well could be developed in any of these areas, particularly within the Watton Canyon Member. However, access would be very difficult, requiring significant construction. The potential recharge areas in the Killyon Canyon and Jeep Creek subunits are fairly large, and some recharge could come from leakage of surface waters along losing parts of streams. These basins are currently undeveloped and thus source protection is potentially relatively easier. Hydrologic parameters of the subunits are unknown and should be carefully evaluated to estimate safe yield prior to potential development a public-water-supply well in this area.

Only general implications of geologic factors to some potential sources have been discussed in this section. Identification of specific sources and completion of specific source protection plans will require additional site-specific studies, as well as consideration of water rights issues, environmental factors, and engineering costs, which are beyond the scope of this report.

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Appendix A. Glossary of Technical Terms

anhydrite- a mineral composed of calcium and sulphate

anisotropic- an aquifer property of having the hydraulic conductivity varying with different directions (e.g. conductivity parallel to bedding is greater than perpendicular to bedding)

anticline- fold that closes upward with the oldest rocks in the core

aquifer- a geologic unit with the ability to transmit water at sufficient rates so as to be economically usable

bedding- arrangement of rock in layers, bedding generally starts out horizontal but can be tilted during deformation, the orientation of tilted bedding is defined by its strike and dip

fossiliferous limestone- limestone with abundant fossil fragments

calcite- a mineral composed of calcium and carbonate

carbonate rock- general term for a combination of limestone and dolostone

claystone- a rock composed mostly of clay-sized particles

cleavage- planar fabric produced by deformation along which rock tends to split

confining interval- an interval of rock layers that limit fluid flow across the interval

cross bedding- local arrangement of rock into layers that are inclined to main bedding

detachment fault- fault that is subparallel to bedding and separates packages of rock that have deformed differently

dip- maximum inclination of a planar layer, measured down from horizontal

discharge- amount of water flowing through a given area, from a well, or from a spring per amount of time, units are length cubed per time or gallons per time

dolostone- a rock composed mostly of dolomite

dolomite- a mineral composed of calcium, magnesium, and carbonate

drawdown- measure of depth to water level below static or pretest level

fault- fracture across which rock has been offset parallel to the fracture

fold- systematically curved layers of rock

fold axis- line that moved parallel to itself generates a fold, the fold axis is parallel to the hinge for simple folds

fold hinge- region of fold with greatest curvature

fold limb- region of fold with less curvature, located between fold hinges

footwall- block of rock below a fault

fracture- break in rock produced by mechanical failure

gypsum- a mineral composed of calcium, sulphate, and water, forms by addition of water to anhydrite

hanging wall- block of rock above a fault

heterogeneous- an aquifer property of having variable hydraulic conductivity depending on location in the aquifer

homogeneous- an aquifer property of having similar hydraulic conductivity regardless of location in the aquifer

hydraulic conductivity- measure of the rate of flow of water through a porous media, units are length per time

hydrostratigraphic unit (HSU)- a sequence of relatively more permeable and fractured rock layers that are separated by lower permeable confining intervals

isotropic- an aquifer property of having hydraulic conductivity the same in all directions

limestone- rock composed mostly of calcite

mudstone- a rock composed of a mixture of clay-sized to silt-sized particles

oolitic limestone- limestone with abundant ooids, which are spherical grains composed of concentric layers of calcite

overturned bedding- bedding that has been tilted more than 90° such that the original top side of a bed is now pointing downward

normal fault- fault with slip about parallel to dip of fault and hanging wall displaced down relative to footwall

permeability- technically, measure of the ability of a porous media to transmit fluid independent of the fluid properties, units are length squared (when water is the fluid permeability and hydraulic conductivity are the same)

porosity- the ratio of volume of the voids divided by the total volume of the rock

plunge- inclination of a line, measured down from horizontal

reverse fault- fault with slip about parallel to dip of fault and hanging wall displaced up relative to the footwall

sandstone- a rock composed mostly of sand-sized particles

shale- a mudstone that has very thin beds along which rock tends to part

shaley limestone- thin-bedded limestone with small clay and calcite grains

strike- azimuth of a horizontal line contained in a plane, measured from north

subunit- a portion of a hydrostratigraphic unit that may have different flow and recharge systems due to presence of structural features such as faults, or due to presence of different topographic drainage basins

syncline- fold that closes downward with the youngest rocks in the core

transmissivity- the measure of the ability of an aquifer to transmit water, equal to the hydraulic conductivity multiplied by the saturated thickness of the aquifer, units are length squared per time

trend- azimuth of the horizontal projection of a line, measured from north

thrust fault- gently dipping reverse fault, typically displays flats with dips $< 10^\circ$ and ramps with dips between 10 and 30°

vein- fracture filled by precipitation of minerals

Appendix B. Explanation of Hydrologic Terms for an Idealized Aquifer

The following summary is based on standard hydrologic principles (e.g. see Fetter, 1994; and Freeze and Cherry, 1979). The ability of an idealized homogeneous, isotropic aquifer to transmit water is given by:

$$\mathbf{Q = K * A * (dh/dl)}$$

where **Q** is the volume of water transmitted by the aquifer (in ft^3/day), **K** is the hydraulic conductivity (in ft/day), **A** is the cross section area of the aquifer (in ft^2), and **dh/dl** is the hydraulic gradient (the change in elevation of hydraulic head with distance in ft/ft). The permeability, **k**, is directly related to the hydraulic conductivity, and for water is given by:

$$\mathbf{k} = \mathbf{K} \propto / \wp\ \mathbf{g}$$

where $\propto$ is fluid viscosity, $\wp$ is fluid density, and **g** is gravity. The average lineal velocity, **V**, that molecules of water actually travel through an aquifer is given by

$$\mathbf{V = Q / (A * f) = (K * dh/dl) / f}$$

where **f** is the effective porosity. Aquifers in unconsolidated alluvial sand and gravel deposits tend to have relatively high hydraulic conductivities (generally on the order of 10 to 1000 ft/day), as well as relatively high porosities (generally in the range of 10 to 30%). Aquifers in fractured bedrock tend to have lower hydraulic conductivities (on the order of 0.1 to 10 ft/day), as well as lower porosities (generally in the range of 1 to 5% for well cemented rocks). Note, for an idealized fractured bedrock aquifer having an average hydraulic conductivity of 1 ft/day, a porosity of 1%, and a hydraulic gradient of 0.1, the average velocity of water would be about 10 ft/day, leading to relatively rapid movement of potential contaminants. Additionally in fractured bedrock aquifers conductivities may vary significantly, such that more fractured intervals may transmit water at faster velocities than the average velocity, potentially leading to even more rapid movement of contaminants.

