BIULETYN PAŃSTWOWEGO INSTYTUTU GEOLOGICZNEGO 404: 85–106, 2002 R.

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GROUNDWATER FLOW IN FRACTURED AQUIFERS IN THE SEVIER THRUST BELT, WASATCH MOUNTAINS, UTAH, USA

(with 10 Figs.)

PRZEPLYW WÓD W SZCZELINOWYCH POZIOMACH WODONOśNYCH W STREFIE NASUNIĘCIA SEVIER, GÓRY WASATCH, UTAH, USA

(z 10 fig.)

Abstrakt. Szczelinowe poziomy wodonośne są coraz częściej eksploatowane w intensywnie rozwijających się zachodnich regionach USA, w tym Emigration Canyon w okolicach Salt Lake City w stanie Utah. Pod względem fizjograficznym obszar badań zlokalizowany jest w górach Wasatch (zachodnia część Gór Skalistych), pod względem strukturalnym – w obrębie pasa płaszczowinowego Idaho–Utah–Wyoming. Obszar badań charakteryzuje się serią uskoków i fałdów płaszczowinowych zbudowanych z miąższych serii skał osadowych, które zostały przesunięte na wschód lub południowy wschód podczas kredowych i wczesnotrzeciorzędowych ruchów górotwórczych. Utwory płaszczowinowe uległy dodatkowym deformacjom tektonicznym w postaci lokalnych spękań, drugorzędnych fałdów i uskoków. Typowe serie osadowe to wapienie, dolomity, piaskowce, mułowce i iłowce deponowane od karbonu do kredy. Lokalnie przykryte są zlepieńcami późnokredowymi. Skały te charakteryzują się stromym upadem. W iłowcach i mułowcach występują lokalne, równoległe do kierunku warstwowania spękania, w skałach gruboławicowych (wapienie, dolomity, piaskowce) występują szczeliny o zmiennej orientacji.

Piaskowce i skały węglanowe stanowią warstwę wodonośną, charakteryzują się wysokimi wartościami współczynnika filtracji, natomiast iłowce i mułowce to utwory słabo przepuszczalne i stanowią zazwyczaj warstwy napinające zwierciadło wody. Pompowania badawcze wykazały, że utwory słabo przepuszczalne mogą przewodzić wodę, aczkolwiek proces ten jest nieporównywalnie wolny w stosunku do przepływu w warstwach wodonośnych. System przepływu wód podziemnych jest również silnie uzależniony od morfologii terenu.

Na badanym obszarze występują dwa poziomy wodonośne o charakterze szczelinowym: dolnojurajska formacja Nugget oraz środkowojurajska formacja Twin Creek, rozdzielone serią słabo przepuszczalnych iłowców. Formacja Nugget składa się głównie z gruboławicowych piaskowców charakteryzujących się wyraźną porowatością szczelinową i porową, formacja Twin Creek – z cienkoławicowych wapieni i wapieni marglistych charakteryzujących się porowatością

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szczelinową. Oba poziomy wodonośne wykazują cechy syngenetycznej porowatości międzziarnowej i postgenetycznej porowatości szczelinowej, co ujawnia się w odmiennych wynikach próbnych pompowań, wahaniach zwierciadła wód podziemnych i wydajności źródeł. Formacja Twin Creek charakteryzuje się wyraźnie większymi wahaniami sezonowymi zwierciadła wód podziemnych, silniejszymi wpływami granic nieprzepuszczalnych, anizotropowością i mniejszą pojemnością warstwy wodonośnej. Wartości przewodnictwa wodnego zawierają się w przedziale 10–100 m^2/dobę i są zazwyczaj niższe w formacji Twin Creek; zależą od litologii i charakterystyki szczelin.

Słowa kluczowe: wody szczelinowe, podwójna porowatość, strefa nasunięć, Góry Wasatch.

Abstract. Fractured bedrock aquifers are becoming increasingly utilized in rapidly developing parts of the western USA, including the Emigration Canyon near Salt Lake City, Utah. The emigration Canyon area is located physiographically in the Wasatch Mountains (western province of the Rocky Mountains), and structurally within the Idaho–Utah–Wyoming thrust belt. The study area is characterized by a series of thrust faults and associated folds that transported a thick section of sedimentary rocks eastward to southeastward during the Cretaceous to Early Tertiary Sevier Orogeny. Locally developed cleavage, minor folds, and minor fault and fracture networks produce additional internal deformation. Stratigraphically, sedimentary rocks in the study area include steeply dipping Pennsylvanian to Early Cretaceous limestone, dolostone, sandstone, mudstone and shale, locally capped with gently dipping Late Cretaceous conglomerate. Shale and mudstone intervals are characterized by smaller-scale, bed-parallel partings, while thicker-bedded limestone, dolostone and sandstone units typically have larger-scale fractures of variable orientation. Sandstones and carbonate intervals have generally higher hydraulic conductivity, whereas shale and mudstones are primary confining layers. The water flow system is also strongly affected by local topography. Two major fractured aquifers are the Lower Jurassic Nugget aquifer and the Middle Jurassic Twin Creek aquifer. The Nugget aquifer consists of thick-bedded sandstone with prominent primary porosity and secondary fracture porosity. The Twin Creek aquifer consists mostly of thin-bedded limestone and shaley limestone, with mostly secondary fracture porosity. The aquifers are separated by a shale interval. Based on results of long-term pumping tests, long-term monitoring of water table elevation and variability of spring discharges, the aquifers react independently and differently to fluid stresses, indicating variable effects of primary grain porosity and secondary fracture porosity. The Twin Creek aquifer is characterized by significantly greater seasonal variations of hydraulic head, stronger effects of impermeable boundaries and anisotropy, and lower storage. Typical values of transmissivity are 10–100 m^2/day, for the Twin Creek and Nugget aquifers, but vary with changes in lithology and fracture characteristics.

Key words: fracture aquifers, double porosity, thrust belt, Wasatch Mountains.

