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EDITED BY PAUL KARL LINK AND BART J. KOWALLIS

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MESOZOIC TO RECENT GEOLOGY OF UTAH

Edited by

Paul Karl Link and Bart J. Kowallis

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CONTENTS

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Cover photos taken by Paul Karl Link.

Top: Upheaval Dome, southeastern Utah.

Middle: Lake Bonneville shorelines west of Brigham City, Utah.

Bottom: Bryce Canyon National Park, Utah.

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Preface

Guidebooks have been part of the exploration of the American West since Oregon Trail days. Geologic guidebooks with maps and photographs are an especially graphic tool for school teachers, University classes, and visiting geologists to become familiar with the territory, the geologic issues and the available references.

It was in this spirit that we set out to compile this two-volume set of field trip descriptions for the Annual Meeting of the Geological Society of America in Salt Lake City in October 1997. We were seeking to produce a quality product, with fully peer-reviewed papers, and user-friendly field trip logs. We found we were bucking a tide in our profession which de-emphasizes guidebooks and paper products. If this tide continues we wish to be on record as producing "The Last Best Geologic Guidebook."

We thank all the authors who met our strict deadlines and contributed this outstanding set of papers. We hope this work will stand for years to come as a lasting introduction to the complex geology of the Colorado Plateau, Basin and Range, Wasatch Front, and Snake River Plain in the vicinity of Salt Lake City. Index maps to the field trips contained in each volume are on the back covers.

Part 1 "Proterozoic to Recent Stratigraphy, Tectonics and Volcanology: Utah, Nevada, Southern Idaho and Central Mexico" contains a number of papers of exceptional interest for their geologic synthesis. Part 2 "Mesozoic to Recent Geology of Utah" concentrates on the Colorado Plateau and the Wasatch Front.

Paul Link read all the papers and coordinated the review process. Bart Kowallis copy edited the manuscripts and coordinated the publication via Brigham Young University Geology Studies. We would like to thank all the reviewers, who were generally prompt and helpful in meeting our tight schedule. These included: Lee Allison, Genevieve Atwood, Gary Axen, Jim Beget, Myron Best, David Bice, Phyllis Camilleri, Marjorie Chan, Nick Christie-Blick, Gary Christenson, Dan Chure, Mary Droser, Ernie Duebendorfer, Tony Ekdale, Todd Ehlers, Ben Everitt, Geoff Freethey, Hugh Hurlow, Jim Garrison, Denny Geist, Jeff Geslin, Ron Greeley, Gus Gustason, Bill Hackett, Kimm Harty, Grant Heiken, Lehi Hintze, Peter Huntoon, Peter Isaacson, Jeff Keaton, Keith Ketner, Guy King, Mel Kuntz, Tim Lawton, Spencer Lucas, Lon McCarley, Meghan Miller, Gautam Mitra, Kathy Nichols, Robert Q. Oaks, Susan Olig, Jack Oviatt, Bill Perry, Andy Pulham, Dick Robison, Rube Ross, Rich Schweickert, Peter Sheehan, Norm Silberling, Dick Smith, Barry Solomon, K.O. Stanley, Kevin Stewart, Wanda Taylor, Glenn Thackray and Adolph Yonkee. In addition, we wish to thank all the dedicated workers at Brigham Young University Print Services and in the Department of Geology who contributed many long hours of work to these volumes.

Paul Karl Link and Bart J. Kowallis, Editors

Bedrock Geology of Snyderville Basin: Structural Geology Techniques Applied to Understanding the Hydrogeology of a Rapidly Developing Region, Summit County, Utah

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ABSTRACT

The availability of ground water is a problem for many communities throughout the west. As these communities continue to experience growth, the initial allocation of ground water supplies proves inadequate and may force restrictions on existing, and future, development plans. Much of this new growth relies on ground water supplies extracted from fractured bedrock aquifers. An example of a community faced with this problem is western Summit County, near Park City, Utah. This area has experienced significant water shortages coupled with a 50% growth rate in the past 10–15 years. Recent housing development rests directly on complexly deformed Triassic to Jurassic sedimentary rocks in the hanging wall of the Mount Raymond-Absaroka thrust system. The primary fractured bedrock aquifers are the Nugget Sandstone, and limestones in the Thaynes and Twin Creek Formations. Ground water production and management strategies can be improved if the geometry of the structures and the flow properties of the fractured and folded bedrock can be established. We characterize the structures that may influence ground water flow at two sites: the Pinebrook and Summit Park subdivisions, which demonstrate abrupt changes (less than 1 mi/1.6 km) within the hydrogeologic systems. Geologic mapping at scales of 1:4500 (Pinebrook) and 1:9600 (Summit Park), scanline fracture mapping at the outcrop scale, geologic cross sections, water well data, and structural analysis, provides a clearer picture of the hydrogeologic setting of the aquifers in this region, and has been used to successfully site wells. In the Pinebrook area, the dominate map-scale structures of the area is the Twomile Canyon anticline, a faulted box-like to conical anticline. Widely variable bedding orientations suggest that the fold is segmented and is non-cylindrical and conical on the western limb with a fold axis that plunges to the northwest and also to the southeast, and forms a box-type fold between the middle and eastern limbs with a fold axis that plunges to the northeast. The fold is cut by several faults including the Toll Canyon fault, which we interpret as a west-directed folded hanging-wall splay off the east-directed Mt. Raymond thrust. These complex geometries may be due to at least two phases of deformation. Results from outcrop analyses show that the fractured bedrock aquifers are lithologically heterogeneous, anisotropic, and compartmentalized. Two exposures of the Toll Canyon fault show that even though the fault cores may be thin, extensive damage zones develop in the Nugget Sandstone and Thaynes Limestone, and shale smears form in the Triassic shales. The damaged zones may be regions of enhanced fracture permeability, whereas the shale smears act as flow barriers. The orientation, density, and hydrogeologic characteristics for predominate fracture sets vary within meters.

In the Summit Park area, chronic water shortages required new wells to be sited in the northeast-plunging Summit Park anticline. The anticline experienced two phases of folding and at least one episode of faulting. Structural analysis of the fold defined the geometry of the structure, and a down plunge projection along the fold hinge was used to estimate the location of the Nugget Sandstone at a depth of 700 ft (213 m). The crestal region of the anticline was drilled in order to intercept regions of higher fracture density in the fold. The test well penetrated the Nugget Sandstone at 698 ft depth, and two production wells with long-term yields of 120 and 180 gpm completed. One well in the Sliderock Member (Twin Creek Formation) experiences seasonal fluctuations whereas production in the Nugget sandstone has only subdued seasonal variations, suggesting the Nugget may have great storage.

Complex structures work against the typical basin yield approach for water budgets, therefore, water supply estimates may benefit from detailed studies within local areas. The results of this study demonstrate how traditional structural analysis may be used as an integral component of ground water resource evaluation and management in regions developed on deformed sedimentary bedrock aquifers.

INTRODUCTION

Growth in the Park City area of western Summit County, Utah (fig. 1), has exceeded 5% per year during the past five years (fig. 2). This rate is expected to continue since Park City will host several events for the 2002 Winter Olympics, and as the area expands to a year-round "bedrock bedroom" community only 32 km/20 mi from Salt Lake City. The majority of this growth lies within the Snyderville basin, a physiographic basin bounded on the west, north, and south sides by high ridges of the Wasatch Range, and on the east by low hills underlain by Tertiary Keetley volcanic rocks. Two principle drainages, Silver Creek and East Canyon-Kimball Creek, flow from south to north and ultimately drain into the Weber River (fig. 1). Ground water flow occurs through complexly folded and fractured bedrock and discontinuous, thin unconsolidated valley-fill deposits, with most new development relying heavily on the fractured bedrock aquifers for municipal water supplies (Ashland et al., 1996).

The increased water supply demands associated with dramatic growth necessitated a basin-wide hydrogeologic study (Ashland et al., 1996) which identifies the likely key hydrostratigraphic units and their future water resource potential. That report was part of a comprehensive evaluation of the ground water resources of the area conducted by the Utah Geological Survey and U.S. Geological Survey, Water Resource Division, for the Utah Division of Water Rights and local water developers.

This field trip presents the results of integrating structural geologic analysis with hydrogeology in a small region, and provides examples of how this integration assists management and development of local ground water resources from fractured bedrock aquifers. Two development sites within the Snyderville basin will be discussed: the Pinebrook and Summit Park subdivisions (fig. 1). These sites depend on water supplies from fractured Mesozoic sedimentary bedrock aquifers (Ashland et al., 1996). Even though the Pinebrook and Summit Park subdivisions are within 1 mile (1.6 km) of each other, the aquifer characteristics and consequent well yields between them are highly variable. The Summit Park area, which consists of approximately 200 single-family homes, experienced water shortages in the 1980s and further development there is limited by available water. At present, the Pinebrook area transfers water shares to Summit Park and consists of at least 700 single family homes, and 300 multiple family dwellings, and a small community services area (Dan Schofield, Gorgoza Water Co., pers.comm., 1996).

Based on a regional analysis of Snyderville basin, Ashland et al., (1996) suggest that at least 16 discrete structural and stratigraphic ground water compartments exist that may influence local water well production and the prediction of sustainable yields. This interpretation supports the need for detailed geologic studies within the proposed compartments to assess future ground water resources in this region.

In this trip, we will provide a regional overview of the physiography, geology, and development history of the area, and we will then visit localities which provide examples of the geometry of the folds, faults, and fractures which influence ground water flow.

GEOLOGIC SETTING

Stratigraphy

Figure 3 summarizes the stratigraphy of the Snyderville basin and the units within Summit Park and Pinebrook. Rocks exposed in the study area include the Triassic Thaynes and Ankareh Formations, the Jurassic Nugget Sandstone, the Jurassic Twin Creek Limestone, and minor amounts of Quaternary alluvium. Knowledge of stratigraphy is vital in recognizing the distribution of productive versus non-productive (confining) units within the hydrogeologic system.