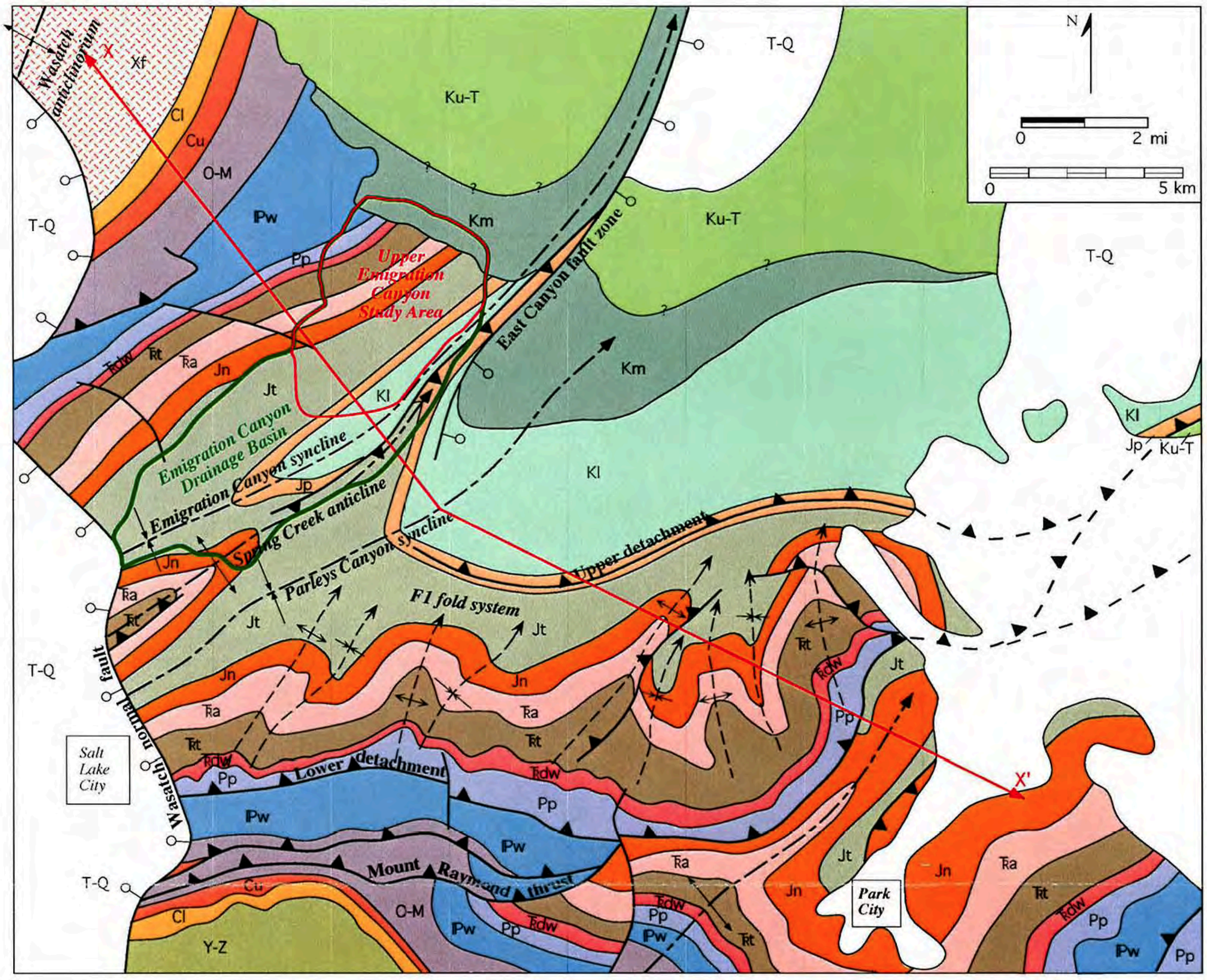
Transmissivity, **T**, which measures the ability of an aquifer to provide water to a well is given by:

$$\mathbf{T = K * L}$$

where **L** is the effective thickness of the aquifer. The transmissivity of an ideal aquifer can be estimated from pump test data, assuming that the pumping rate is constant, flow is radial and laminar, and the well is 100% efficient, using the method developed by Theis (1935) and modified by Jacob (1940). In this method the slope of the drawdown curve, plotted as drawdown verses the logarithm of time the well has been pumped, is proportional to the pumping rate (well discharge) divided by the transmissivity. In complex aquifers the drawdown curve may not be linear over all times, and a line fitted to linear parts of the curve is used to estimate an apparent transmissivity.

Figure 1 A. Regional Geologic Map

(modified from Bryant, 1990)



Explanation of Symbols

- thrust fault (dashed where concealed)
- normal fault
- F1 anticline fold trace
- F1 syncline fold trace
- F2 anticline fold trace
- F2 syncline fold trace

Explanation of Geologic Units

T-Q	Late Tertiary to Quaternary deposits
	Cretaceous to Early Tertiary-
Ku-T	upper synorogenic sequence
Km	middle synorogenic sequence
Kl	lower synorogenic sequence
	Jurassic strata-
Jp	Preuss Formation
Jt	Twin Creek Limestone
Jn	Nugget Sandstone
	Triassic strata-
Tra	Ankareh Formation
Trt	Thaynes Formation
Trdw	Dinwoody Formation and Woodside Shale
Pp	Permian Park City Formation
IPw	Pennsylvanian Weber Sandstone
O-M	Ordovician to Mississippian strata
Cu	upper Cambrian strata
Cl	lower Cambrian strata
Y-Z	Middle to Upper Proterozoic strata
Xf	Farmington Canyon Complex