INTRODUCTION

This study concentrates on analysis of fractured bedrock aquifers within the Wasatch Range of northern Utah, USA. Lithologically, the region exposes a thick sequence of Cambrian to Tertiary sedimentary rocks that display a tremendous range of matrix and fracture characteristics (Ashland *et al*., 1996). Structurally, the region had a complex history, including thrust faulting during the Cretaceous Sevier orogeny and normal faulting during Tertiary to Recent Basin-and-Range extension, resulting in complex fault and fold patterns (Fig. 1). Major faults exposed in the region include the Crawford thrust, Mount Raymond thrust, East Canyon fault zone, and younger Wasatch normal fault. Large-scale folds, which developed mostly during thrusting, include the Emigration Canyon syncline, Spring Creek anticline, and Parleys Canyon syncline. Cleavage, minor folds, and minor fault and fracture networks produced additional internal deformation (Mitra and Yonkee, 1985; Keighley *et al*., 1997). Slip along the Wasatch normal fault uplifted and tilted the Wasatch Range, which displays rugged topography.

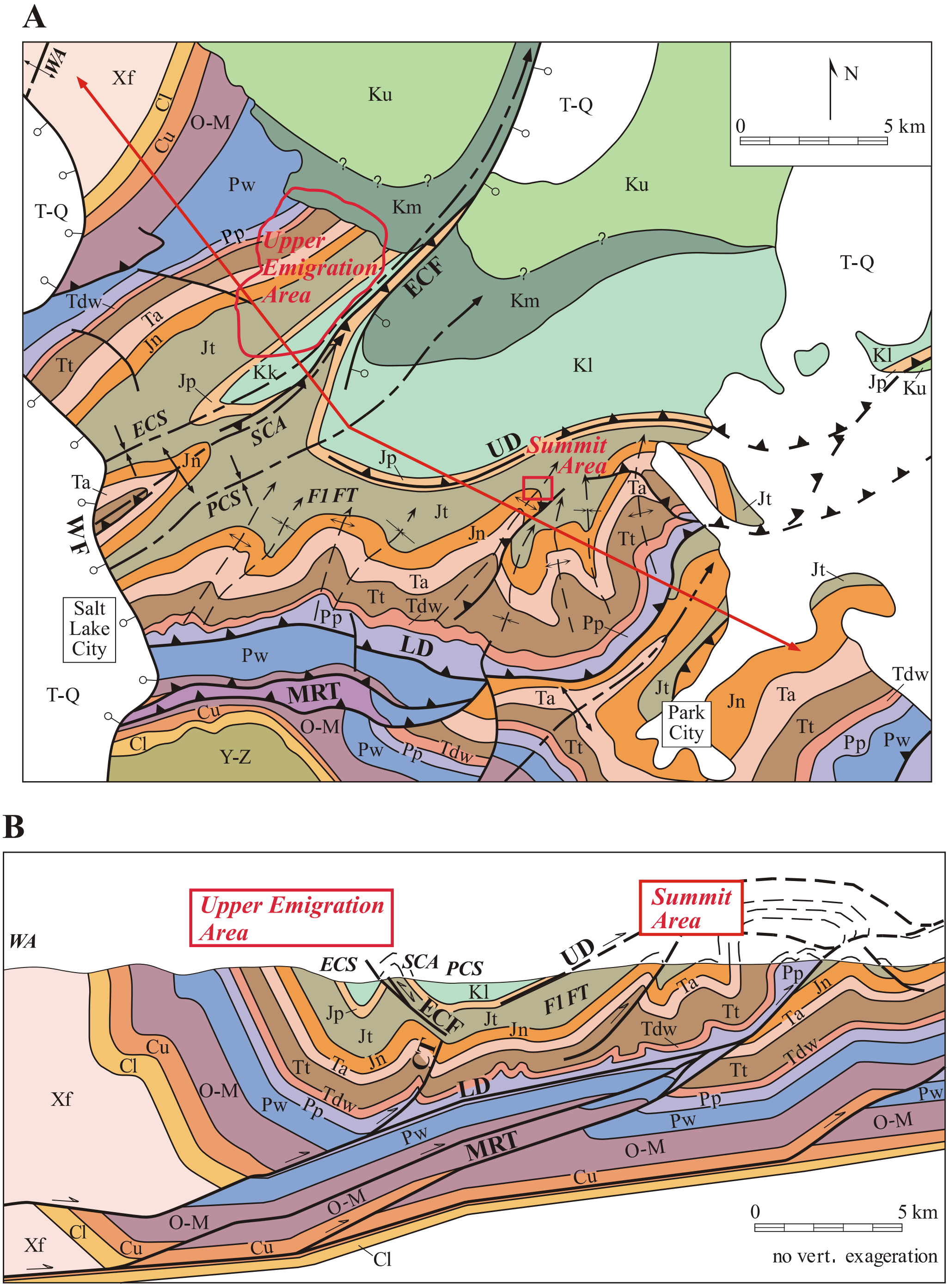
The complex lithology, structural geometry, and topography of the region likely result in complex fluid flow patterns. However, characteristics of bedrock are currently poorly understood in most areas, specifically including the Upper Emigration Canyon area, making estimates of safe yield problematical. As communities in the area experience growth, the availability and sustainability of water resources has become a major concern, with increased demands for water, combined with lack of adequately developed sources, leading to water rationing and shortages. As a first step to better understanding of the hydrogeology of this area, we conducted geologic mapping, lithologic description, and structural analysis of rock units to determine general characteristics of aquifers. Two aquifers, corresponding to the Upper Twin Creek Limestone and the Nugget Sandstone, contain water wells and were examined in detail to determine hydrologic properties, including analysis of pump tests and long-term monitoring of water levels. These two aquifers have distinctly different lithologies, respond differently to pumping, and illustrate difficulties in understanding flow patterns in fractured bedrock systems.

Fractured bedrock aquifers, including those in the study area, display tremendous ranges of lithologic, structural, and hydrologic properties. Various models have been proposed to analyze and model fluid flow patterns in these complex systems, including discrete fracture models (e.g. Cacas *et al*., 1990; Jones *et al*., 1999), double-porosity models (Moench, 1984), and equivalent porous media models (e.g. Oda, Hatsuyama, 1987). Fault zones, which may act as complex fluid barrier and conduits, must also be considered in developing models of regional flow (e.g. Evans *et al*., 1997). To better understand applicability of various models to fractured aquifers, we have analyzed drawdown data for long-term pump tests, which show the importance of spatial variations in aquifer properties.