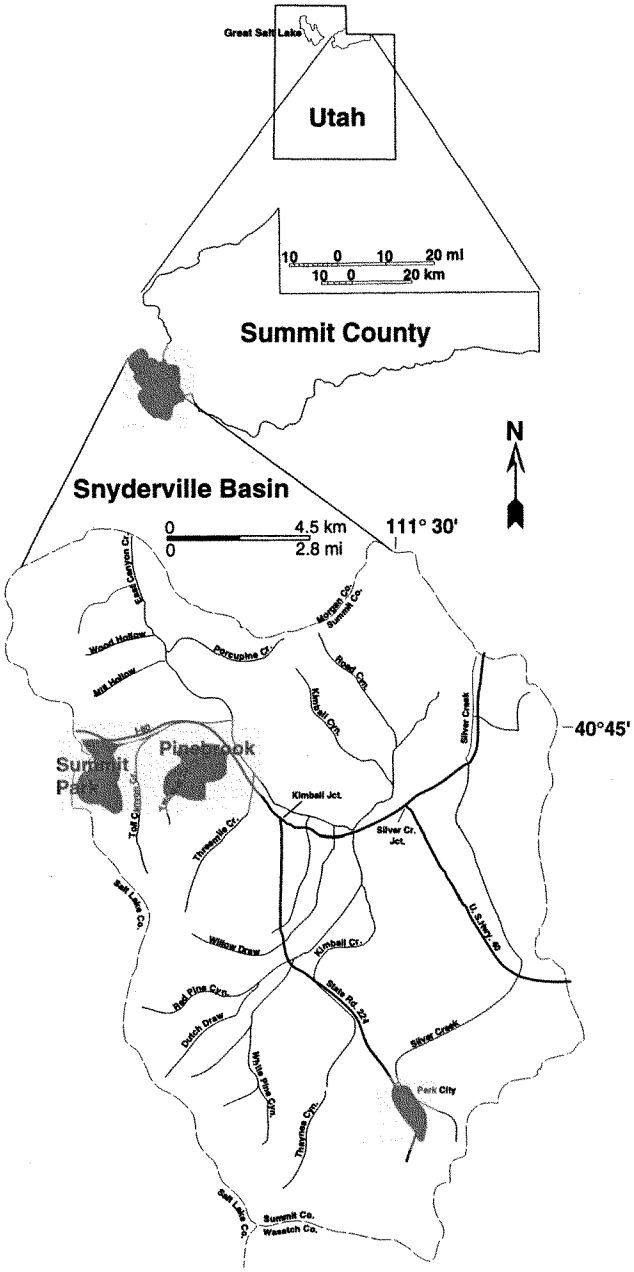


Figure 1. Geographic location map of the Snyderville hydrologic basin, and the Pinebrook and Summit Park subdivisions in western Summit County, Utah (modified from Ashland et al., 1996, and the USGS Salt Lake City 30 x 60 minute quadrangle).

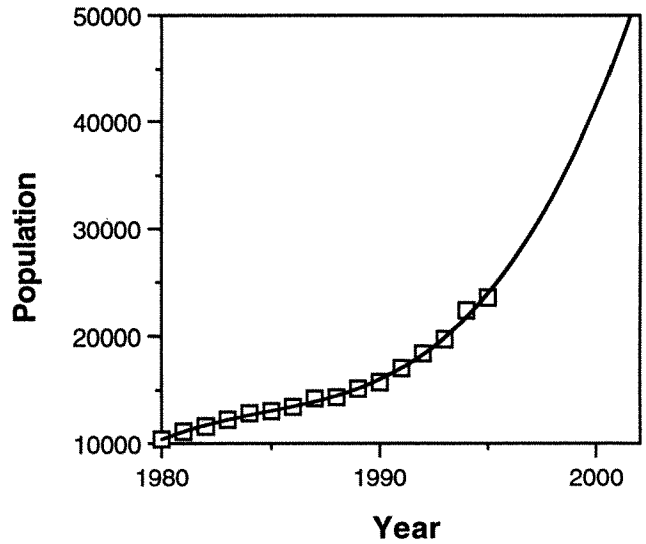


Figure 2. Population of Summit County. Growth at the current rates would result in a five-fold increase in population between 1980 and 2002. Source of data through 1995: Department of Planning and Analysis, 1997.

The Thaynes Formation (Ŧt) is comprised of thin- to thick-bedded, greenish-brown to brown, light-gray, pale-red, and ocher, fine-grained, limy sandstone and slitstone interbedded with olive green to dull-red shale and thick bedded, light gray, fine grained, fossiliferous limestone (Crittenden et al., 1966; Bromfield and Crittenden, 1971). Boutwell (1912) and Barnes and Simos (1968) described a Mid-Red Shale unit that separates the Thaynes into upper and lower members of nearly equal thickness. The Thaynes Formation in this area is between 335 to 475 m (1,100 and 1,500 ft) thick (Bromfield, 1968).

The Ankareh Formation consists of the lower Mahogany Member (Ŧam), the middle Gartra Grit Member (Ŧ ag), and the upper member (Ŧau). The Mahogany Member consists of approximately 305 m (1000 ft) of reddish-brown and pinkish-brown, locally ripple-laminated to finely-laminated, fine-grained sandstone and siltstone, purplish mudstone, and a few thin limestone beds. The Gartra Grit Member is composed of white, pinkish-white, and pale-purple massive, cross-bedded, coarse-grained to pebbly, strongly silica cemented sandstone grading to a deep maroon to dark purple, coarse-grained to pebbly, poorly cemented sandstone near the uppermost contact. Thickness ranges for this formation are between 75 to 200 feet in the Pinebrook subdivision study area. The upper member includes moderate-red, grayish-red, and grayish-purple mudstone and fine-grained sandstone and is gradational with the underlying Gartra Grit Member. This unit is very poorly exposed within the study area and approximate thicknesses range between 69 to 275 m (225 to 900 ft) (Bromfield, 1968; Bromfield and Crittenden, 1971).

The Jurassic rocks consist of the Nugget Sandstone (Jn) and the Twin Creek Limestone (Jtc). The Nugget Sandstone is a salmon colored, fine- to medium-grained, medium to thick bedded, internally finely cross-bedded sandstone. The Nugget Sandstone is about 244 m (800 ft) thick in the

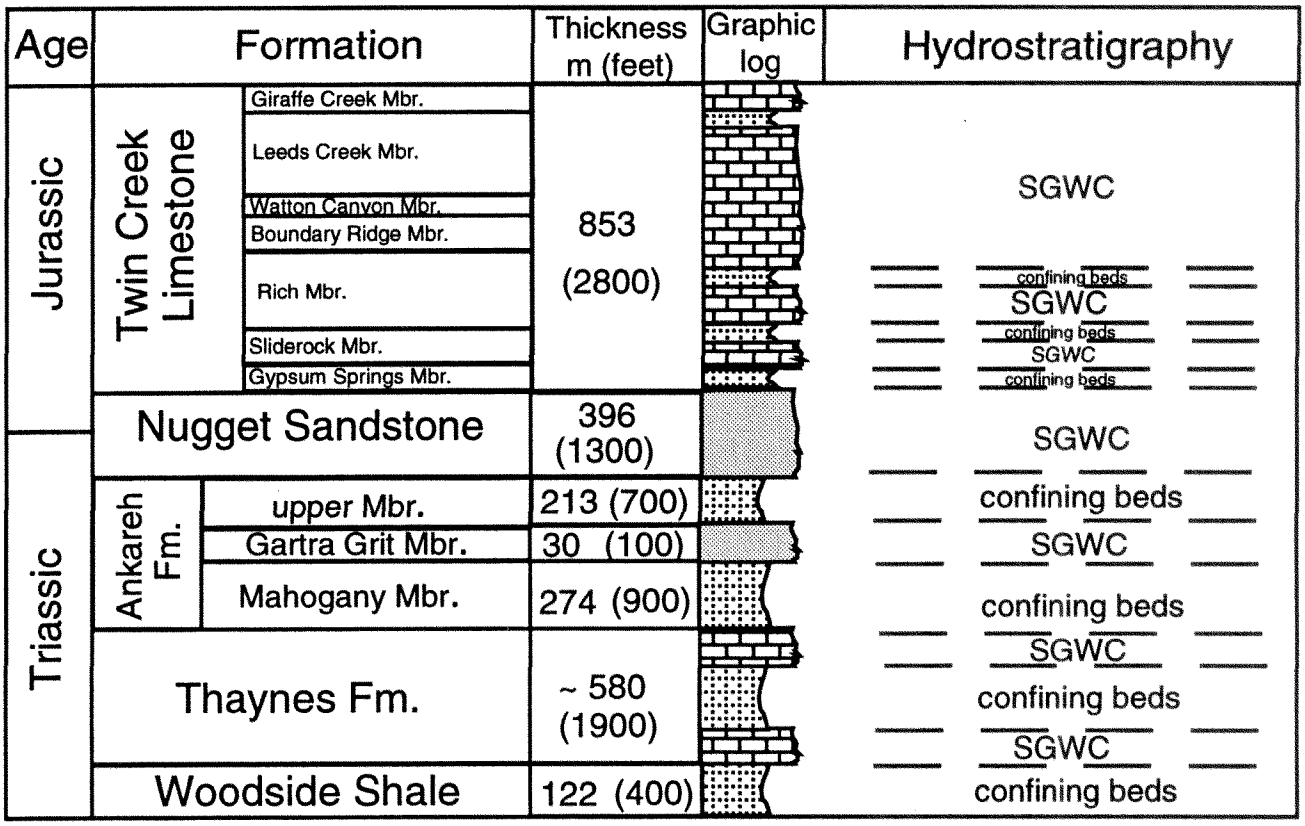


Figure 3. Stratigraphy and hydrostratigraphy of the Pinebrook and Summit Park subdivisions, Summit County, Utah (modified from Hintze (1988) and Ashland (1996)).

Park City area, and approximately 475 m (1,500 ft) thick in the Summit Park and Pinebrook areas (Jarvis and Yonkee, unpublished report, 1993).

The Twin Creek Limestone contains seven members: the Gypsum Spring, Sliderock, Rich, Boundary Ridge, Watton Canyon, Leeds Creek, and Giraffe Creek. The basal Gypsum Spring Member is a gypsiferous, red to reddish-brown clayey siltstone and silty claystone containing local blocks of gray to pink limestone. The upper members of the Twin Creek Limestone in the Snyderville basin area are primarily olive-drab-weathering, gray, oolitic, finely crystalline, and clayey to silty (micritic) limestone. The Twin Creek is about 792 m (2,600 ft) in the Summit Park study area (Crittenden et al., 1966; Hintze, 1988; Imlay, 1967; Jarvis and Yonkee, unpublished report, 1993).

Ashland et al., (1996) established a preliminary hydrostratigraphy of the layered rock units in the study area (fig. 3). They propose that stratigraphic ground water compartments (SGWCs) consisting of fractured limestone and sandstone are separated by confining shaly beds which may have local hydraulic conductivities approaching those of unfracture rock. This separation of permeable fractured rock units by poorly permeable confining beds is evidence of stratigraphic compartmentalization.

Important aquifers (SGWCs) in the study region include the two limestone units of the Thaynes Formation, the Nugget Sandstone, the Rich and Leeds Creek Members of the Twin Creek Limestone, and potentially the Gartra Grit Member of the Ankareh Formation (Ashland et al., 1996). The confining beds or units that likely inhibit ground water flow include the Mid Red shale unit of the Thaynes Formation, the lower part of the Mahogany Member and the upper member of the Ankareh Formation, and the Gypsum Spring and Boundary Ridge Members of the Twin Creek Formation.