Figure 1B.
Regional Cross Section

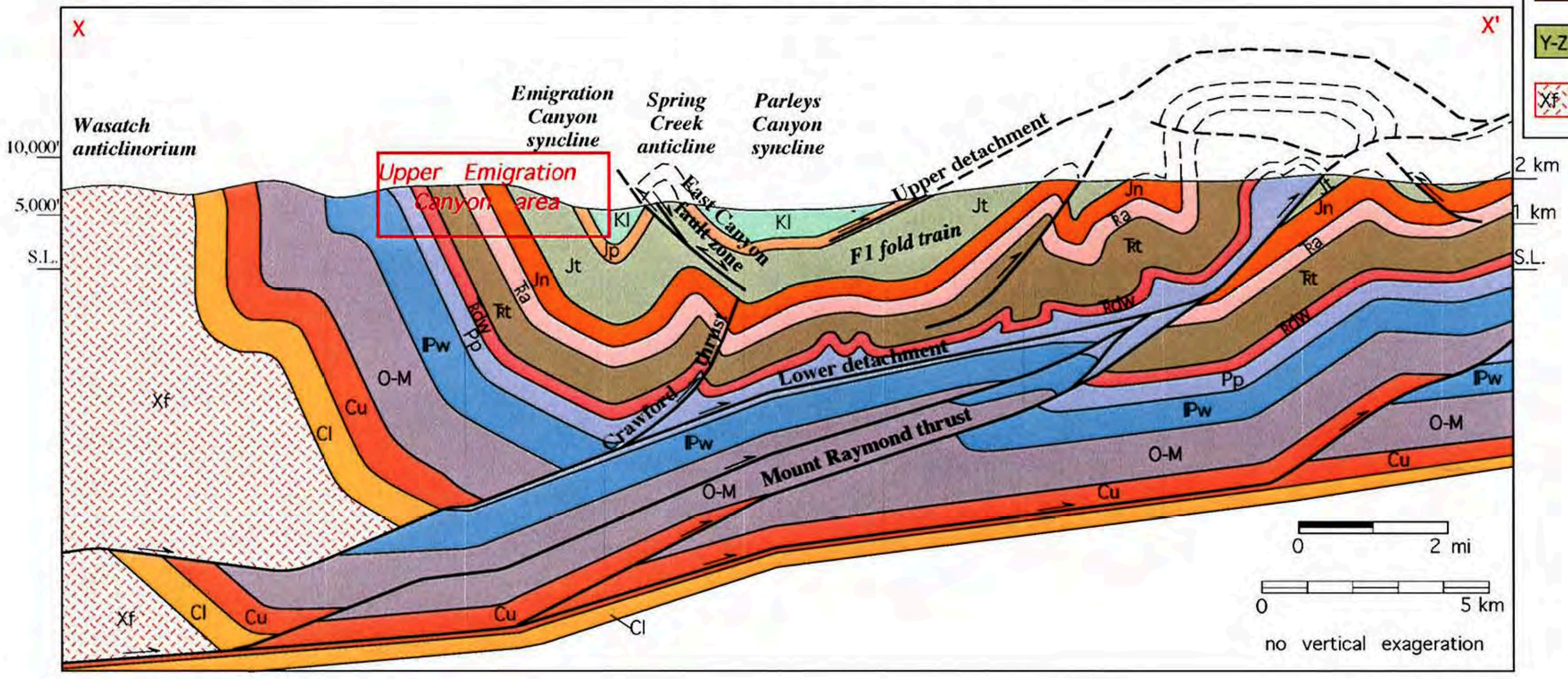


Figure 2. General Stratigraphic Column of Upper Emigration Canyon Area

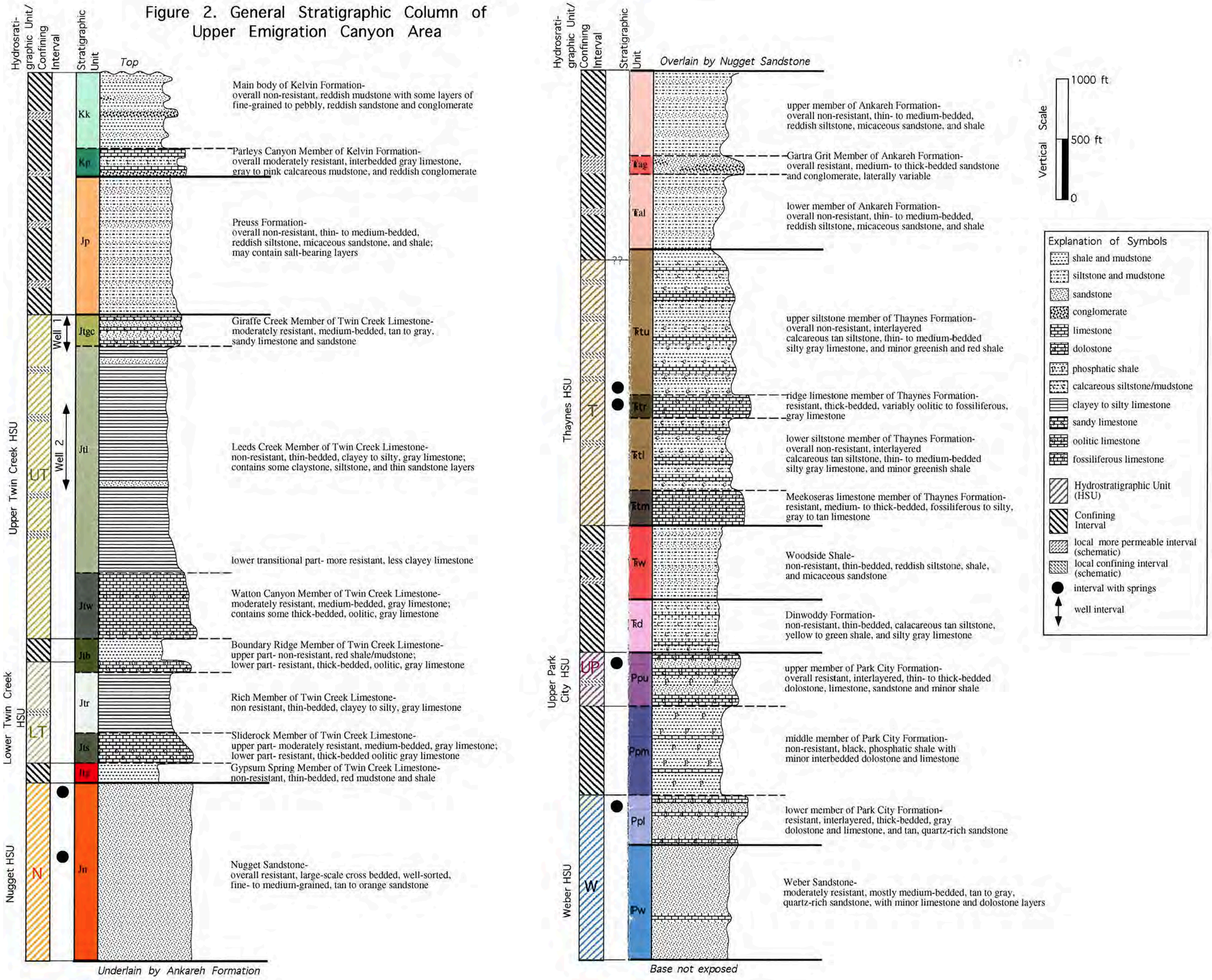
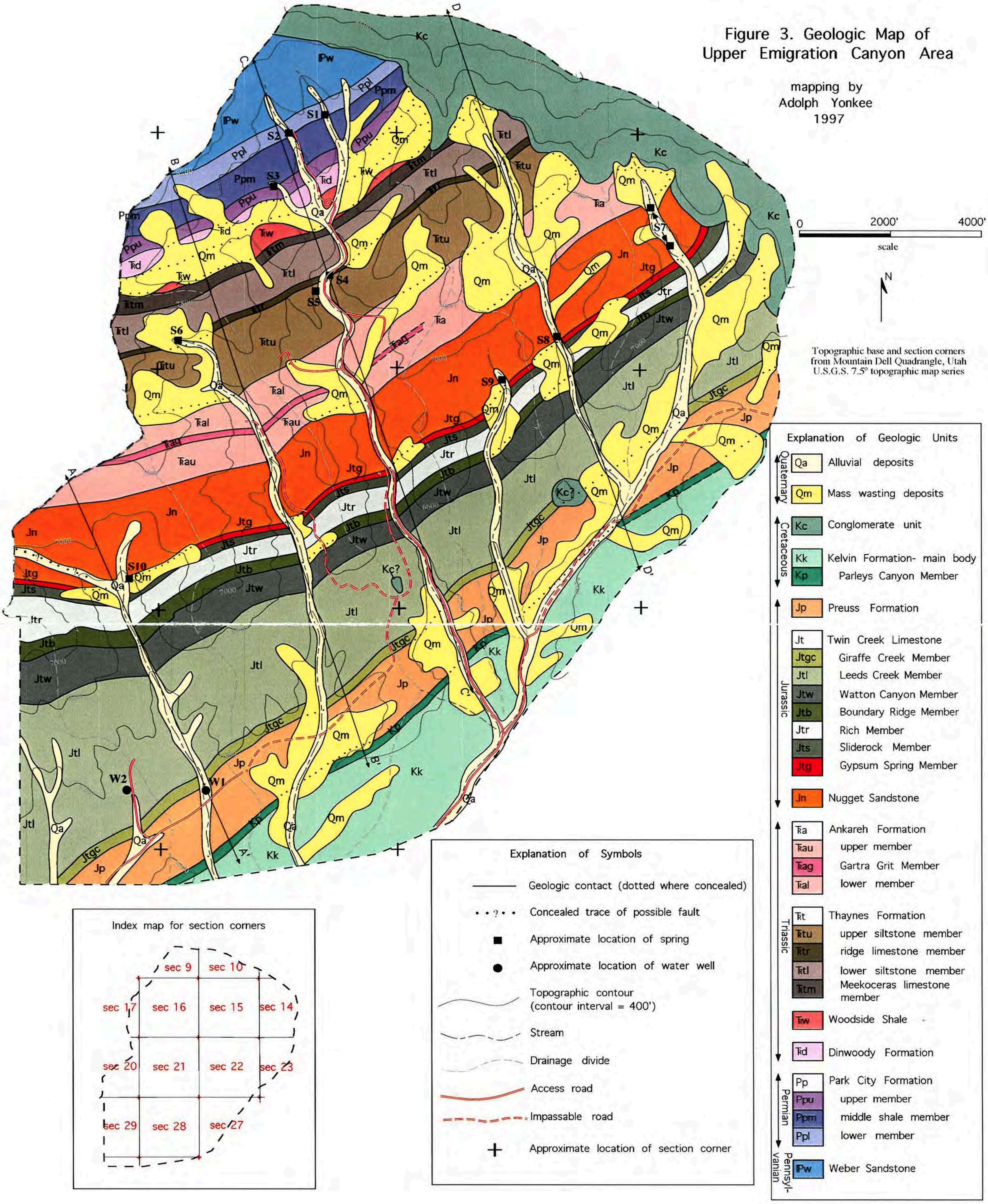