HYDROSTRATIGRAPHY

Lithologic and fracture characteristics of bedrock units strongly influence the nature of ground water flow in the Emigration Canyon area. Geologic units in the study area comprise a thick bedrock sequence of Pennsylvanian to Early Cretaceous sedimentary strata, which are locally capped with angular unconformity by gently dipping Late Cretaceous conglomerate, and locally covered by thin, Quaternary unconsolidated deposits (Fig. 2). Ashland and others (1996), studying a similar sequence of rock in the nearby Park City area, showed that fractured sandstone and carbonate intervals have higher permeabilities and form hydrostratigraphic units (HSUs), whereas shale and mudstone intervals have much lower permeabilities and act as confining intervals. Lithologic characteristics of geologic units are now combined with available hydrologic data to develop a provisional hydrostratigraphic model.

The Weber HSU, following the nomenclature of Ashland and others (1996), comprises the Weber Sandstone and the lower member of the Park City Formation (Fig. 2). The Weber Sandstone consists mostly of fine- to medium-grained, well-sorted, variably fractured sandstone, with variable primary and secondary permeability. The lower member of the Park City Formation consists of sandstone, dolostone, and limestone cut by fractures with local solution widening and brecciation, resulting in enhanced permeability. The Weber HSU is the source of two springs (S1 and S2 in Figure 3), which have discharges of about 2 to 6 L/s and display moderate seasonal variations with peak flow during late spring to early summer; average annual discharge also increases during years with greater snowpacks. Although no wells have been completed in this HSU in the study area, Holmes and others (1996) reported transmissivity values on the order of 10 to 100 m^2/day for wells and mine workings in the nearby Park City area (transmissivity calculated using the Cooper-Jacob method). The variation in values probably reflects variations in fracture intensity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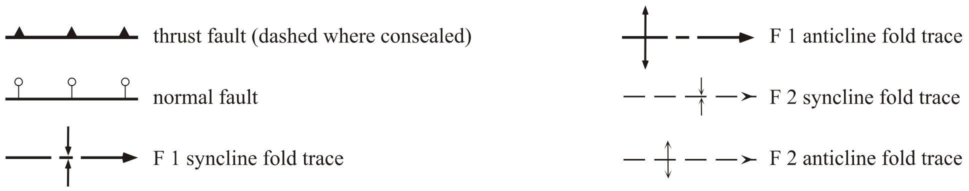

WA – Wasatch anticlinorium, **WF** – Wasatch Fault, ***ECS*** – Emigration Canyon syncline, ***SCA*** – Spring Creek anticline, ***PCS*** – Parleys Canyon syncline, **UD** – Upper detachment, **ECF** – East Canyon Fault zone, **CT** – Crawford thrust, **LD** – Lower detachment, **MRT** – Mount Raymond thrust, ***F1 FT*** – F1 fold train

T-Q	Late Tertiary to Quaternary deposits
Ku	Cretaceous to Early Tertiary upper synorogenic sequence
Km	Middle synorogenic sequence
Kl	Lower synorogenic sequence
Jp	Jurassic strata – Preuss Formation
Jt	Twin Creek Limestone
Jn	Nugget Sandstone
Ta	Triassic strata – Ankareh Formation
Tt	Thaynes Formation
Tdw	Dinwoody Formation and Woodside Shale
Pp	Permian Park City Formation
Pw	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

Fig. 1. A: Regional geologic map illustrating setting of Emigration Canyon area; major faults and folds labeled (modified from Bryant, 1990). B: Regional cross-section illustrating structural style; location of study area along northwest limb of Emigration Canyon syncline indicated

and connectivity that depend on structural setting (Keighley *et al*., 1997). This HSU is bounded by a confining interval of phosphatic shale in the middle member of the Park City Formation.

The Upper Park City HSU comprises the upper member of the Park City Formation (Fig. 2). This member contains medium- to thick-bedded dolostone, limestone, and sandstone with longer fractures that may enhance permeability. This HSU is the source of one small spring (S3 in Figure 3). This HSU is bounded by a confining interval that corresponds to the Triassic Dinwoody and Woodside Formations, which contain abundant shale, siltstone, and minor sandstone with limited large-scale fracturing.

The Thaynes HSU is lithologically complex and heterogeneously fractured (Fig. 2), with complex fluid flow. The formation is divided into a basal limestone member, lower siltstone member, middle limestone member, and upper siltstone member. Overall, thick-bedded limestone intervals