Structure

Crittenden et al., (1966) mapped the Summit Park and Pinebrook areas which are also included in the 1:100,000 scale map of Bryant (1990). The dominant structure in this region is the northeast striking Mount Raymond thrust (fig. 4), which carries Pennsylvanian through Cretaceous rocks in its hanging wall (Crittenden et al., 1966; Bryant,1990).

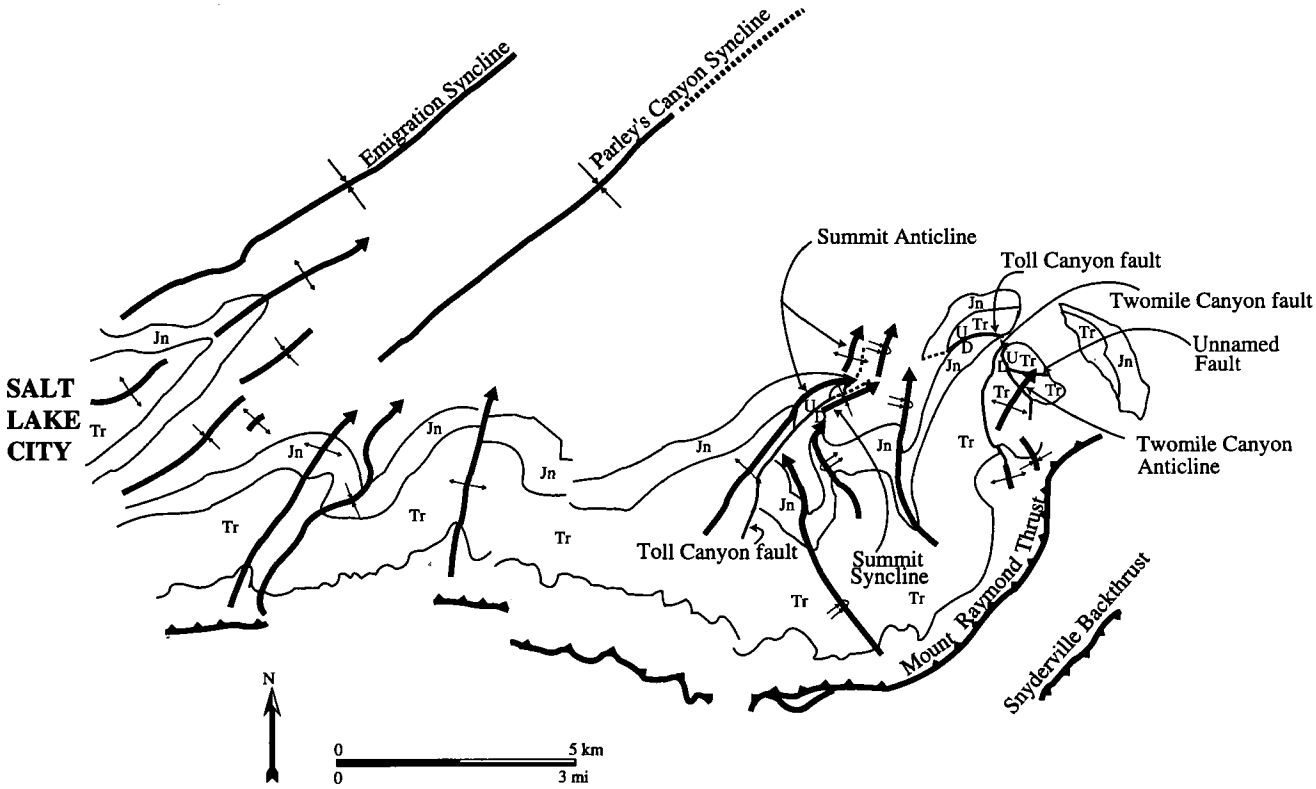


Figure 4. Regional fold train in Triassic (Tr = Thaynes and Ankareh Formations) and Jurassic (Jn = Nugget Sandstone) rocks in hanging-wall of Mount Raymond thrust (modified from Bryant, 1990; Ashland et al., 1996; Jarvis and Yonkee, 1993; Crittenden, et al., 1996). Macroscopic faults and folds present within study areas are noted.

The traditional interpretation of the thrust is that the sinuous trace, interpreted on the basis of a small thrust in the Snyderville basin, reflects folding of the thrust plane (Crittenden, 1974; Crittenden et al., 1966; Bradley and Bruhn, 1988; Bryant, 1990; Yonkee et al., 1992). In contrast, Lamerson (1982) and recent mapping for Mobil Oil by McBride (pers. comm., 1996), suggests the thrust has a relatively straight strike across the area, eliminating the need for post-thrust folding. The Mount Raymond thrust plane dips gently north (fig. 5), and appears to be a smoothly undulating surface that records northward tilting but little or no folding of the thrust plane.

Rocks in the hanging wall of the MRT are cut by a series of imbricate thrusts and folded within a fold train that extends for 20 km (13 mi) west of Park City (fig. 4; Bryant, 1990). The folds trend northeast to northwest, plunge between 5° to 72°, and are expressed in Triassic and Jurassic rocks with open to close box-like geometries. First-phase folds (referred to as F1) consist of a series of smaller-scale anticlines and synclines with generally north to northeast plunging fold axes, including the Summit Park anticline, the Toll Canyon syncline, and the Twomile Anticline examined here. These folds developed above detachments within Pennsylvanian to Triassic strata, are locally associated with moderate to high angle reverse faults, and formed during an early phase of shortening. An early spaced cleavage (referred to as S1), defined by spaced seams of clay-rich material, is widely developed within the Twin Creek Formation. S1 is subparallel to F1 fold axes and strongly fanned about F1 folds, indicating that cleavage formed during initial shortening. Second-phase folds (referred to as F2) consist of larger-scale anticlines and synclines with gently east-northeast plunging fold axes, including the Parley's Canyon syncline and adjacent Spring Creek anticline and Emigration Canyon syncline. A weakly developed second cleavage (referred to as S2) formed during F2 folding. F2 folds may correlate with a series of folds exposed further north that formed during large-scale slip on the Crawford thrust (Yonkee and others, this volume) development of the Uinta-Cottonwood arch, or during Medicine Butte, and Absaroka thrust systems.

The structures of interest on this trip are the informally named, Summit Park anticline and syncline, the Toll Canyon syncline, the Twomile Canyon anticline, and the Toll Canyon and Twomile Canyon faults (fig. 4). We believe that understanding the aquifer and confining layer geometries

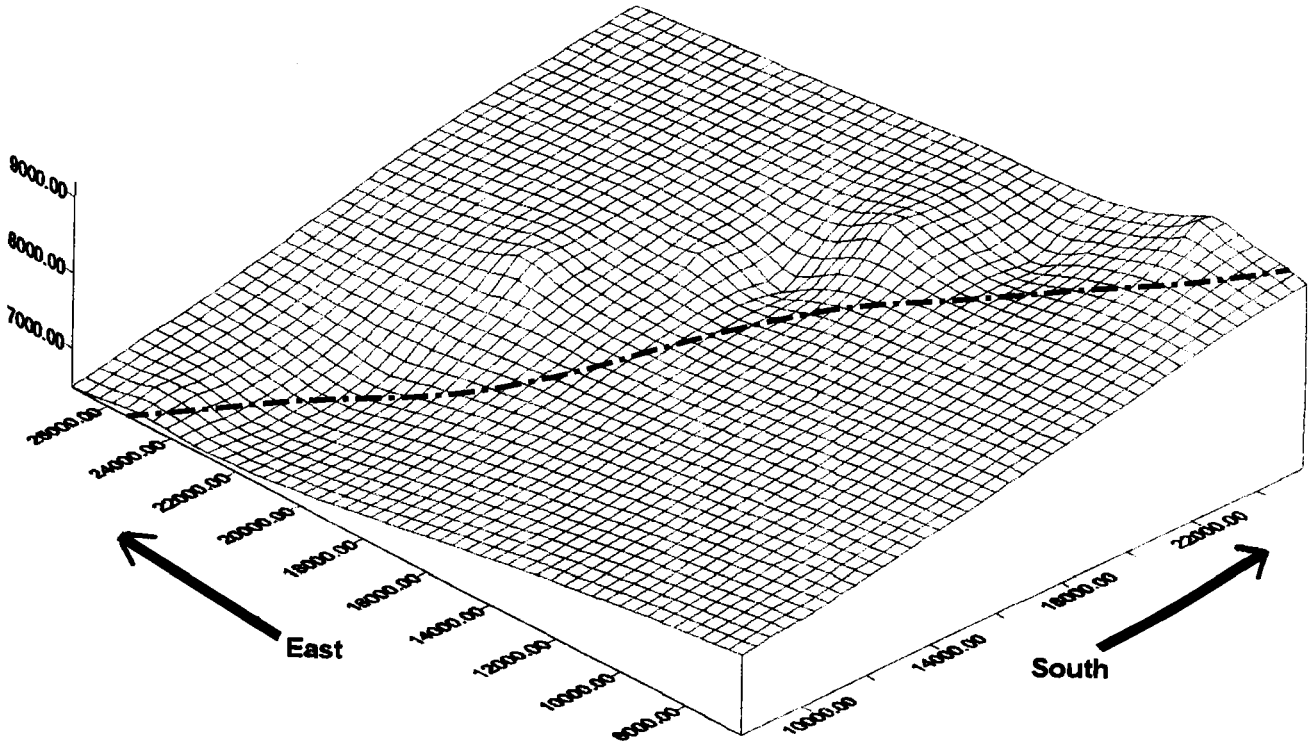


Figure 5. View to the southeast of the best-fit surface (in grids) of the Mt. Raymond thrust. Surface is a minimum curvature surface calculated from digitized points along the thrust trace (dashed line) using SURFER software. Gentle north dip of a smooth surface is suggested by the data. Coordinates are in feet from a datum on the Park City West quadrangle. Vertical scale is in feet above sea level.

are important for ground water resource management and development in this region.

Data Collection and Methods

Geologic mapping and structural analysis at a scale of 1:4500 were completed over an approximately 6 km^2 (2.25 mi^2) area to characterize the geometry of the Twomile Canyon anticline and macroscopic faults within the Pinebrook subdivision. Fracture systems in the sedimentary bedrock were characterized by using a modified version of the scanline technique (LaPointe and Hudson, 1985). Geologic mapping and cross-sections at a scale of 1:9600 were completed as part of a well siting and well head protection plan for the Summit Park subdivision conducted by Weston Engineering in 1994–95.