Figure 3. Geologic Map of Upper Emigration Canyon Area

mapping by
Adolph Yonkee
1997



Topographic base and section corners from Mountain Dell Quadrangle, Utah U.S.G.S. 7.5° topographic map series

Explanation of Geologic Units

Age	Symbol	Unit
Quaternary	Qa	Alluvial deposits
	Qm	Mass wasting deposits
Cretaceous	Kc	Conglomerate unit
	Kk	Kelvin Formation- main body
	Kp	Parleys Canyon Member
Jurassic	Jp	Preuss Formation
	Jt	Twin Creek Limestone
	Jtgc	Giraffe Creek Member
	Jtl	Leeds Creek Member
	Jtw	Watton Canyon Member
	Jtb	Boundary Ridge Member
	Jtr	Rich Member
	Jts	Sliderock Member
	Jtg	Gypsum Spring Member
	Jn	Nugget Sandstone
Triassic	Ҟa	Ankareh Formation
	Ҟau	upper member
	Ҟag	Gartra Grit Member
	Ҟal	lower member
	Ҟt	Thaynes Formation
	Ҟtu	upper siltstone member
	Ҟtr	ridge limestone member
	Ҟtl	lower siltstone member
	Ҟtm	Meekoceras limestone member
	Ҟw	Woodside Shale
	Ҟd	Dinwoody Formation
Permian	Pp	Park City Formation
	Ppu	upper member
	Ppm	middle shale member
	Ppl	lower member
Pennsylvanian	IPw	Weber Sandstone

Explanation of Symbols

Symbol	Meaning
―	Geologic contact (dotted where concealed)
• • ? • •	Concealed trace of possible fault
■	Approximate location of spring
●	Approximate location of water well
~	Topographic contour (contour interval = 400')
—·—	Stream
- - -	Drainage divide
―	Access road
- - -	Impassable road
+	Approximate location of section corner

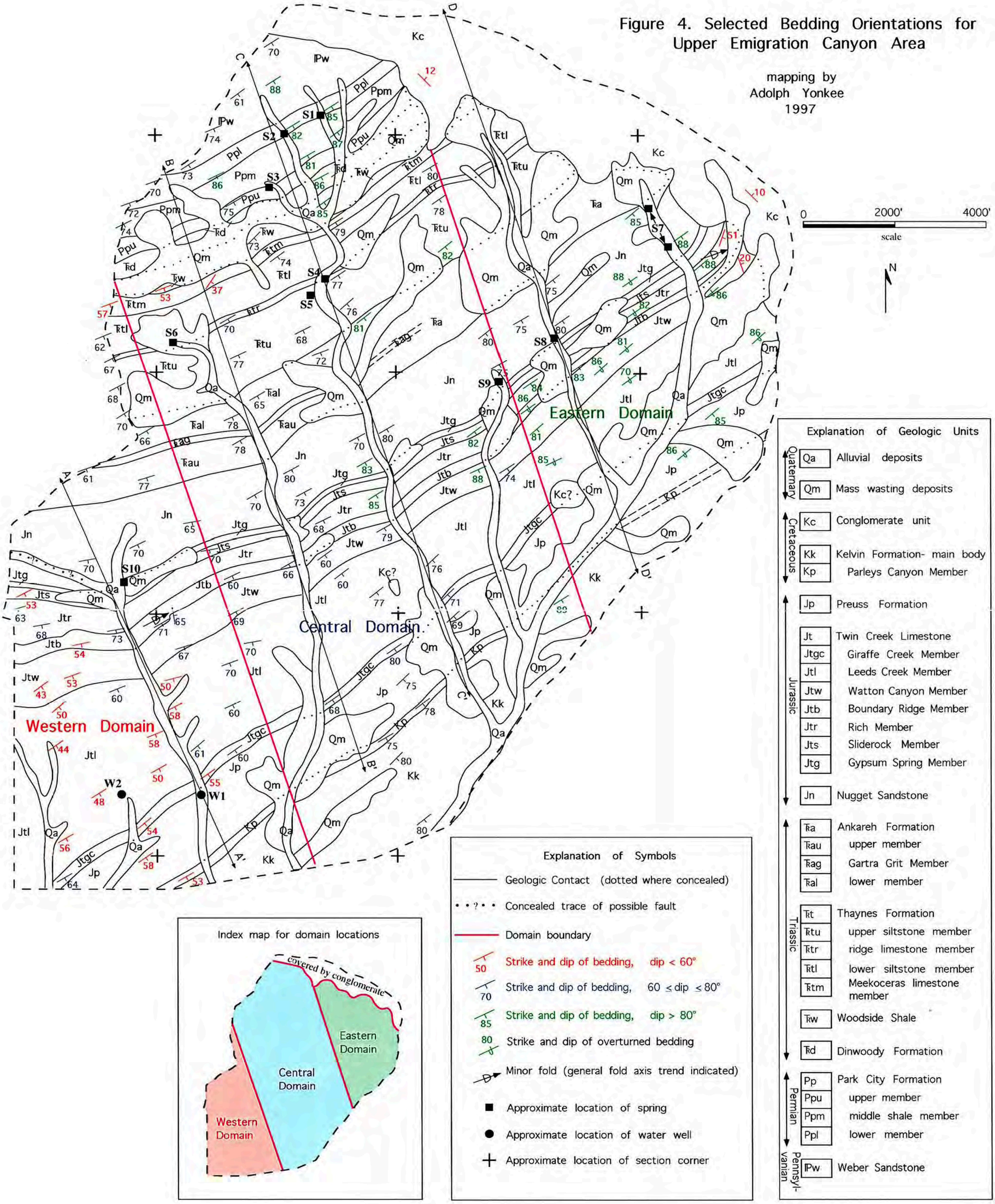
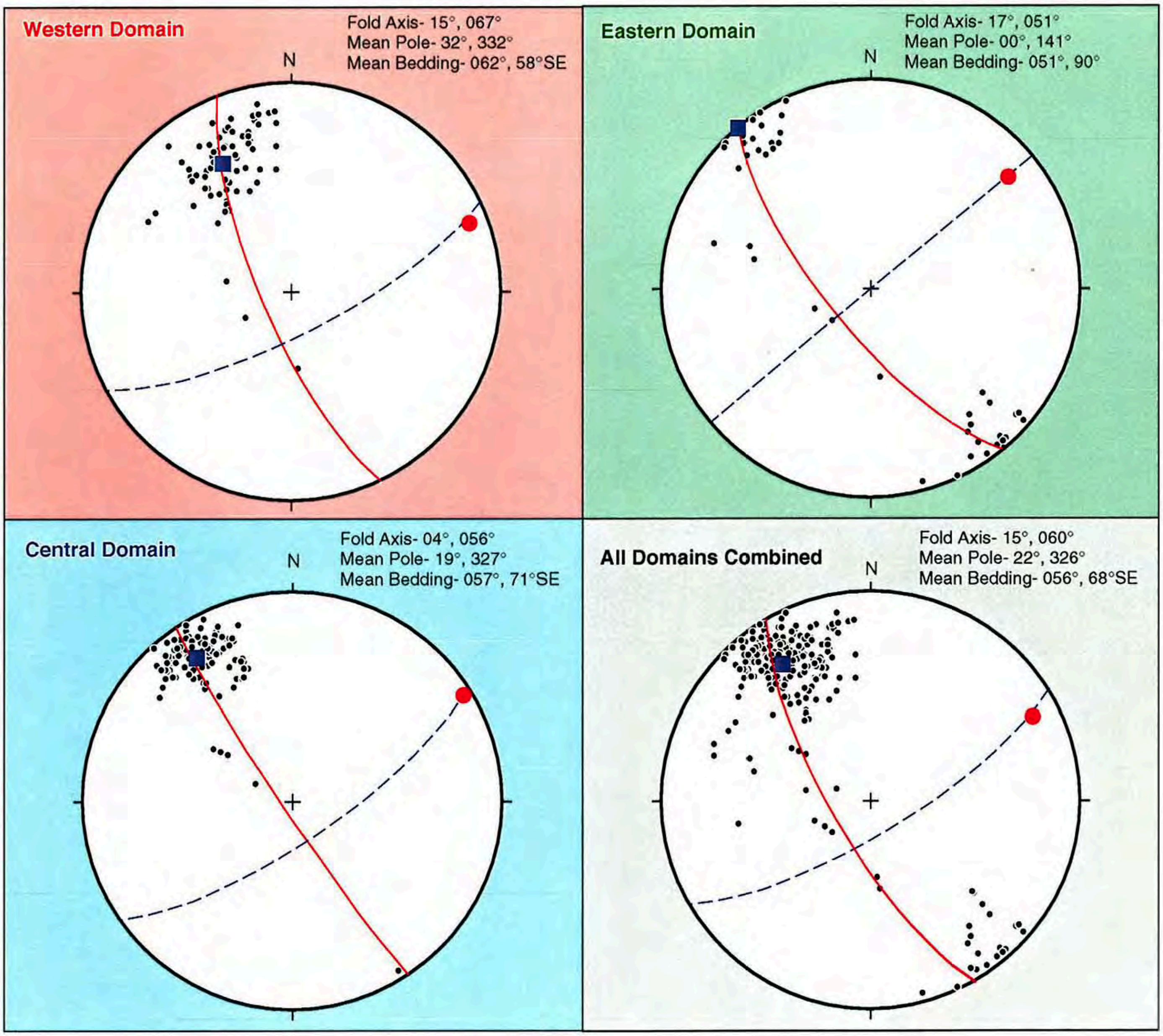