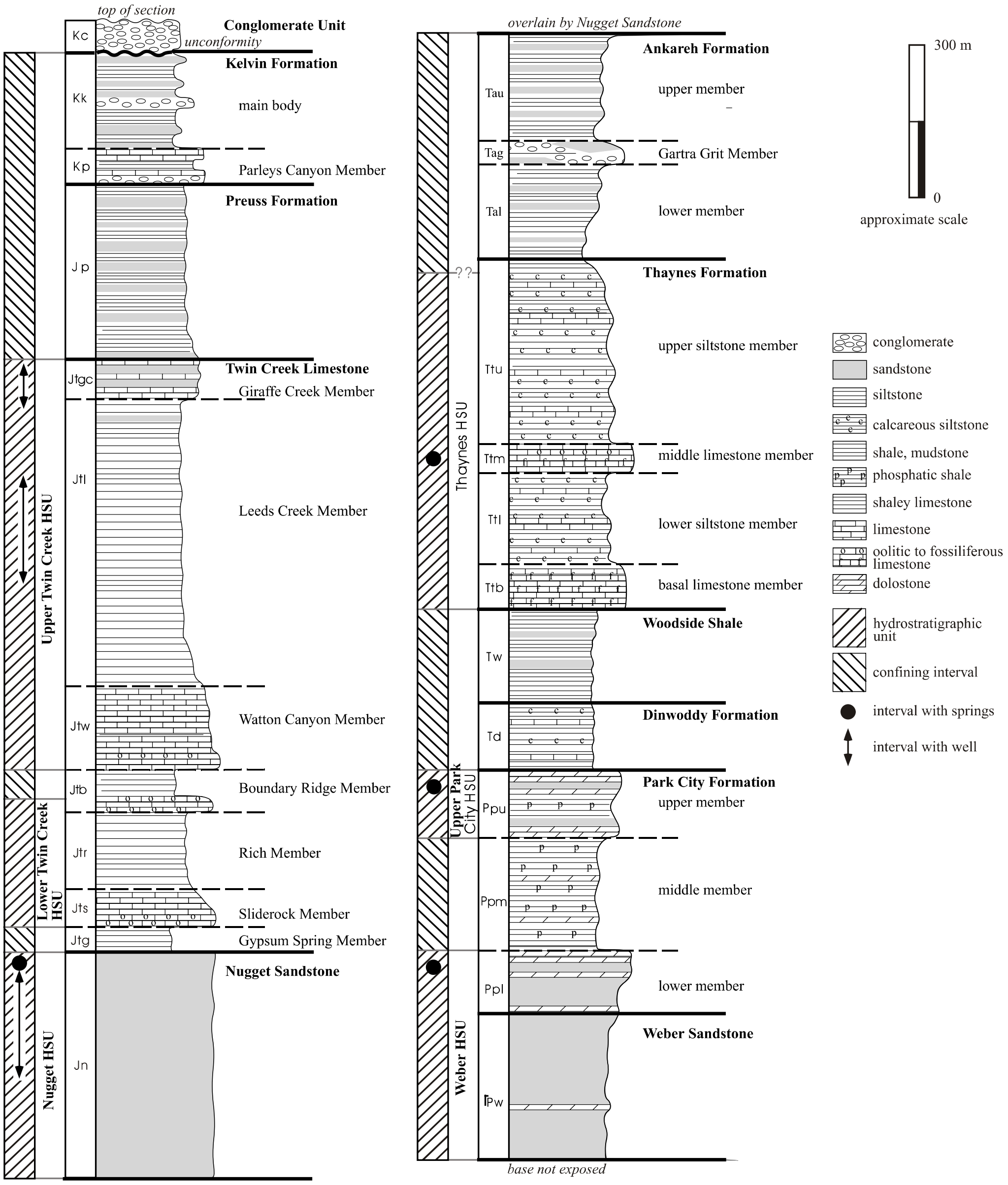

Fig. 2. General lithologic column of Upper Emigration Canyon area showing rock types and relations between stratigraphic and hydrostratigraphic units

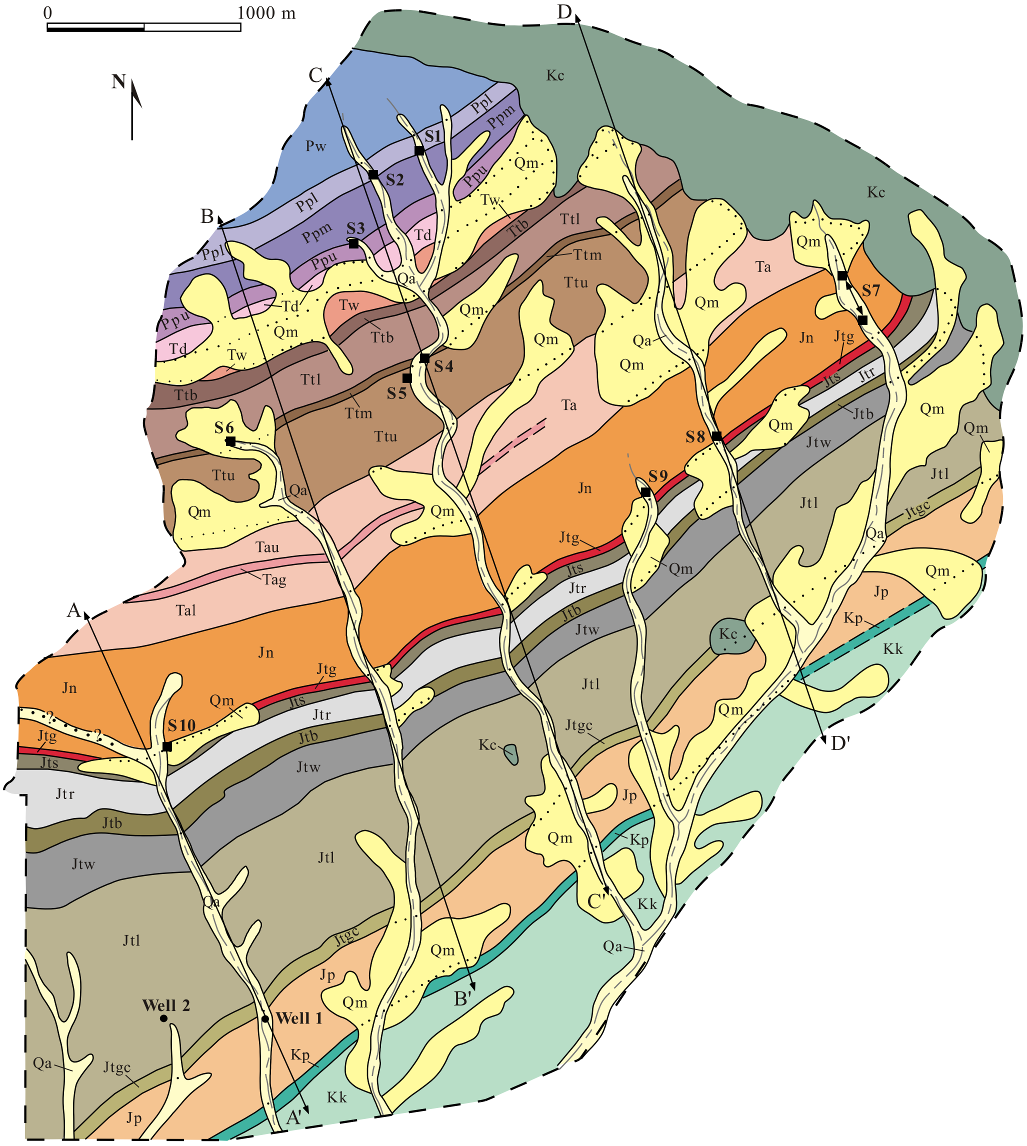

Fig. 3. Geologic map of Upper Emigration Canyon area showing outcrop patterns of stratigraphic units

See Figure 2 for explanation of bedrock units; Qm — Quaternary mass wasting deposits, Qa — alluvial deposits

have longer fractures and higher permeabilities, thin-bedded siltstone has shorter fractures and probably lower permeabilities, and thin shale beds form local confining layers. The Thaynes HSU is the source of several springs (S4 to S6 in Figure 3), which display significant seasonal and long-term variations in discharge (Yonkee, Barnett, 2000). Although no wells have been completed in the Thaynes Formation in the study area, Holmes and others (1996) reported highly variable transmissivities in the nearby Park City area, partly related to variable fracture intensity. This HSU is bounded by a confining interval that corresponds to the Ankareh Formation, which contains mostly shale, siltstone, and fine-grained sandstone with limited large-scale fracturing.