ROAD LOG

elapsed mileage	total mileage	
0	0.0	Start trip from Salt Palace.
0.3	0.3 (approx)	(approx) Travel south from the Salt Palace until a left (east) turn can be made. Downtown construction alters this.
0.3	0.6	Turn right (south) onto State Street. Travel south to I-80.
3.2	3.8	Turn left (east) onto I-80 east bound.
1.4	5.2	Cross approximate trace of western splay of WFZ which has Holocene fault scarps. The East Bench fault forms prominent scarps along the 9th–11th East area in Salt Lake City (Personius and Scott, 1993). View to southeast of central part of the Wasatch Range. The steep slope of Mount Olympus consists of Tintic Quartzite in the footwall of the Mount Raymond thrust. Precambrian Big Cottonwood Formation and basement rock of the Little Willow Series core the Cottonwood arch to the south. Oligocene granite and quartz monzonite intrusions locally cut the crest of the arch.
2.2	7.4	Junction with Interstate 215. Continue west on I-80.
0.6	8.0	Cross approximate trace of eastern splay of WFZ along base of mountains.
1.1	9.1	Fractured and faulted sandstone beds of

		Nugget Sandstone are exposed in road cut. A locally faulted contact between Nugget Sandstone and Sliderock and Gypsum Spring Members of the Twin Creek Limestone is exposed to the northeast. Heading northeast on I-80 we will be cutting obliquely across the SSE limb and hinge zone of the Parleys Canyon syncline, a major ENE trending F2 fold, and also across a series of smaller scale, N- to NE-trending F1 folds developed in Triassic to Jurassic strata above detachments in Permo-Pennsylvanian strata (fig. 4).
0.6	9.7	Argillaceous, fine-grained limestone of the Rich Member of the Twin Creek Limestone is exposed in roadcuts, and is deformed by spaced cleavage, multiple vein arrays, and minor faults. An early, strongly developed, N- to NE-striking, steeply dipping cleavage is associated with F1 minor folds and early layer-parallel shortening. A later, weakly developed, ENE-striking, gently dipping cleavage is associated with the Parleys Canyon syncline (see Yonkee et al., this volume, for details).
0.7	10.4	Overpass. Complex folds are developed in the Watton Canyon Member of the Twin Creek Limestone, and spaced cleavage is strongly fanned about the folds.
1.6	12.0	Ranch exit. Argillaceous to silty limestone beds are cut by minor fault zones in road cut to northwest. Cores of minor faults contain scaly, clay-rich material that may form impermeable barriers to ground water flow.
2.0	14.0	Mountain Dell exit. The ENE-plunging Spring Canyon anticline is exposed to the NNW (Crittenden, 1965). The anticline is cored by faulted Triassic rocks, and may continue northeast into the frontal anticline of the Crawford thrust sheet. Conglomerate beds exposed to the north along East Canyon may display progressive unconformities above the underlying tighter Parleys Canyon syncline and Spring Canyon anticline, recording mostly Late Cretaceous development of F2 folds (Mullens, 1971).
1.9	15.9	Lambs Canyon exit. NNW-dipping sandstone and conglomerate beds of the Cretaceous Kelvin and Frontier Formation crop out further north toward the hinge of the Parleys Canyon syncline.
2.4	18.3	Parleys Summit. Red siltstone and sandstone beds of Preuss Formation dip NNW in road cuts. This information also contains salt-bearing intervals, and appears to have formed an important regional decollement during Cretaceous thrusting (Yonkee et al., this volume).
0.9	18.2	Road cut in micrite beds of Twin Creek Formation. Summit Park is to southwest.
2.3	20.5	Pass exit to Jeremy Ranch. Sandstone beds of Nugget Formation exposed in the quarry to the west lie within the northwest limb of the hanging-wall ramp anticline which is discussed in stops 1 and 4.
1.0	21.5	Junction with Utah Highway 224 from Park City. Exit I-80. Turn right (south) on Highway 224. Travel 1 block to traffic light, turn right.
0.1	21.6	Turn right at the traffic light. Travel 1 block, and turn right onto the frontage road. Proceed north along the frontage road.
1.0	22.6	Hi-Ute Ranch on left. The hills north across the freeway are underlain by northeast dipping Triassic and Jurassic rocks in the hanging wall of the Mount Raymond thrust.
1.0	23.6	Junction with Pinebrook Drive—Entrance to Pinebrook Development. Turn left.
0.35	24.0	Turn right.
0.1	24.1	Turn left. Proceed along Pinebrook Road.
1.6	25.7	Sharp bend in street. Veer left (south).
0.35	30.0	Hair pin bend in street. Veer north.
0.4	30.4	Road bends west. Stop 1.

Stop 1. Pinebrook Overview

The Pinebrook subdivision (figs. 1 and 6) is an excellent example of the extensive "bedrock community" development that is occurring within western Summit County and the Park City area. Pinebrook includes the southeast half of section 10 south through the east half of section 15, to the southern half of section 11 and south through section 14, T.1.S. R.3.E., Park City West 7.5 min quad.), bounded on the west by Summit Park and Timberline subdivisions and by I-80 to the north. The development boundaries are also Pinebrook's water rights boundaries. Pinebrook is intriguing because its wells are more productive than those in surrounding communities, it contains abundant high-quality bedrock exposures, and the structures are poorly understood.

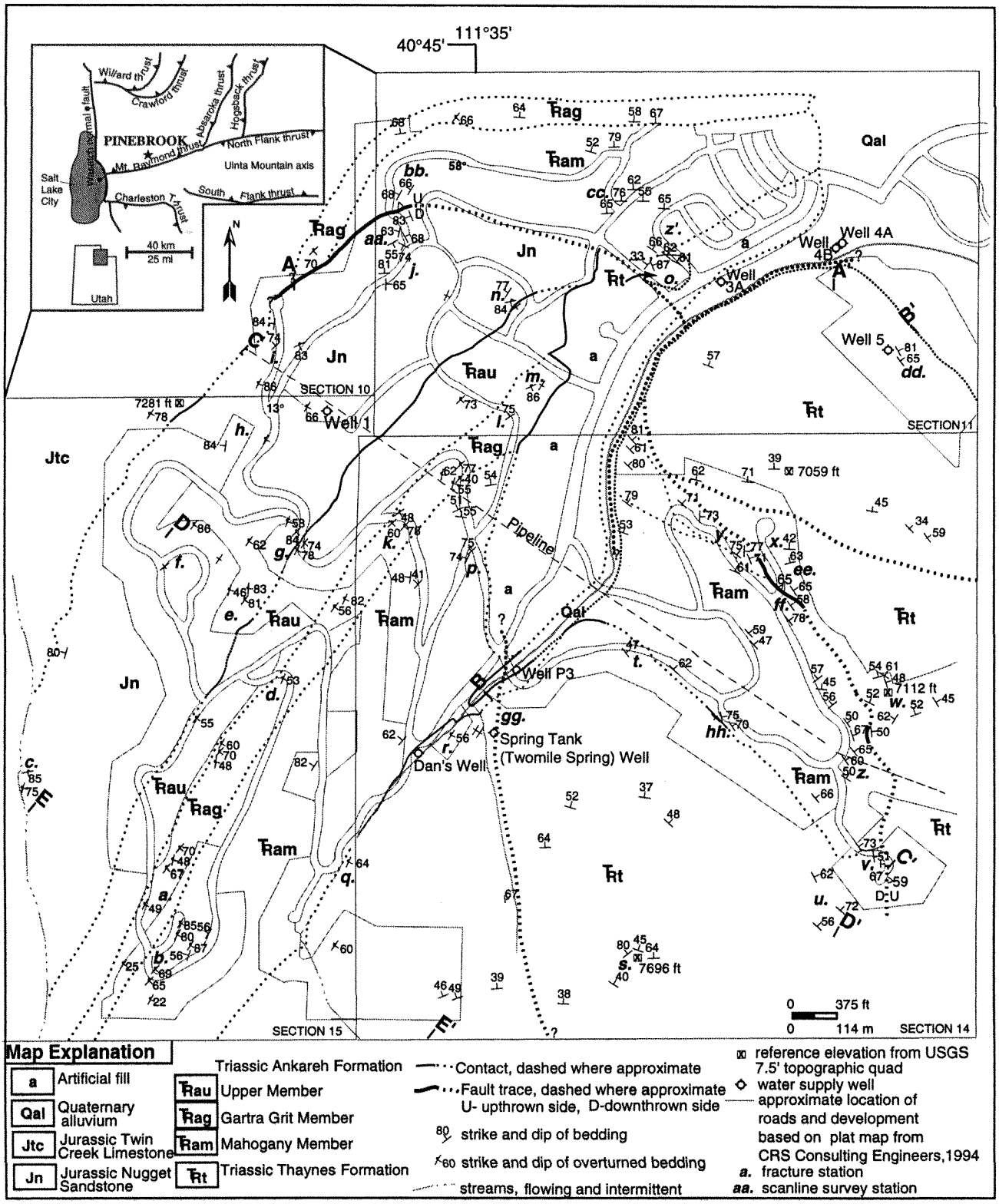


Figure 6. Location, regional geologic setting, geologic map and development of the Pinebrook subdivision area in western Summit County, near Park City, Utah. Field mapping was completed in sections 10, 11, 14, 15; T1S, R3E using the USGS Park City West quadrangle.

Table 1. Summary of Hydrogeology for Pinebrook Wells (CRS Consulting Engineer's Inc., 1995; Gorgoza Mutual Water Company, oral comm., 1997)

Well # / Name	Formation Penetrated (see Figure 6)	Well Depth (feet)	Well Yield (gpm)	Description
1	Nugget Sandstone	710	40–175	Seasonal production fluctuations common
3A	Thaynes Formation	305	150–200	High turbidity, low usage; 7/97 yield @ 80 gpm
4A	Thaynes Formation	500	300	85 feet of alluvium; 7/97 yield @ 240 gpm
4B	Thaynes Formation	1200	1000	Thaynes at 535 feet; artesian flow March–June
5	Thaynes Formation	500	—	Not in use 7/97
6	Thaynes Formation	1100	300	Deepened from 800 ft (6/96)
Spring Tank (Twomile Spring)	Thaynes Formation	—	60–240	Natural spring; 7/97 yield @ 195 gpm
Dan's Well	Thaynes Formation	750	125–200	Seasonal production fluctuations common

This setting provides an excellent opportunity to use structural analysis at various scales to understand the subsurface structure and its relation to the hydrogeologic system.

Structural and Hydrogeological Setting

Fractured bedrock units include the Triassic Thaynes and Ankareh Formations and the Jurassic Nugget Sandstone (fig. 3). The Thaynes Formation and Nugget Sandstone provide Pinebrook with its' water supply (refer to Table 1 for well information and fig. 6 for well locations). Average production rates for wells in these aquifers range from 40–1000 gpm, with higher average yields associated with increased annual precipitation (Gorgoza Mutual Water Co., oral comm., 1996). These formations lie within a hanging wall ramp-anticline, referred to as the Twomile Canyon anticline (figs 4 and 6) after Ashland et al., (1996), of the Mount Raymond thrust (MRT). The nearest exposure of the MRT occurs approximately 3 km (1.9 mi) southeast of Pinebrook (fig. 4). This fold train consists of a series of generally north-northeast plunging folds that most likely developed with movement and/or re-activation on the MRT and/or related backthrusting. A second phase of east-northeast trending folds (F2) appears to have rotated some of the F1 folds, locally up to 40°–60°. Elsewhere, northwest plunging folds may have folded northeast plunging folds. Possible causes of the F2 folds include: (1) reactivation along the MRT or younger thrust systems, (2) slip on a lateral ramp, or 93) rotation related to uplift of the Uinta arch (Bradley and Bruhn, 1988; Bruhn et al., 1986; Bryant, 1990; Yonkee et al., 1992).