Figure 4. Selected Bedding Orientations for Upper Emigration Canyon Area

mapping by
Adolph Yonkee
1997

Figure 5.
Stereograms of Bedding Orientations for Upper Emigration Canyon Area



Explanation of symbols

- • Pole to bedding
- ● Best fit fold axis
- — Profile plane
- ■ Mean bedding pole*
- - - - Mean bedding plane

* excludes areas of minor folding

Index map for domain locations

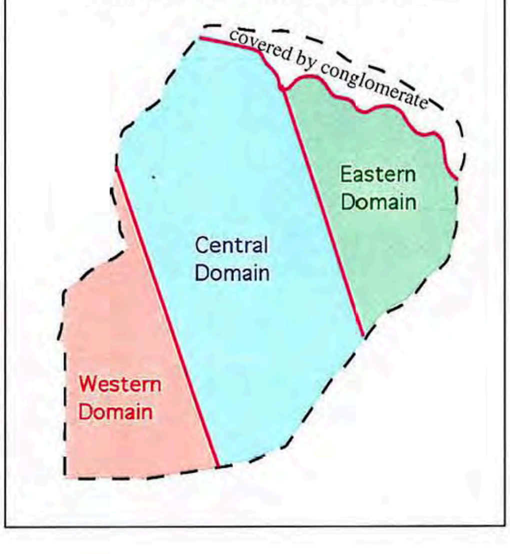


Figure 6. Geologic Cross Sections of Upper Emigration Canyon Area

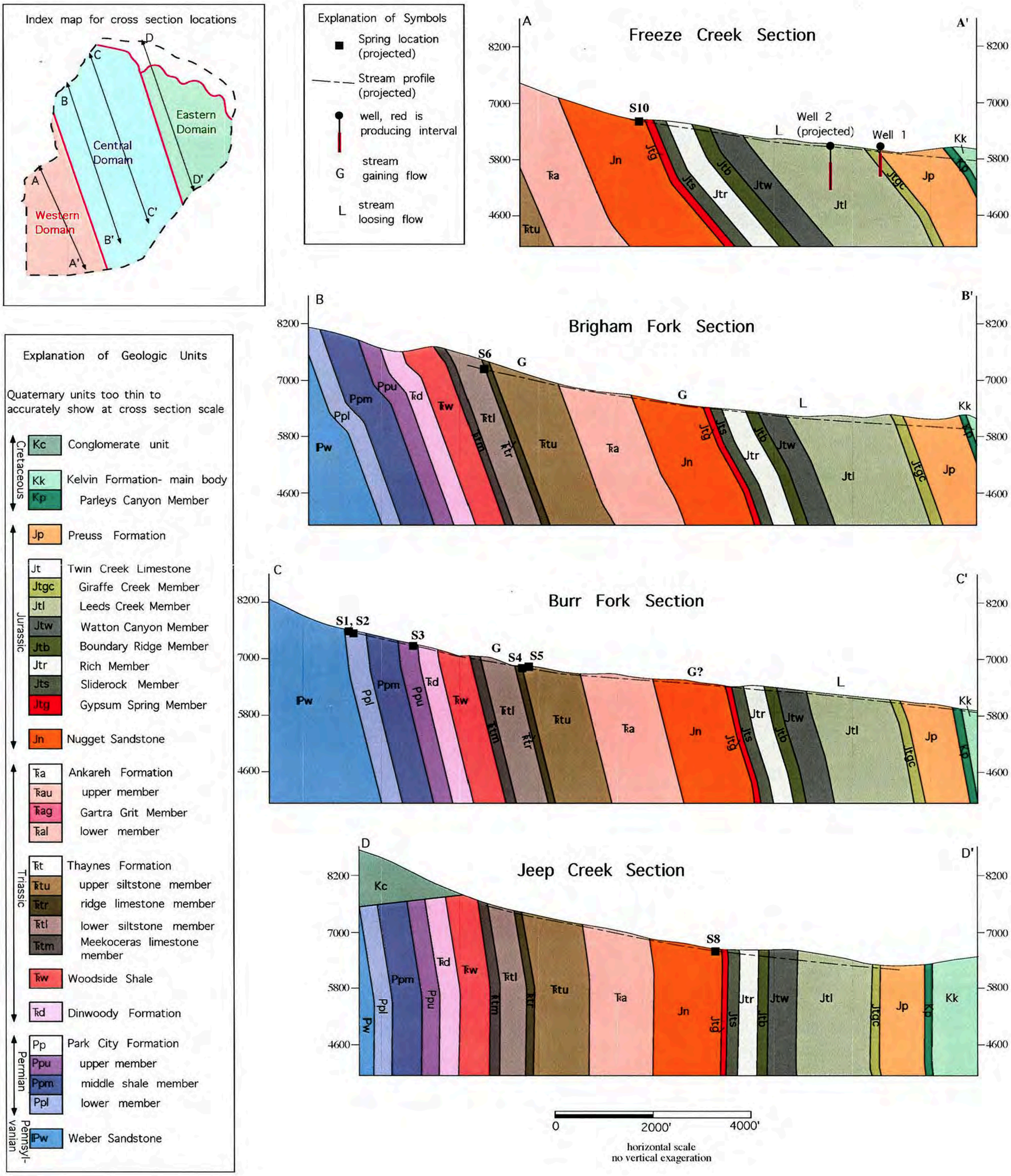


Figure 7. Topographic Features and Selected Topographic Profiles for Upper Emigration Canyon Area

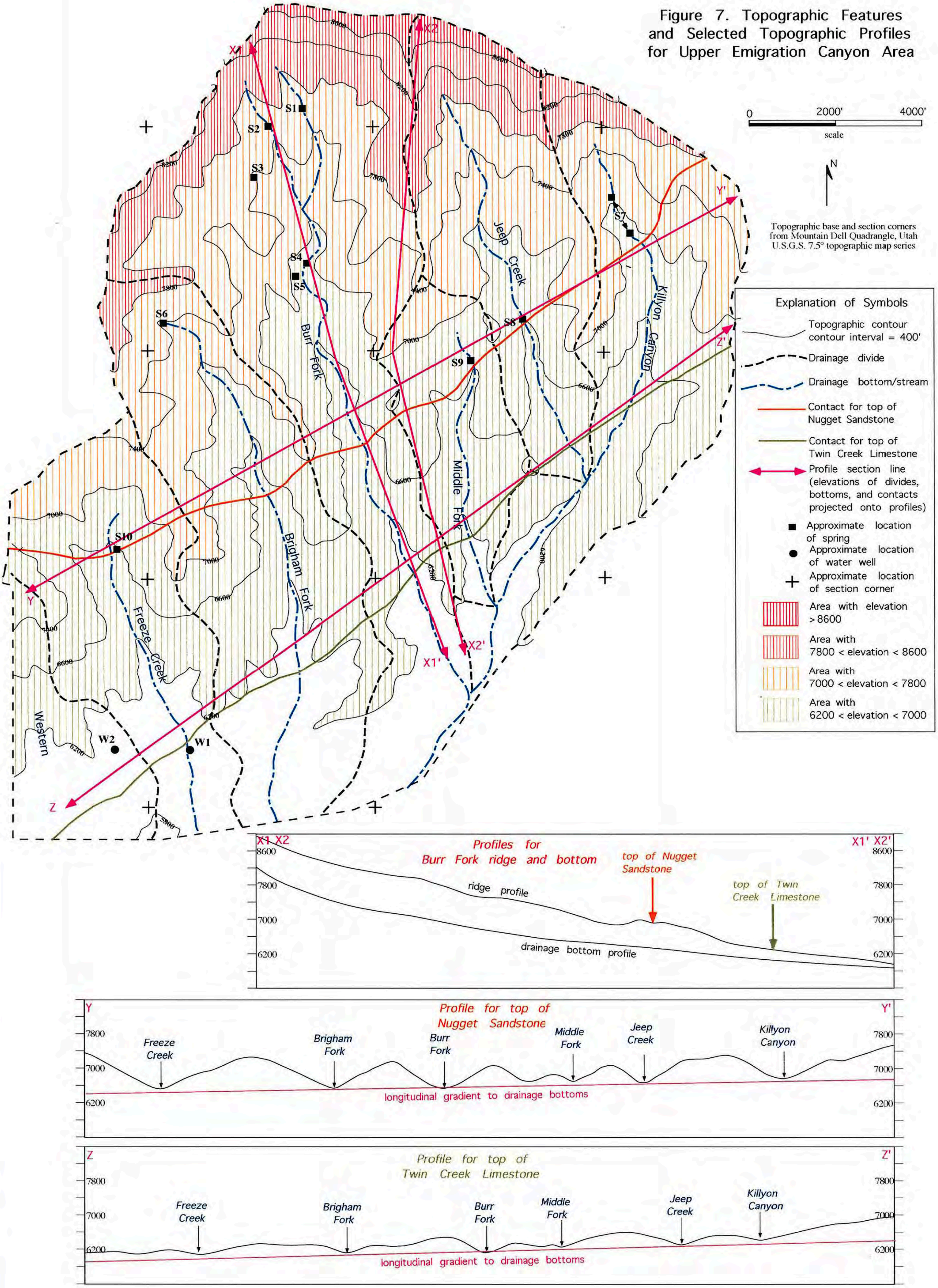


Figure 8. Drainage Basin Areas, Potential Hydrostratigraphic Units, and Potential Topographic Subunits for Upper Emigration Canyon Area