The Nugget HSU, one of the units examined in detail in this study, consists mostly of sandstone with variable primary and secondary porosity related to variable grain cementation and fracture intensity (Fig. 2). The formation contains two lithologic facies: (1) an eolian facies with cross-bedded, medium-grained, well-sorted, weakly cemented sandstone having primary porosities from 10 to 15%, and (2) a fluvial facies with thin-bedded, fine-grained, moderate-sorted, strongly cemented sandstone and siltstone having primary porosities less than 10%, with some coarse-grained sandstone channels (Picard, 1975; Lindquist, 1988). The formation is cut by widely to moderately spaced, large-scale fractures, with local zones of higher fracture intensity. Some fractures are open, whereas other fractures are sealed by silica cement and may act as local barriers to fluid flow. A series of springs (S7 to S10 in Figure 3) are located where this HSU is exposed along topographic lows near the contact with a confining interval at the base of the Twin Creek Limestone, and streams that cross this HSU are overall gaining. Discharges of larger springs are about 4 to 7 l/s, with subdued seasonal variations. Transmissivity values of 20 to 40 m^2/day were crudely estimated in the Nugget HSU in the study area from limited short-term pump test data reported on drilling logs for home-water-supply wells, which often overestimate well performance. Holmes and others (1996) reported transmissivities of about 10 to 30 m^2/day for wells completed in the Nugget Sandstone in the nearby Park City area, broadly consistent with a more detailed analysis discussed in the section on aquifer properties.

The Twin Creek Limestone is lithologically complex (Imlay, 1967), and includes: a basal confining interval corresponding to the Gypsum Spring Member; a Lower Twin Creek HSU comprising the Sliderock, Rich, and lower Boundary Ridge Members; a confining interval in the upper Boundary Ridge Member; and the Upper Twin Creek HSU comprising the Watton Canyon, Leeds Creek, and Giraffe Creek Members (Fig. 2). Fluid flow, however, is likely to be complex within both HSUs, which may contain intervals with lower and higher permeabilities. The Gypsum Spring Member consists of mudstone and shale, with anhydrite preserved in the subsurface (Peterson, 1957). The Sliderock Member contains thick-bedded, variably fractured limestone, overlain by thin- to medium-bedded, slightly clayey limestone, with tectonic stylolites and partings parallel and subperpendicular to bedding. The Rich Member consists mostly of moderately clayey to silty limestone with weakly to strongly developed tectonic cleavage, defined by spaced seams of clay-rich material subperpendicular to bedding. The Boundary Ridge Member has a lower interval of thick-bedded, variably fractured limestone, overlain by red mudstone and shale that marks the boundary between the lower and upper HSU's. The Watton Canyon Member contains medium- to thick-bedded, slightly clayey to silty limestone, with tectonic stylolites and partings subperpendicular and parallel to bedding. The Leeds Creek Member consists mostly of thin-bedded, moderately clayey to silty limestone, with some interbedded claystone, siltstone, and fine-grained sandstone that increase in abundance upward in the member. Many limestone beds display weakly to moderately developed tectonic cleavage subperpendicular to bedding, and partings along both cleavage and bedding produce pencil fracturing. The Giraffe Creek Member contains thin- to thick-bedded, sandy limestone and sandstone cut by moderate-spaced fractures. Within both HSU's, thick-bedded limestone with longer fractures may have relatively higher permeability, whereas claystone intervals may form local confining layers. No springs are found in the Upper and Lower Twin Creek HSU's in the study area, and streams are overall losing during late summer and fall where they cross the HSU's. However, a major spring discharges from the Watton Canyon Member in the Park City area, and displays marked seasonal and yearly variations in flow, with peak discharges during late spring to early summer, and greater average discharge during years with greater snowpack.

The overlying Preuss and Kelvin Formations represent an overall confining interval. The Preuss Formations consists of thin- to medium-bedded siltstone, shale, and fine- to medium-grained sandstone, with some salt-bearing intervals in the subsurface (Yonkee *et al*., 1997). The Kelvin Formation consists mostly of mudstone and sandstone, with lenses of conglomerate. A number of single-family water supply wells have been drilled into these formations in the Emigration Canyon area, but productions are low and saline waters have been encountered in several wells.

STRUCTURAL GEOLOGY

The area was affected by two phases of Cretaceous thrust-related deformation, and by Tertiary to Recent extensional deformation (Yonkee *et al*., 1997). Early-phase, north-trending folds and associated early cleavage are best developed south of the study area (Fig. 1). Second-phase, northeast-trending folds, including the Spring Creek anticline and Emigration Canyon syncline, formed during slip along the Crawford thrust and the East Canyon fault zone. A locally developed, second-phase cleavage is generally northeast-striking, subparallel to second-phase fold axes, and remains subperpendicular to bedding along fold limbs. Complex fracture networks probably developed during thrusting, but most fractures were sealed by precipitation of calcite, forming veins. Tertiary to Recent extension formed the large-scale Wasatch normal fault, along with small-scale normal faults and steep extensional fractures in the Wasatch Range. Decrease in lithostatic pressure during uplift and erosion, plus a change to horizontal extension also resulted in fracturing along pre-existing cleavage and bedding planes.