The other major structures in Pinebrook subdivision include high-angle faults (fig. 6) : (1) the Toll Canyon fault; (2) the Twomile Canyon fault, and (3) a previously unmapped fault, a possible splay from the Toll Canyon, in the northern section of the study area. The presence of these faults and the superposed folding within the study area complicate the interpretations of the structural and hyrdogeological setting.

Regional hydrogeologic studies suggest that the aquifers in this area may be structurally (e.g. faults) and stratigraphically (e.g. Mid Red shale unit in the Thaynes Formation) compartmentalized (Ashland et al., 1996). Additional aquifer-test data will be needed to delineate and confirm the hydrogeologic compartments associated with the proposed geology for the Pinebrook and Summit Park subdivisions.

Structural Analysis

Structural analysis in the Pinebrook subdivision (fig. 7) are: (1) bedding attitudes are very scattered and do not conform to a single great-circle (interpret as a non-cylindrical fold if formed by one deformational event or evidence for refolding about a non-parallel fold axis); (2) cylindrical best-fit tests to the bed data generate an overall fold axis orientation of 55°/038° for the Twomile Canyon anticline (fig. 7a); and (3) a Kamb contour plot (fig. 7b) delineates four dip domains (Ia-steep to overturned SE dips; Ib-steep to overturned NW and SE dips; IIa-moderate to steep NE dips; and IIb-moderate-steep N-NE dips). The preferred fold geometry interpretation for these data is Interpretation A shown in figs 7c.–e. Interpretation A suggests a partly non-cylindrical, northwest to southeast plunging conical fold (figs 7c. And 7d.) in the western portion of the study area that rotates into a cylindrical, north plunging box-like fold to the east (fig. 7e.). Another, less complex, fold geometry is Interpretation B shown in figs 7f.–h. This interpretation assumes cylindrical folding and suggests a gently to moderately plunging, segmented box-like fold with three distinct axial surfaces: a. 282°/14° NW, b. 339°/75° NE, and c. 196°/82° NW.

The distribution of the predominate fracture trends present throughout the study area are shown in rose diagrams in fig. 8. These plots demonstrate the variation in fracture orientations within very short distances, as indicated by comparing the plots at each station with the station locations shown in fig. 6. The plots may be useful in determining flow directions throughout the Twomile Canyon anticline.

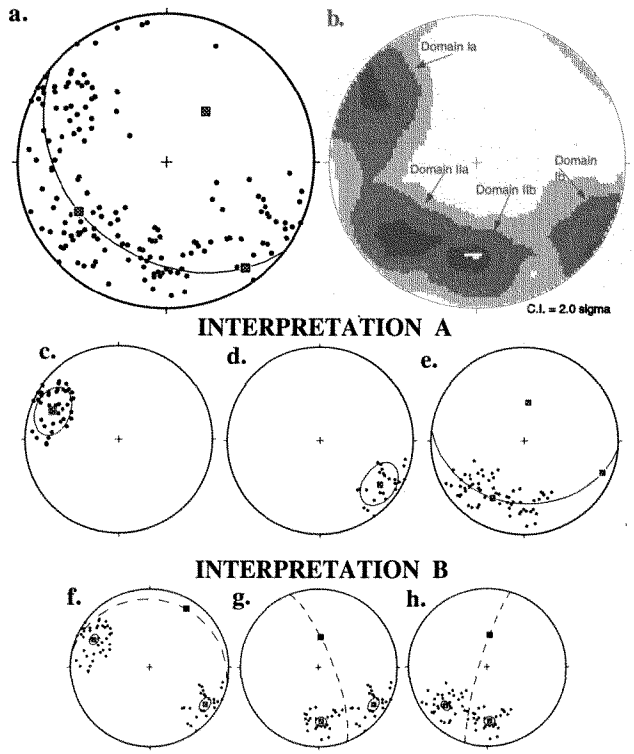


Figure 7. Fold analysis plots of bedding data in the Pinebrook subdivision, Summit County, Utah. a. Cylindrical fit to bedding plane poles generates a fold axis trend and plunge of 038°/55°. b. Dip domains determined from Kamb contour of bedding plane poles and map relationships shown in fig. 6. Interpretation A: c. Conical fit to overturned western limb (Dip Domain Ia) generates a fold axis of 298°/23°, half-apical angle of 18°; d. Conical fit to northwest dipping to vertical, non-overturned limb (Dip Domain Ib) generates a fold axis of 126°/21°, half-apical angle of 17°; e. Cylindrical fit to north-dipping and north-east dipping limbs (Domains IIa and Iib) generates a fold axis of 005°/56°. Interpretation B: f. Cylindric fit to Domains Ia and Ib generates a fold axis of 032°/13°; g. Cylindrical fit to Domains Ib and IIb generates a fold axis of 004°/58°; h. Cylindrical fit to Domains IIa and IIb generates the same fold axis shown in e.

Turn vehicles around. Return down Pinebrook Road.

0.4	30.8	Hair pin in street.
0.35	31.1	Junction at hair pin. Veer right.
0.1	31.2	Dirt road to Spring Tank. Park here and walk to stop.

Stop 2. Spring Tank Outcrop

This site is situated at the Spring Tank (Twomile Spring) well shown in fig. 6. The Twomile Canyon fault, a north-striking, east-dipping to vertical reverse fault that cuts the Thaynes Formation near the crest of the anticline, is inferred to pass just to the east of this site. The Twomile Spring well at this location, and Dan's well to the southwest, penetrate the Thaynes aquifer with yields between 125–300 gpm (Table 1). Spring discharge hydrographs and well logs suggest that ground water flow at this location is controlled by interconnected fractures (CRS Consulting Engineers, Inc., 1995).

The Thaynes Formation consists of interbedded limestones and shales, strikes northeast, and is nearly vertical at this location (figs 9a. and 9b). Fracture data was collected along vertical and horizontal scanlines through beds of

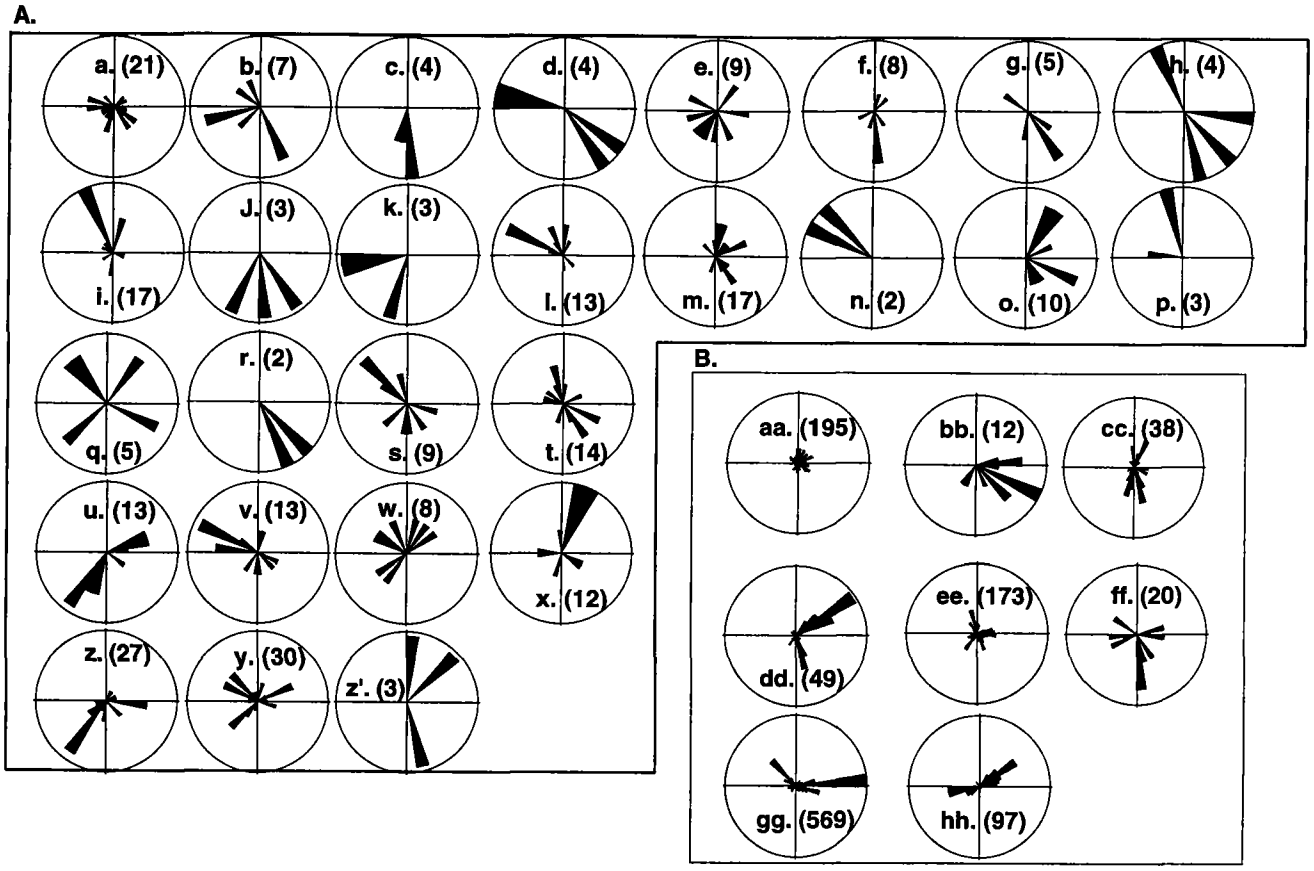


Figure 8. Equal area rose diagrams showing relative frequency of fracture trends for each of the stations located in fig. 6. Circle perimeters range between 25–50%. A. Major fracture sets observed at qualitative sampling stations. B. Results from detailed sampling methods using fracture scanline survey techniques at indicated stations.

varying thicknesses. The predominate fracture sets for thick, medium, and thin beds are highlighted in fig. 9a. Four main fracture sets and the fracture sets with small amounts of offset are observed on the stereonet plots (figs 9d.,9e., 9c.). Results from this analysis of the scanline data supports the sets determined qualitatively using the photograph in fig 9a. For each fracture set, the spacing increases with bed thickness, with the most common sets, the southeast-dipping joints (J2) and joints parallel to bedding (J1) present throughout the outcrop in the thick, medium, and thin beds.