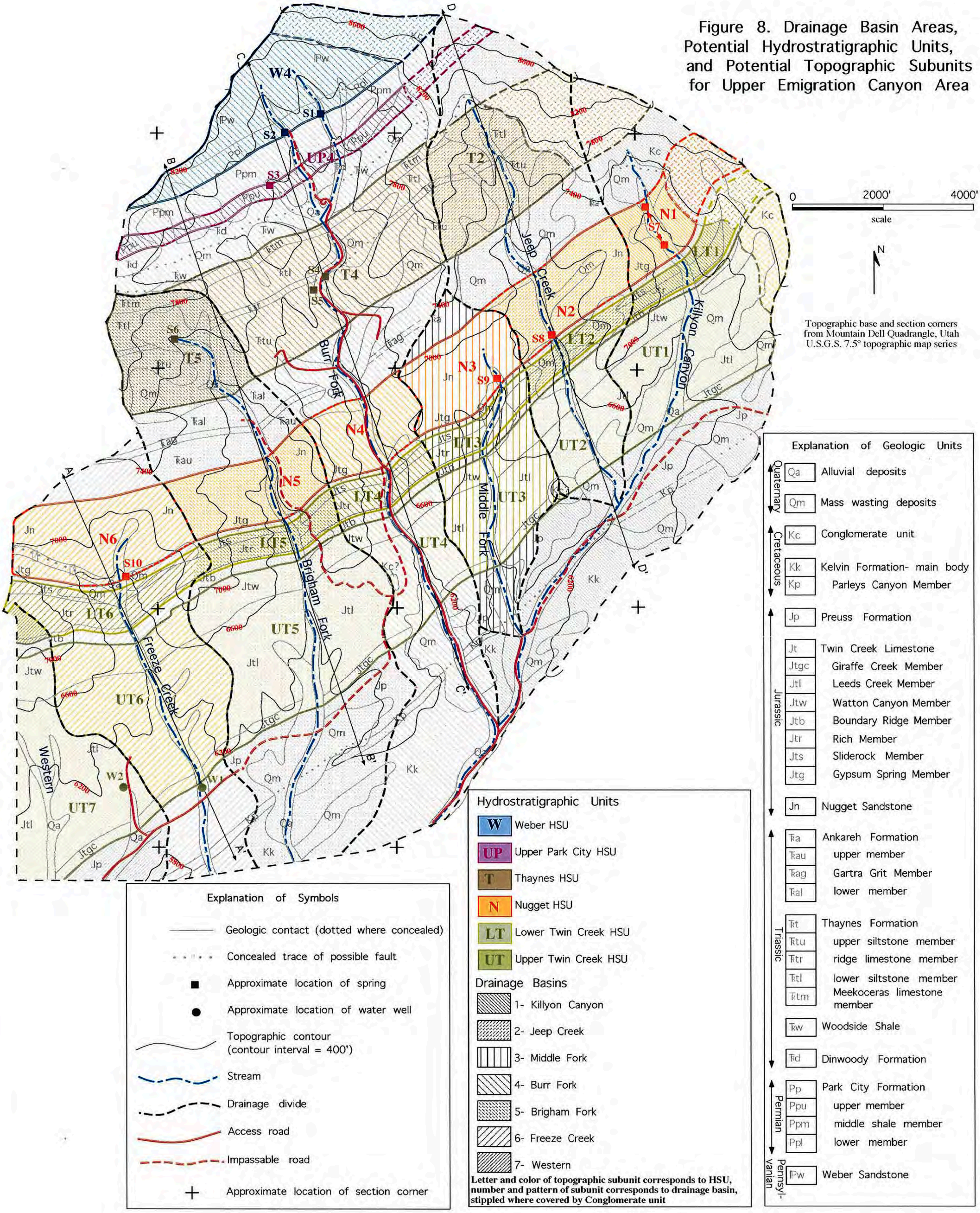


Figure 9. Cross Sections
Illustrating Potential Hydrostratigraphic Units
for Upper Emigration Canyon Area