The study area lies within the northwest limb of the Emigration Canyon syncline, which displays overall northeast striking, steeply southeast dipping bedding. The hinge of the syncline trends roughly along the topographic bottom of upper Emigration Canyon just southeast of the study area. In detail, bedding displays minor variations in strike and dip across the study area, which can be divided into three structural areas. Within the western area, bedding generally dips from 40^o to 70^o southeast; within the central area, bedding dips from 60^o to 90^o southeast; and in the eastern area, bedding is nearly vertical (Fig. 4). Minor cm- to m-scale folds are also developed in well-bedded intervals, such as parts of the Twin Creek Limestone. Minor fold axes plunge moderately to gently northeast, overall subparallel to the best-fit fold axis for the study area, which plunges 15^o toward 60^o. These folded strata are locally capped with angular unconformity by gently dipping Late Cretaceous conglomerate.

Faults may also partly control fluid flow, acting as complex conduit-barrier systems that further subdivide HSUs into structural subunits, with different flow and recharge systems, as has been shown for the Park City area (Ashland *et al*., 1996). Geologic mapping, however, indicates that large-scale surface faulting is limited in the Emigration Canyon study area, although major faults exist at depth. Thus fracture network characteristics, including partings along earlier cleavage, along with the large-scale structure of the Emigration Canyon syncline, are likely to be the most important structural features influencing fluid flow.

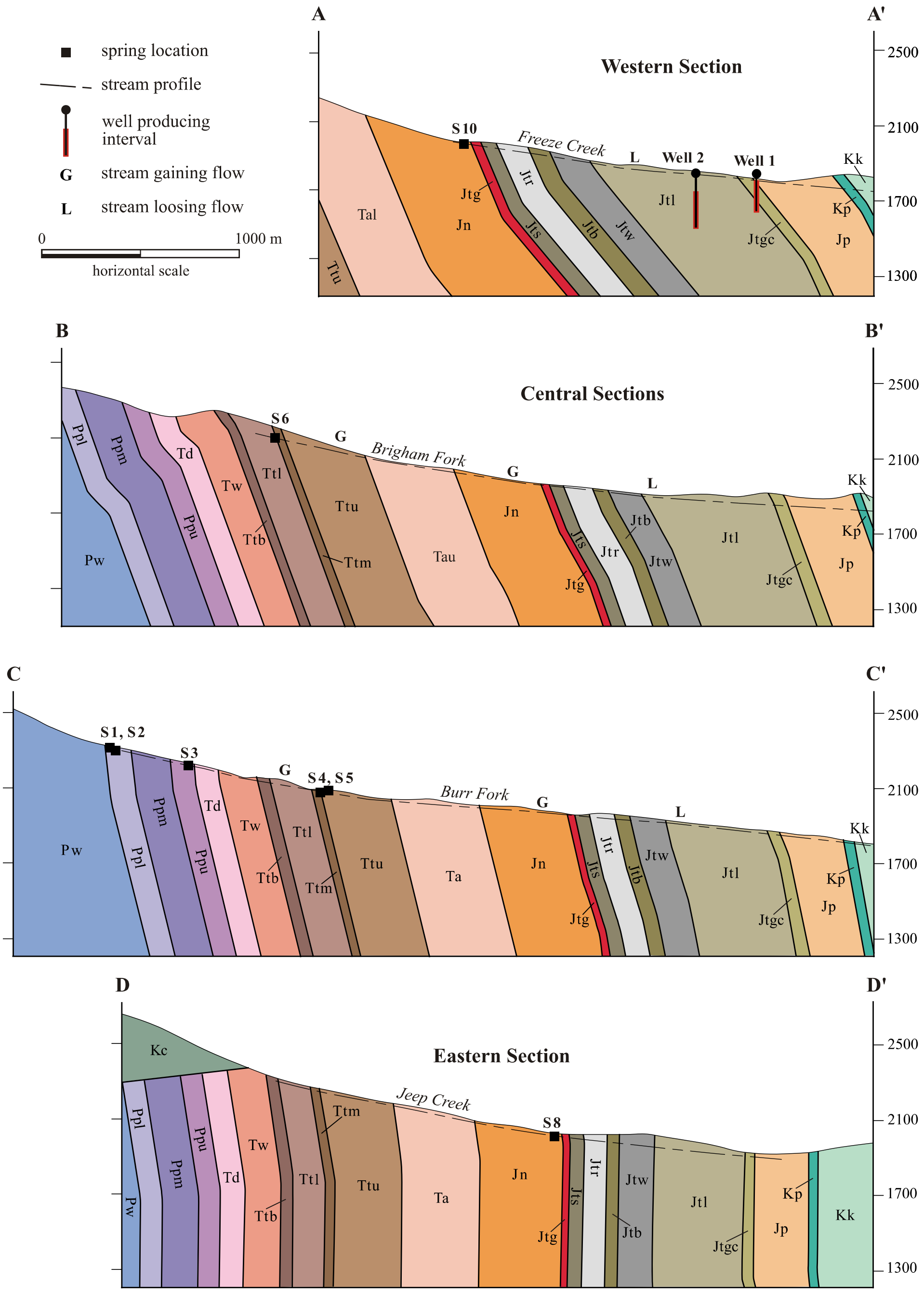

Fig. 4. Cross-sections for Upper Emigration Canyon area. Locations of springs (S), gaining/loosing sections of streams (G/L), and culinary water wells indicated. See Figure 3 for locations of lines of sections

DRAINAGE BASINS

The study area displays rugged topography, which influences the nature of ground water flow and recharge. Elevations range from about 2,700 m along the ridge at the northeastern edge of the area to 1,750 m along streams at the southwestern edge of the area. The area lies within the upper, northeastern part of the first-order Emigration Canyon drainage basin, which slopes gently southwest, subparallel to the hinge of the Emigration Canyon syncline, and is drained by Emigration