0.4	31.6	Intersection with Big Spruce Way. Turn right.
0.3	31.9	Intersection with Tall Oaks Drive. Turn left.
0.3	32.2	Note complexly deformed Triassic Ankareh beds on left side of road.
0.2	32.4	Intersection with Tall Oaks Circle. Turn left and park. Stop 3.

Stop 3. Tall Oaks Circle—The Ecker Hill Fault

The Ecker Hill fault juxtaposes the Thaynes Formation and Mahogany Member of the Ankareh Formation. This fault may connect or splay off of the Toll Canyon fault in the western portion of the subdivision. The fault surface is undulatory with an average orientation of 305°/65° NE. Figure 10 is a geological map of the site plan view and structural geology of this site. A damage zone of intense fracturing extends for at least 3.5 m (11.5 ft) north of the fault into the Thaynes Formation, with 0.25 to 0.50 m (0.8 to 1.6 ft) of clay gouge adjacent to the fault core. The damage zone on the south side of the fault is represented by a 1 m (3 ft) thick clay smear in the lower Ankareh Formation (fig. 11). Filled veins, open fractures, and small faults extend for several meters north of the fault core and immediate damage zone in the Thaynes Formation. Based on these observations and the high clay content of the fault core, the fault may act as a combined conduit-barrier system as described by Caine et al., (1996). Ground water flow may be minimal

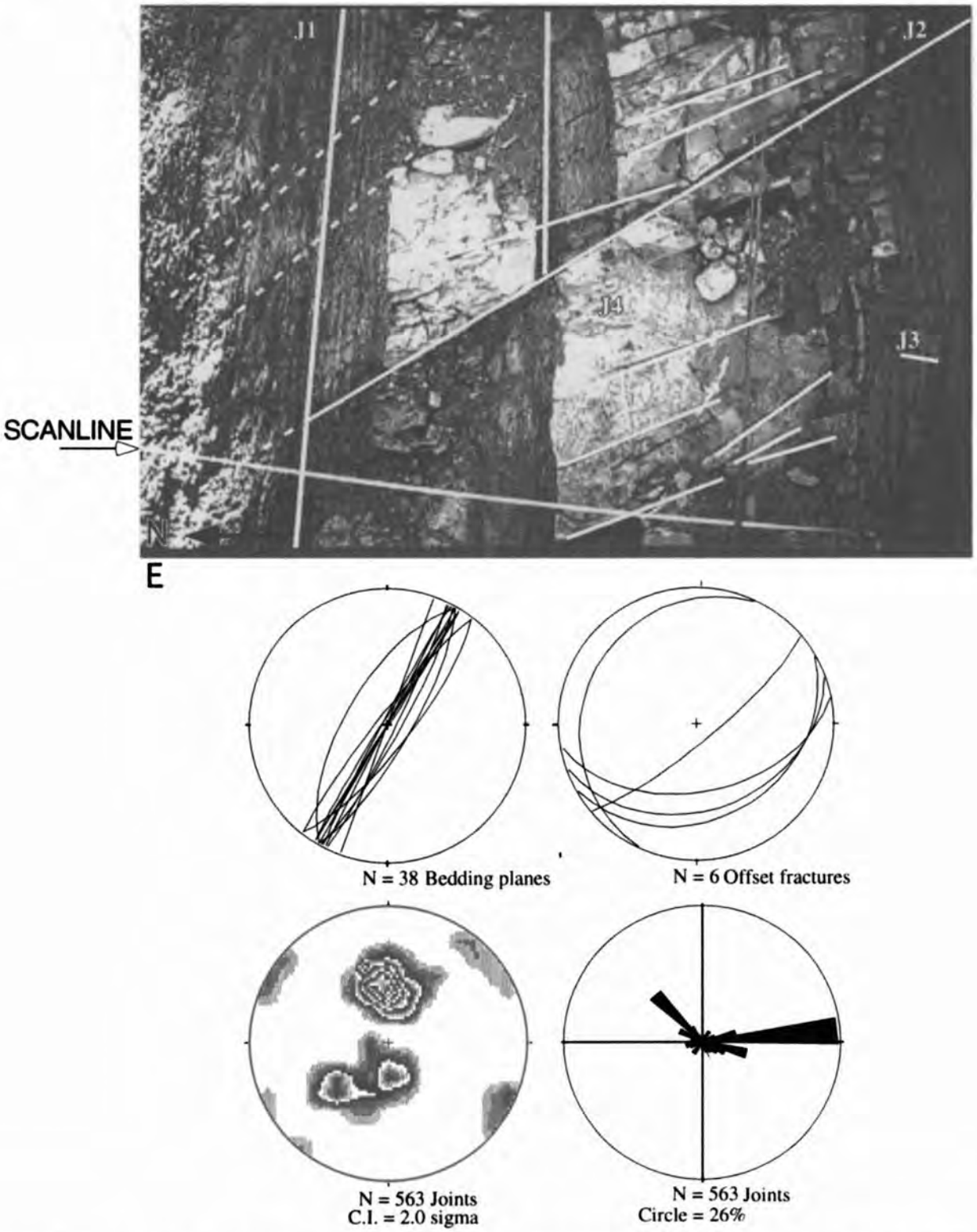


Figure 9. Structural analysis of the Spring Tank outcrop (station gg. in fig. 6). a. Major fracture sets are: i.) J1—020°–030°/80°–90° SE; ii.) J2—0.65°–90°/18°–40°; iii.) J3—105°/33° SW; iv.) J4—315°/35°–45°. Scanline results: b. Average bedding at this outcrop is 030°/90°. c. Orientation of fractures with offset; d. Poles to joint planes measured at scanlines; and e. Rose diagram of joint strike data further illustrates the dominant fracture sets at this location.

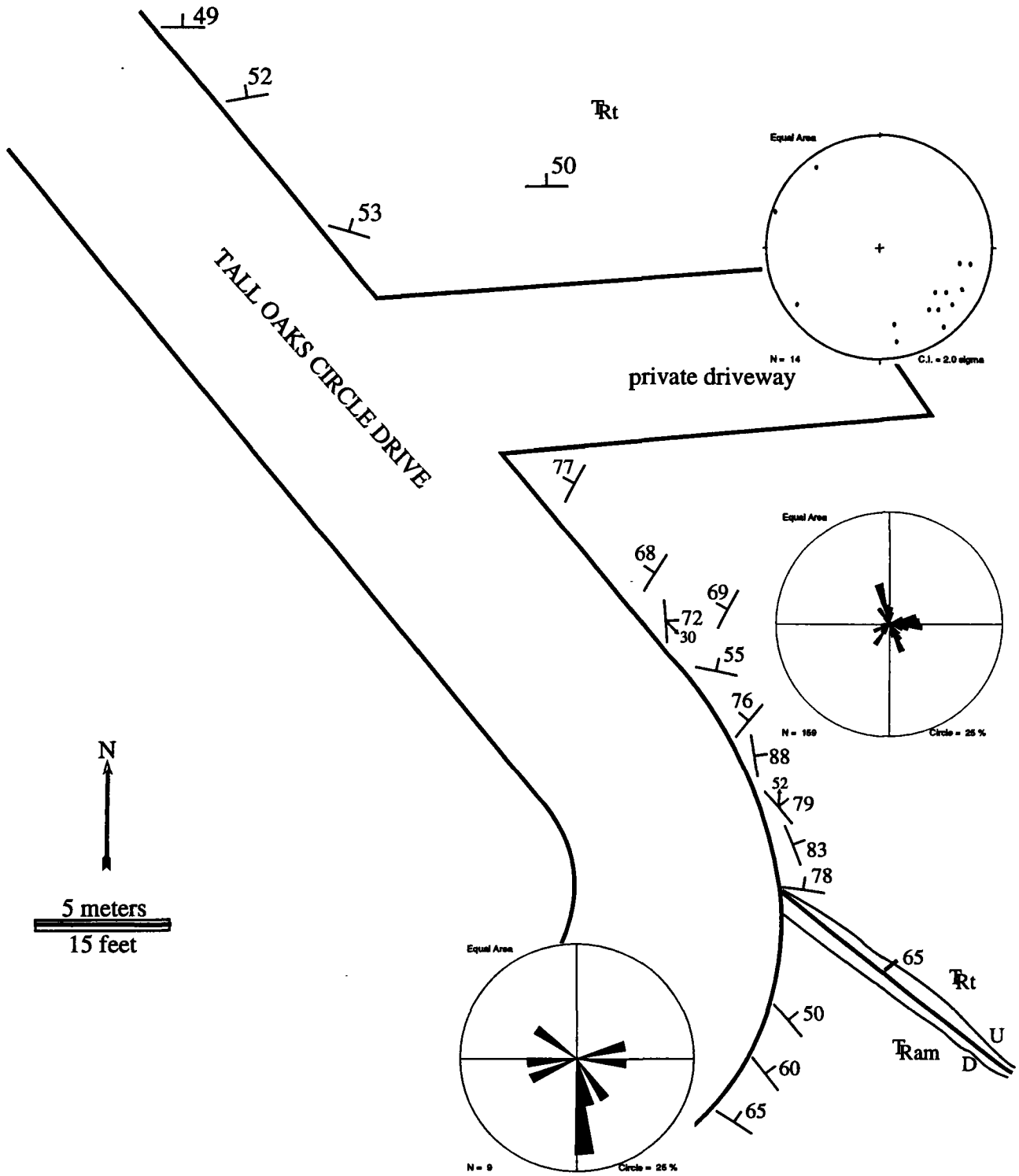


Figure 10. Map view of Tall Oaks Circle outcrop. Orientations of joints are plotted with Rose diagrams south of the fault within the Triassic Mahogany Member of the Ankareh Formation (TRam), and north of the fault in the Thaynes Formation (TRt). Poles to small planes in the Thaynes Formation are also shown. The main fault is the Toll Canyon fault (or related splay) outlined with the relative thicknesses of the gouge zones on either side of the fault.

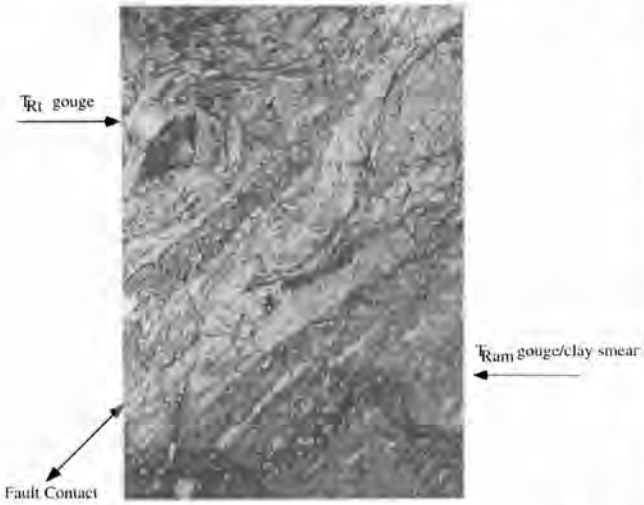


Figure 11. Gouge present at fault contact between the Thaynes Formation and Mahogany member, lower Ankareh Formation. Gouge zones in the Thaynes and Ankareh Formations are approximately 0.25 to 0.50 m (0.75–1.5 ft) and up to 1 m (3 ft) thick, respectively. Extent and pervasive fracturing within the damage zone coupled with the high clay content near the fault core suggest the Toll Canyon fault at this location acts as a conduit-barrier system (after Caine et al., 1996).

perpendicular to the fault within the immediate fault core and damage zone, but may increase to the north of the fault into the heavily fractured limestone beds. Flow to the south of the fault would most likely be parallel to bedding but the abundance of clay-fill within the fractures in the shaly unit would tend to impede flow.