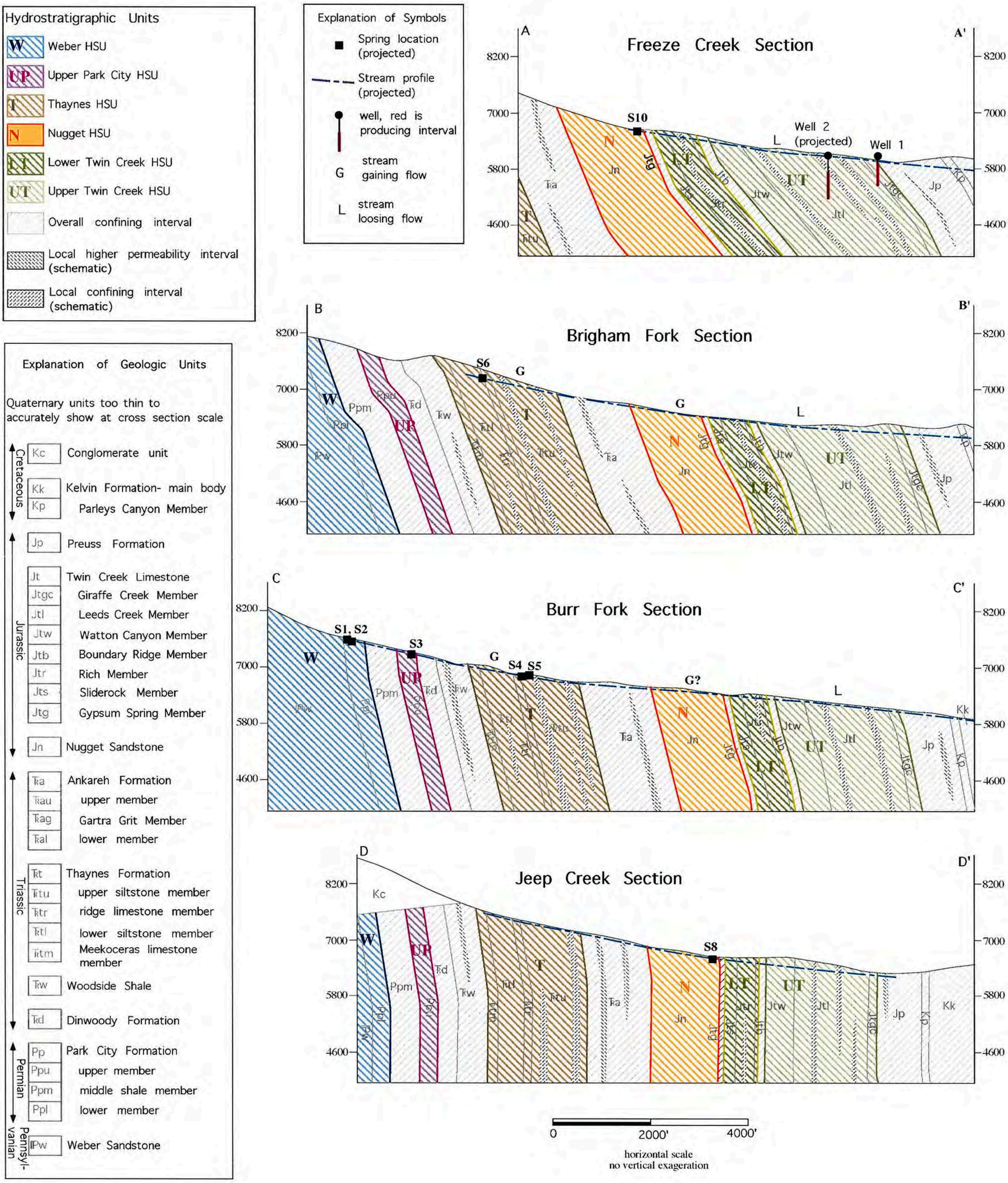


Figure 10 — Pump Test, Recovery and Monitoring Data

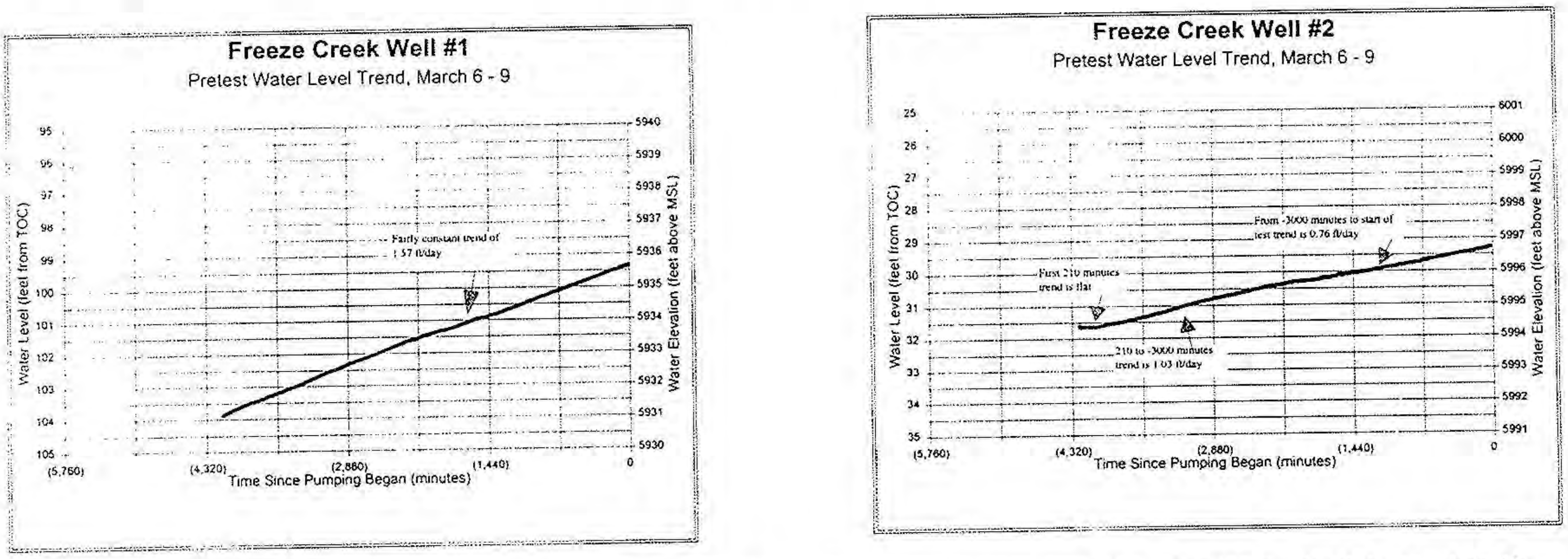


Figure 10a — Pretest water level trend in Freeze Creek Wells #1 and #2. Note trend in water level rise in Well #1 is about double Well #2, but actual elevation in Well #2 is approximately 60 feet higher than Well #1.

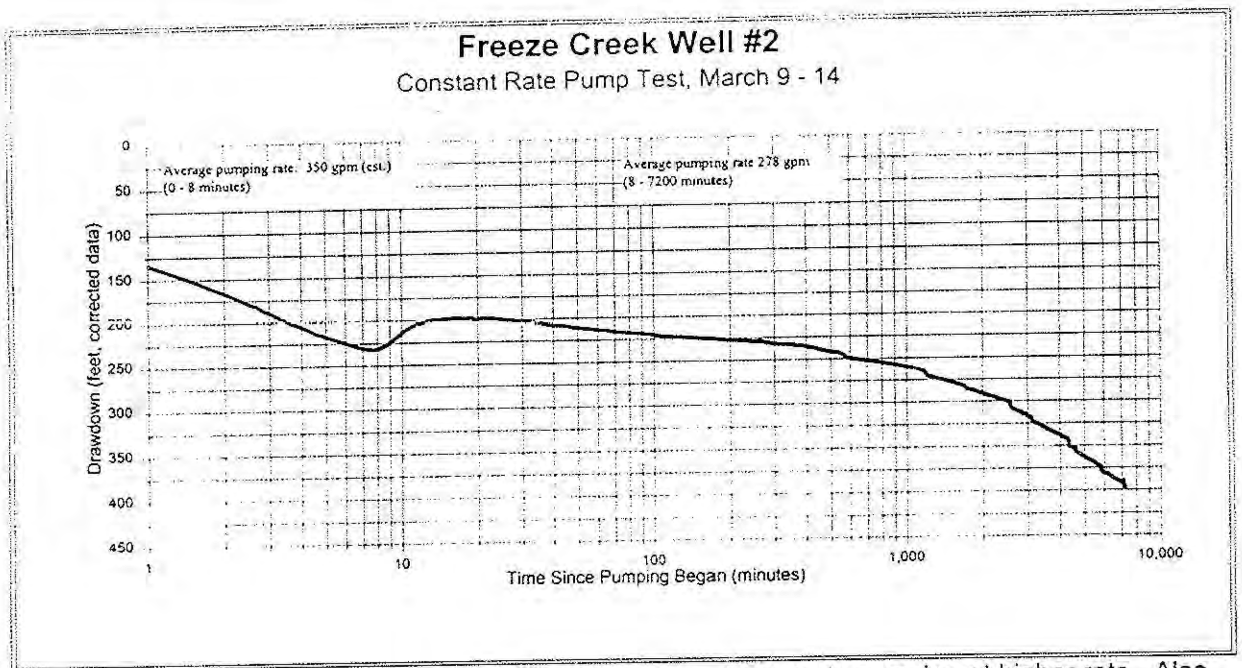