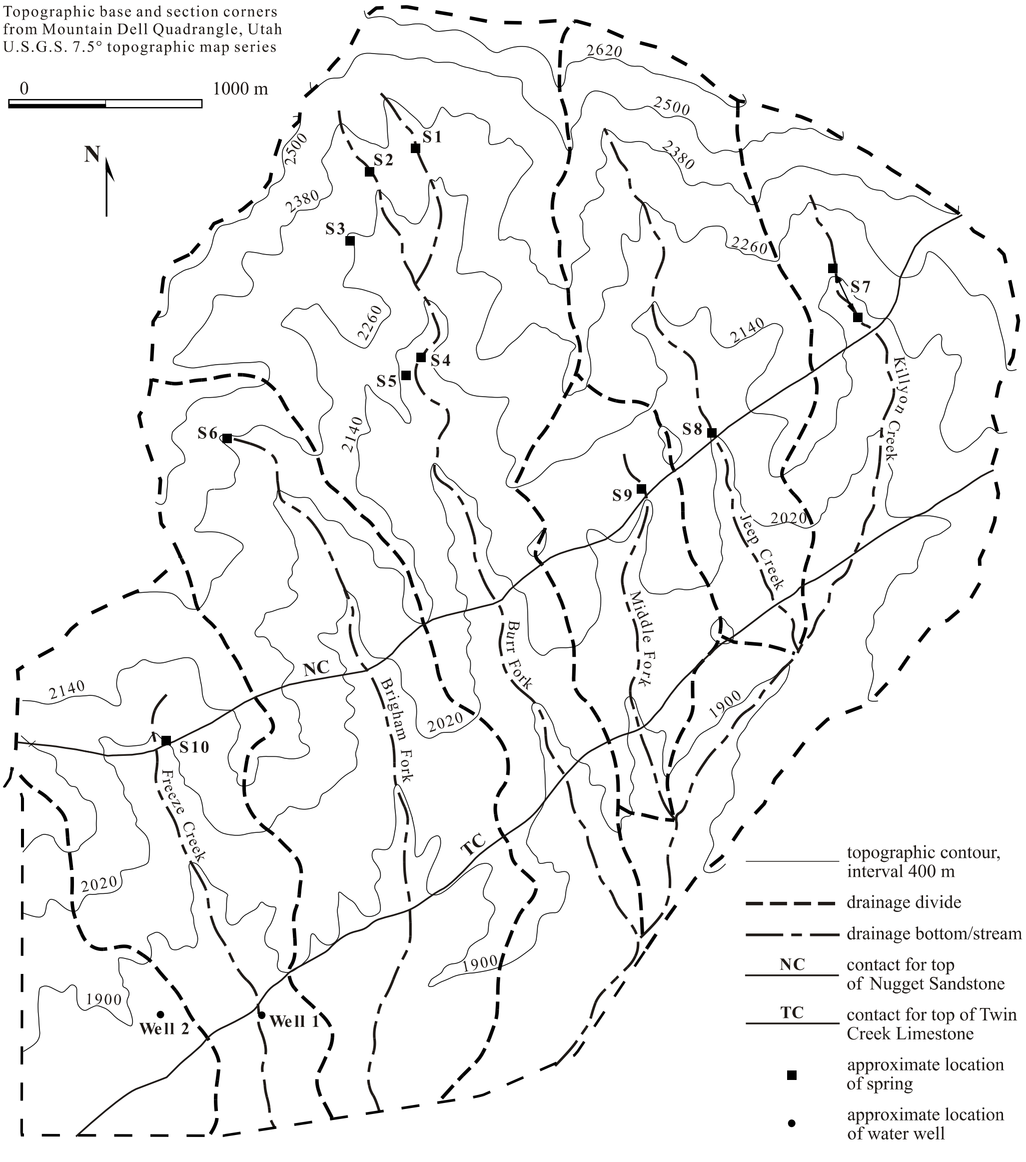

Fig. 5. Drainage basins for Upper Emigration Canyon area

Creek (Fig. 1). The area is also subdivided into a series of second-order drainage basins that slope moderately to gently southeast, toward Emigration Creek (Fig. 5). The second-order basins are about perpendicular to the average strike of bedding, and minor streams that drain each basin transverse across stratigraphically older to younger units going southeastward (Fig. 4). Drainage divides along intervening ridges have elevations generally 100 to 300 m above corresponding parts of streams, such that outcrops of individual stratigraphic units significantly increase and decrease in elevation across drainage basins (Fig. 5). However, ridges are locally less than 100 m above streams in the southeastern part of the area where less resistant rocks of the upper Twin Creek to Kelvin Formations are exposed.

Topographic divides may roughly correspond to ground-water divides, which subdivide HSUs into subunits, with different flow and recharge systems in different basins. Interlayering of relatively permeable and impermeable intervals, and presence of bed-parallel fractures, probably produce anisotropic permeability that favors northeast-southwest fluid flow parallel to bedding. Drainage divides are about perpendicular to bedding, and northeast-southwest slopes toward stream bottoms also favor northeast-southwest fluid flow. If topographic and ground water divides approximately coincide, then areas for direct recharge of individual subunits correspond approximately with surface exposures of a HSU within a drainage basin. Subunits may also have indirect recharge by leakage of surface water from losing parts of streams, which is particularly important for the Lower and Upper Twin Creek HSUs, leakage of shallow ground water from overlying unconsolidated deposits, minor flow between HSU's, and minor flow across drainage divides. Importantly, because of potential 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. Additionally, ground water and topographic divides may not coincide in areas of structural complications, and ground water divides may be dynamic, changing with seasonal variations in depths to water tables and with drawdown from pumping of water wells.

AQUIFER PROPERTIES

METHODS

Two aquifers, the Upper Twin Creek HSU and the Nugget HSU, were examined in detail in this study. Fractured bedrock aquifers may display a variety of responses to aquifer stress, depending on properties of matrix and fractures. When rock matrix has very low permeability, most flow occurs along fractures. If fractures are relatively closely spaced and interconnected, the aquifer can be treated as an equivalent porous medium with permeability and storage related to statistical characteristics of the fracture network (Long, Witherspoon, 1985; Oda, 1985). Flow along fractures is generally modeled assuming laminar (Darcian) flow, yielding the cubic law:

$$Q = Cw^3 (dh / dL),$$

where Q is fluid flux through the fracture, C is a constant related to fracture geometry and fluid properties, w is effective aperture, and dh/dL is the hydraulic gradient parallel to the fracture (Witherspoon *et al.*, 1980; Oda, 1985). However, natural fracture surfaces display roughness at a variety of scales, with a range of correlation (matting) between adjacent fracture surfaces, such that opening width varies along a fracture and fluid flow may not be laminar in detail (Brown, 1987).