Return to Pinebrook Road. (Note: An optional trip is to continue south to the end of Tall Oaks Drive, for overview of Winter Park Sports Park, Snyderville Basin, and Park City region.)

0.5	32.9	Intersection with Big Spruce Way. Turn right.
0.3	33.2	Intersection with Pinebrook Drive. Turn right.
0.3	33.5	Turn left on Ecker Hill Drive.
0.35	33.9	Turn right on Stage Coach Drive.
0.2	34.1	Sunridge Drive intersection. Turn right and park for Stop 4.

Stop 4. Nugget Sandstone at Sunridge-Toll Canyon fault

Pervasive fracturing and faulting of the Nugget Sandstone in the footwall of the Toll Canyon fault occurs at this location. The Toll Canyon fault contact was uncovered briefly during excavation of lot sr-43. The fault is inferred to extend from this lot southwest through the gully north of sr-1, and to the east represented in fig. 6 by the approximate contact between the Nugget Sandstone and the Mahogany member of the Ankareh Formation. A damage zone at lot sr-1 characterized by pervasive fracturing and faulting of the Nugget Sandstone extends for at least 50 m (164 ft) to the south of the concealed Toll Canyon fault contact (fig. 13). Scanline data were collected at sr-43 and sr-1, but not at the fault contact because it was buried before detailed work was completed. The fault cores present throughout outcrops sr-43 and sr-1 are composed of brecciated sandstone and clay gouge, but are very thin 2–4 cm (0.8 to 1.6 in) average (fig. 14). Because of the nature of the damage zone, we suggest the Nugget Sandstone has enhanced permeability in this region and corresponds to a distributed conduit system as described by Caine et al., (1996). Other observations that suggest the Nugget Sandstone and the Toll Canyon fault form conduits at this location include: (1) during spring runoff flowing water occurs parallel, with seepage perpendicular, to the small faults at outcrops sr-1, sr-42, and sr-43; (2) pooling water was present into early summer at the sr-43 basement excavation; (3) builders have had to install pumps to divert water at the Sunridge lots identified on the map in fig. 12.

0.7	34.8	Proceed on Sunridge Drive. The Ridge to the north is underlain by the Cartra Grit. Turn right on Gambel Drive.
0.1	34.9	Intersection with Boothill Drive. Turn right.
0.1	35.0	Intersection with Wagon Wheel Drive. Turn right.
0.2	35.2	Intersection with Pinebrook Road. Turn left. Return to Frontage Road.
0.9	36.1	Frontage Road. Turn left (northwest).
2.4	38.5	Exit from I-80. Begin to enter Summit Park Subdivision. Continue straight.
0.4	38.9	Road bends sharply south (left)
0.2	39.1	Road intersection. Turn sharply left. Continue on this road.
0.75	39.9	Road widens at outcrop of Jurassic Twin Creek Formation. Park here for Stop 5.

Stop 5. Summit Park

Development in the Summit Park area, combined with large seasonal fluctuations in water production from existing wells, had led to water shortages in this area during the 1980s and early 1990s. Because of the need for more water, a test well siting program was initiated in 1993, and two final production wells were completed in 1996. Successful siting and completion of the wells illustrates the impor-

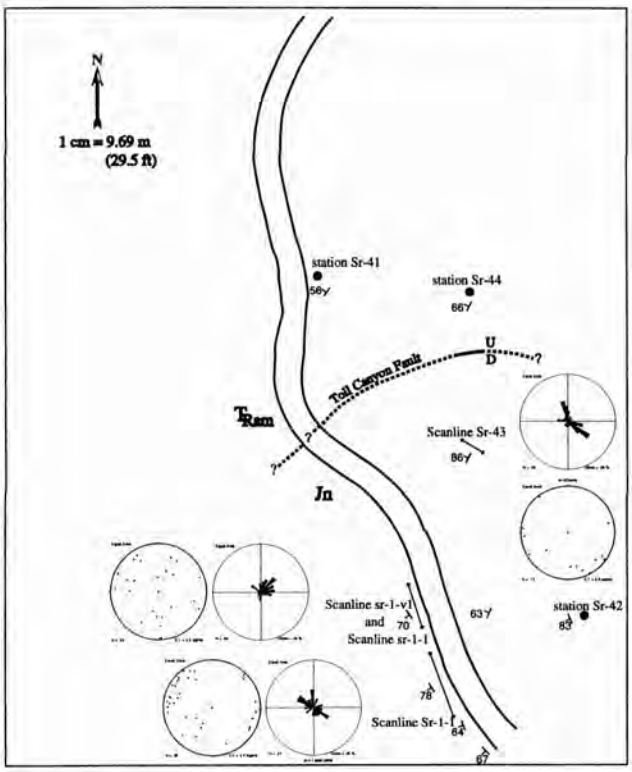


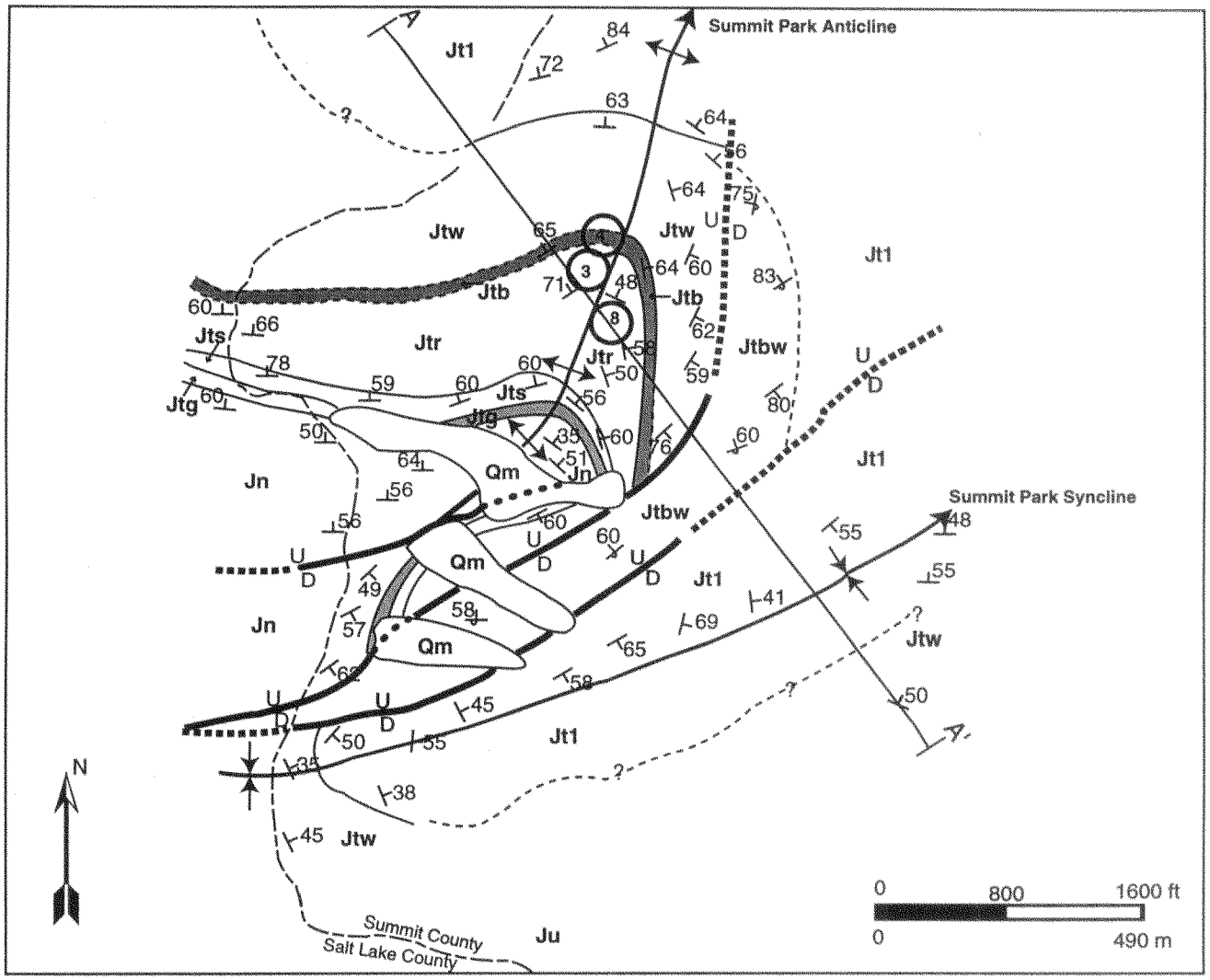
Figure 12. Sunridge outcrop site map. Rose diagram plots represent joint strikes and stereograms display poles to fault planes for data collected along each scanline.

Figure 13. Photo of a portion of the Sunridge sr-1 outcrop showing location of scanline sr1-2; a. represents location of fault core photo in figure 15.

Figure 14. Fault at 6.32 meters along scan sr-1-2. Fault core composed of 2 centimeters of foliated clay with intense iron-oxide weathering. Damage zone extends from 5.9 meters to 6.55 meters. This fault is approximately 50 meters to the southeast from inferred Toll Canyon fault contact. The percentage of damage zone relative to fault core is high, suggesting a distributed conduit system as defined by Caine et al., (1996).

tance of incorporating expertise from a variety of areas, including structural geology and hydrogeology. Pre-existing wells in this area had been completed in the complexly deformed Jurassic Twin Creek Limestone, but had only produced moderate amounts of water. Fractured sandstone of the underlying Jurassic Nugget Sandstone was selected as a likely target for a test well, but because of the complex structure and varying lithologies present in the area, detailed mapping and structural analysis were first undertaken. Here we discuss lithological and structural characteristics used to site the test well and briefly summarize completion of the production wells.