Figure 10b — Semi-log plot of pump test drawdown data. Note early pumping at higher rate. Also note increasing rate of drawdown with time.

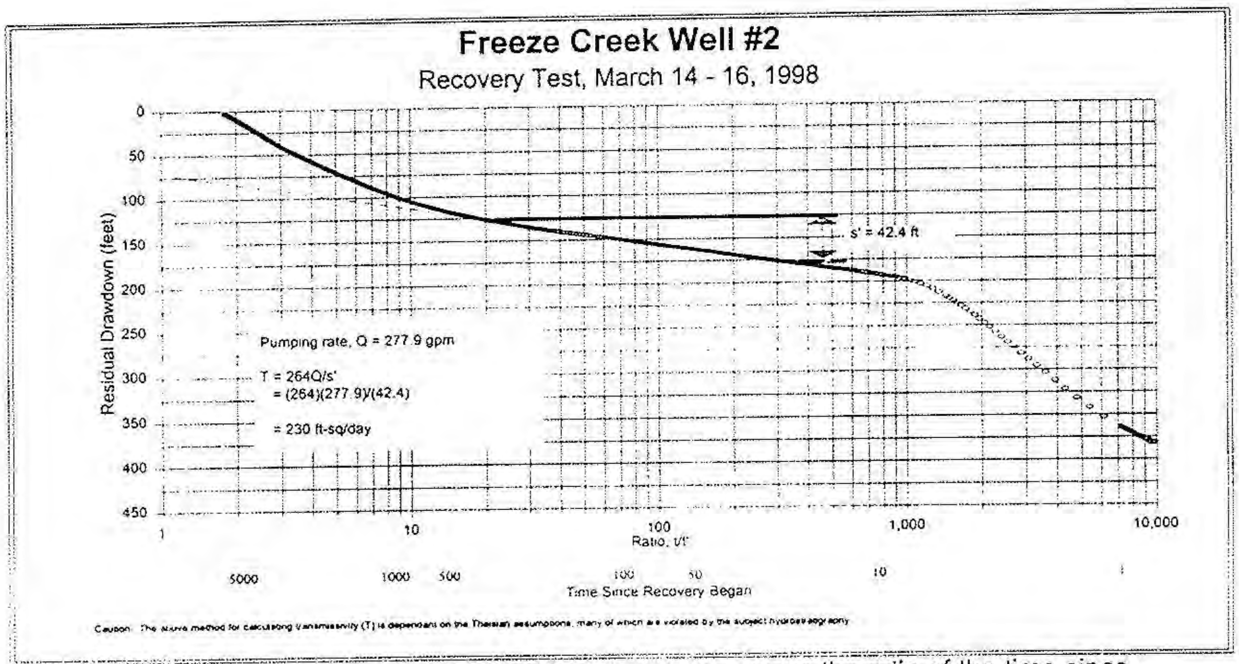


Figure 10c — Semi-log recovery plot of residual drawdown versus the ratio of the time since pumping began to the time since pumping ended (t/t'). Note the projection of middle curve intercepts the y-axis at 75 feet.