The main rock intervals of interest in the Summit Park area are the Nugget Sandstone and Twin Creek Limestone (figs. 3 and 15). The Nugget Sandstone consists of well sorted, variably cemented sandstone cut by widely to closely spaced fractures. Permeability is variable, being highest in areas of more intense fracturing and lowest in areas with silica cementation. The Twin Creek Limestone is divided into lithologically distinct members that have important controls on ground water flow. The basal Gypsum Spring Member consists mostly of mudstone and forms a groundwater compartment barrier with very low permeability perpendicular to bedding (Ashland et al., 1996). The overlying Sliderock Member consists mostly of thick-bedded, bioclastic to oolitic limestone that is moderately to strongly fractured, and probably has variably high permeability. The Rich Member consists of clayey to silty, fine-grained limestone that displays well developed spaced cleavage at high angles to bedding. Secondary fractures along cleavage seams are generally small and probably mostly closed at depth, suggesting overall low permeabilities. The Boundary Ridge Member includes thin-bedded silty limestone and mudstone that probably have very low permeabilities perpendicular to bedding and form another ground-water com-



Stratigraphy, Map, and Cross section Explanation

Quaternary	Qm	Qm - mass wasting and other deposits
Jurassic	Jtu	Twin Creek Limestone undivided
	Jt1	Leeds Creek Member
	Jtw	Watton Canyon Member
	Jtbw	Boundary Ridge and Watton Canyon Members
	Jtb	Boundary Ridge Member
	Jtr	Rich Member
	Jts	Sliderock Member
	Jtg	Gypsum Spring Member
Triassic	Jn	Nugget Sandstone
	Tra	Ankareh Formation (on cross section only)

Contact, dashed where approximate dotted where concealed

U/D Fault trace, dashed where approximate dotted where concealed

Axial trace of anticline, plunge of hinge indicated, location approximate

Axial trace of syncline, plunge of hinge indicated, location approximate

45 Strike and dip of bedding

70 Strike and dip of overturned bedding

Area of complex deformation

Figure 15. Location, geologic map, and explanation of the Summit Park subdivision, western Summit County, Utah. Refer to fig. 16 for structures shown in cross-section A-A′.

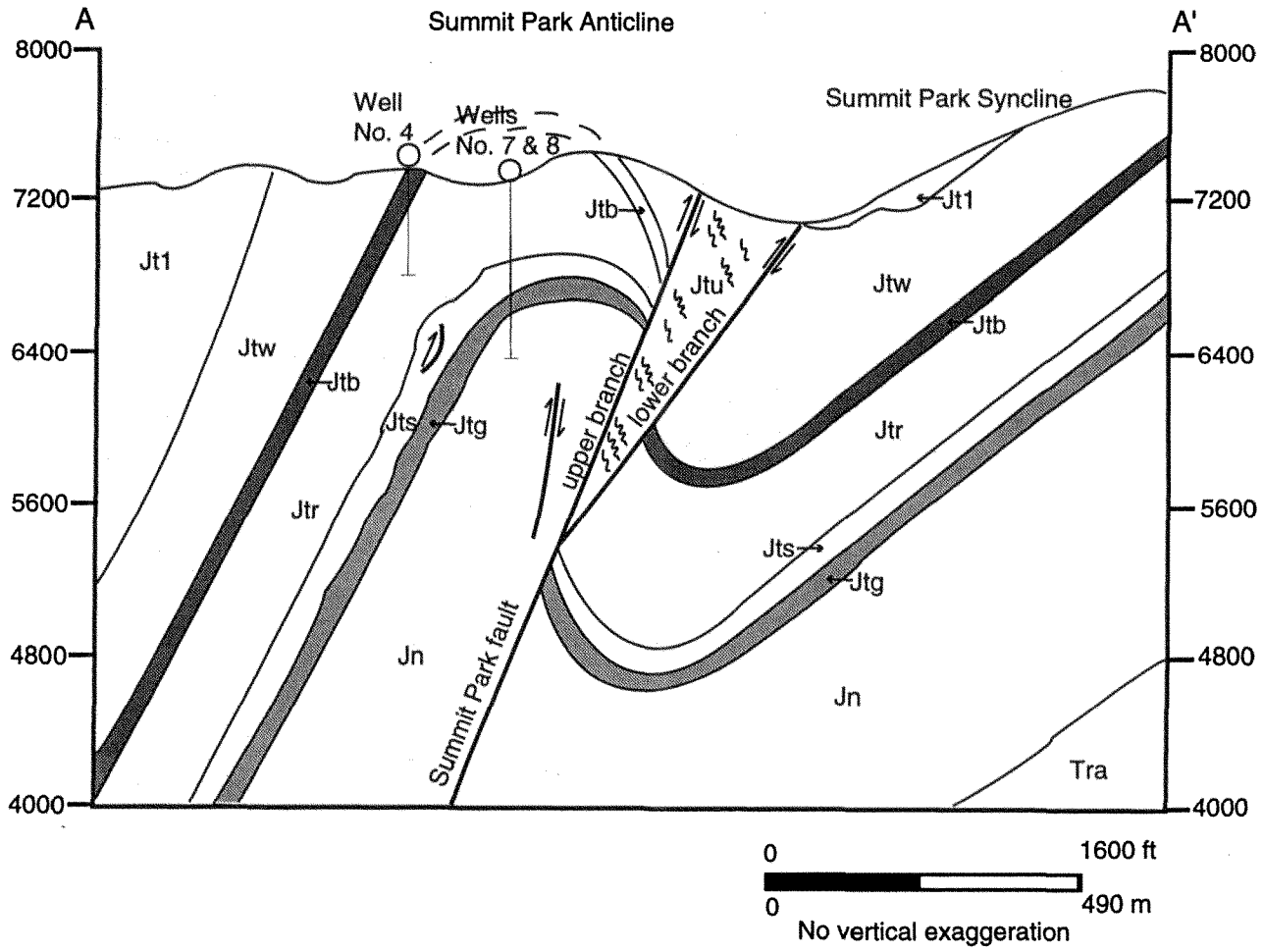


Figure 16. Geologic cross section A-A′ through the Summit Park area.

partment barrier (Ashland et al., 1996). The Watton Canyon Member consists mostly of dense limestone cut by moderately to widely spaced, thicker cleavage seams. Longer, wider secondary fractures along these seams may be partly open at depth and some fractures may have undergone dissolution widening, resulting in overall moderate to high permeabilities. The Leeds Creek Member consists mostly of clayey to silty, fine-grained limestone that displays variably developed spaced cleavage and pencil fracturing, but most fractures are small and probably closed at depth resulting in overall low permeability.

The Summit Park area lies within complexly deformed rocks affected by F1 and F2 phases of folding and at least one phase of faulting (Crittenden and others, 1966; Bradley and Bruhn, 1988; Bryant, 1990; Yonkee and others, 1992; Jarvis and Yonkee, 1993; fig. 4). The dominant structural feature in the area is the Summit Park anticline. The anticline has a moderately southeast-dipping southeastern limb, a moderately north- to northwest-dipping northwestern limb, and a complex hinge region that changes geometry with structural level (figs. 15 and 16). Within the Nugget Sandstone the two limbs are separated by a high angle fault along a sharp hinge; within the lower Twin Creek Limestone the fold is box-like with a central, planar hinge region; and in the upper Twin Creek Limestone a broad, rounded hinge region is marked by disharmonic minor folding and faulting. The fold is overall northeast plunging, but is noncylindrical, being partly conical and also having a curvilinear hinge line. The anticline is bounded on the southeast by the Summit Park fault zone, which includes two branches that bound a complexly deformed, steeply southeast-dipping to overturned panel of rocks. The lower fault branch bounds the northwestern limb of the Summit syncline and dips steeply northwest. The upper fault branch bounds the southeastern limb of the anticline and curves slightly, probably reflecting a steeply dipping fault that changes strike and diverges upward from the lower branch. Although exact slip directions on the fault branches are unknown, both

faults probably have a significant component of top-to-the-southeast reverse slip. Geometric and spatial relations between the fault branches and anticline are consistent with a general model of fault propagation folding. A variety of small-scale deformation features are also present in the anticline hinge region. The Nugget Sandstone is cut by widely to closely spaced fractures, the Sliderock Member is locally faulted and thickened by minor folding, and the Rich Member displays vein arrays and well developed spaced cleavage at high angles to bedding.

Jarvis and Yonkee (1993) completed a report incorporating mapping and structural analysis, and proposed a test well site in the hinge region of the Summit Park anticline (figs. 15 and 16). This site was chosen based on access and estimated depths to fractured strata of the Nugget Sandstone in the subsurface. The Nugget Sandstone, as well as the Sliderock and Gypsum Spring Members, are exposed south of the test well site, and using the mapped location of the Nugget contact and an average apparent dip of 55° NE along the fold hinge, the estimated depth to the top of the Nugget was about 210 m (700 ft) at the proposed test well site. However, this estimate was somewhat problematical due to possible variations in bedding orientations from non-cylindrical folding and complex internal thickening in the hinge region.

The test well was drilled from 1994 to 1995 under the supervision of Weston Engineering. The well started in the Rich Member, drilled through fractured, permeable limestone of the Sliderock Member and impermeable mudstone of the Gypsum Spring Member, and encountered the top of the Nugget Sandstone at 698 feet (212 m). Initial pump tests indicated adequate water quality and quantity from both the Sliderock Member and Nugget Sandstone. Two final production wells were then drilled from 1995 to 1996 under the supervision of Weston Engineering, with well 7 cased through the Twin Creek Limestone and completed in the Nugget Sandstone and well 8 completed in the Sliderock Member (Weston Engineering, 1996). Pump tests indicated that well 7 could sustain a long-term yield of 180 gpm and well 8 could sustain a long-term yield of 120 gpm, and that pumping of each well did not produce drawdown in the adjacent well or in other nearby wells, probably indicating that the Nugget and Sliderock aquifers are separate and confined. Well 7 had a static water level of about 26 ft (8 m) below ground level that showed subdued seasonal fluctuations, whereas well 8 had a static water level between about 100 and 150 ft (30 and 45 m) below ground level that varied with seasonal variations in infiltration of rain and snowfall. These relations may reflect rapid recharge and low storage within fractured limestone of the Sliderock aquifer, versus greater storage within the Nugget aquifer, which has variable grain-scale porosity in addition to fractures.

The well locations were selected along the crest of the plunging Summit anticline partly because of the likelihood of finding through-going, high-angle extensional fractures in such a structural setting (Huntoon, 1993), and the occurrence of water yielding zones in the Nugget Sandstone and Sliderock Member appears to confirm the presence of such fractures. The setting of the wells also appears to confirm observations by Stone (1967) and Bruce (1988) that mudstone beds act as confining layers even where folded. Although the integrity of the Gypsum Spring Member as a confining interval appears to be preserved in this area, Bruce (1988) also indicated that regionally this member was locally broken during detachment faulting.

Turn vehicles around. Retrace route to I-80 on ramp.

0.75	40.6	Turn right at intersection
0.2	40.8	Turn right at bend.
0.4	41.2	Intersection with I-80 on ramp. Turn left. Take I-80 west bound to Salt Lake City.

End of trip.

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