Thus effective aperture may be a complex function of surface roughness, matting, and characteristics of fracture intersections, and significantly less than the average opening. For a single-porosity media, assuming spatially homogeneous, isotropic properties, fluid flow is controlled by the differential equation:

$$K \ {}^{2}h = Ss * (\delta h / \delta t),$$

where K is hydraulic conductivity, h is hydraulic head, and Ss is the specific storage (Theis, 1935). If fractures are relatively widely spaced with highly concentrated flow along only a few fractures, then the system is best treated as a discrete fracture network (Long, Witherspoon, 1985; Jones *et al.*, 1999).

In some aquifers, fracture flow is accompanied by significant flow from matrix blocks, and the system can be treated using a double-porosity model (Barenblatt *et al.*, 1963). In this model, the rock mass consists of two interacting, overlapping continua: lower permeability matrix blocks with relatively higher primary porosity; and a higher permeability system of fractures with lower secondary porosity. Hence, storage of the aquifer is controlled mostly by depositional and lithification processes that affected the matrix, while permeability is controlled mostly by tectonic, thermal, and unloading stresses that produced fractures. Two distinct approaches are used for double-porosity models: pseudo-steady state conditions (Warren, Root, 1963); and fully transient conditions (Kazemi, 1969). The first approach provides greater mathematical simplicity, but fails to account for some physical aspects of flow, whereas the second approach is theoretically more acceptable, but involves additional parameters (Moench, 1984). Interestingly, both approaches yield similar results in interpretation of many pumping tests. In the double porosity model, two representative elemental volumes (REV's) are considered: a fracture REV containing a large number of cracks and having properties that depend on statistical properties of the crack network; and a block REV with properties that depend on grain-scale porosity characteristics. A double-porosity system is characterized by two parameters, σ and λ, given by:

$$\sigma = Ss'/Ss,$$

$$\lambda = \alpha \, (K'/K) * r_w^2,$$

where α is geometric factor, Ss' and Ss are specific storages of the matrix and fracture REVs, K' and K are the hydraulic conductivities of the matrix and fracture REV's, and r_w is well diameter (Moench, 1984). The controlling differential equation for double-porosity model is:

$$K \ {}^{2}h = Ss * (\delta h / \delta t) + q_x$$

where q_x is a source term related to flow from matrix to fractures. The Laplace transform, line source solution for dimensionless drawdown in the fractures is:

$$h_D = (2 / p) K_o [r_D (r_D + q_D)^{0.5}]$$

where h_D is dimensionless drawdown, K_o is the modified Bessel function of second kind and order zero, r_D is dimensionless distance ($r_D = r/r_w$), p is the the Laplace transform variable, and q_D is the dimensionless flow from block to fracture (Moench, 1984). For the pseudo-steady flow model:

$$q_D = p / (1 / \sigma + 1 / \lambda),$$

(Barrenblatt *et al.*, 1963). For the transient flow model for slab-shaped blocks:

$$q_D = \gamma^2 m \tan h (m),$$

with $m = (\sigma p)^{0.5} \gamma$ and $\gamma = (r_w/b)(K'/K)^{0.5}$,

where b is slab width (Streltsova, 1983). For the pseudo-steady state model, flow is initially derived mostly from storage along fractures, followed by fluid derived from storage in the blocks, such that at very early and late times results will be similar to those given by the Theis solution respectively for fracture and matrix properties. For the transient flow model, flow in both blocks and fractures determines the hydraulic head in the blocks, with an early, gradual transition from the Theis curve for fractures. Block surfaces are assumed to be covered by a thin skin that has a lower hydraulic conductivity. Presence of a very low-conductivity skin results in most of changes in hydraulic head occurring across the skin, which reduces the transient flow model to the pseudo-steady flow model.

PROPERTIES FOR UPPER TWIN CREEK HYDROSTRATIGRAPHIC UNIT

Two public-water-supply wells have been completed within parts of the Upper Twin Creek HSU in the study area (Fig. 3). Freeze Creek Well 1 is open from depths of 36 to 116 m through the Giraffe Creek and uppermost Leeds Creek Members of the Twin Creek Limestone, whereas Freeze Creek Well 2 is perforated from depths of 97 to 241 m through the middle part of the Leeds Creek Member, and is located about 400 m west of Well 1. Wells 1 and 2 were reported to have seasonally flowed under artesian pressure during early spring of 1994 until 1997, indicating that local confining layers may be present. The wells exhibit large seasonal fluctuations in water levels, with especially significant drawdown from prolonged pumping during the summer of 2000.

A long-term (5-day), constant-rate pumping test was conducted on Well 2 during March, 1998, to better understand the hydrologic properties of the aquifer, including potential spatial heterogeneity. Water levels in Wells 1 and 2 were rising at average rates of about 0.5 and 0.25 m/day respectively prior to the test, and Well 2 had a “static” water levels about 15 m below ground surface just prior to onset of the test. During the test Well 2 was pumped at a rate of 4.2 m^3/min, except for the first 9 minutes when the discharge rate was being adjusted, and changes in water levels were recorded in both wells. Total drawdown in Well 2 was about 120 m during the test. No drawdown was observed in Well 1, which is consistent with the estimated radius of influence for the cone of depression induced by the aquifer test being less than the distance between the two wells.

Interpretation of the pumping test using the Theis method produced satisfactory results with an average transmissivity of 17 m^2/day, indicating that the single-porosity model is appropriate for the Upper Twin Creek Limestone (Fig. 6A). Analysis using the Cooper–Jacob method suggests that transmissivity decreases from about 30 m^2/day in the initial part of the pump test with a stronger contribution of the upper part of the aquifer, to 6 m^2/day in the later part of the pump test with a stronger contribution of flow from the lower part of the aquifer (Fig. 6B). This increase in slope may reflect some combination of: fluid flow from fractures with smaller apertures at deeper levels and reduced fluid pressures as drawdown increases; varying contributions of fluid flow from different fracture percolation networks; the cone of depression reaching less permeable hydrologic boundaries, such as claystone layers or less fractured material; and decreasing effective thickness of the aquifer with increasing drawdown. Recovery data suggest that transmissivity increases from about 5 m^2/day in the lower part of the aquifer to 25 m^2/day in the upper of the aquifer

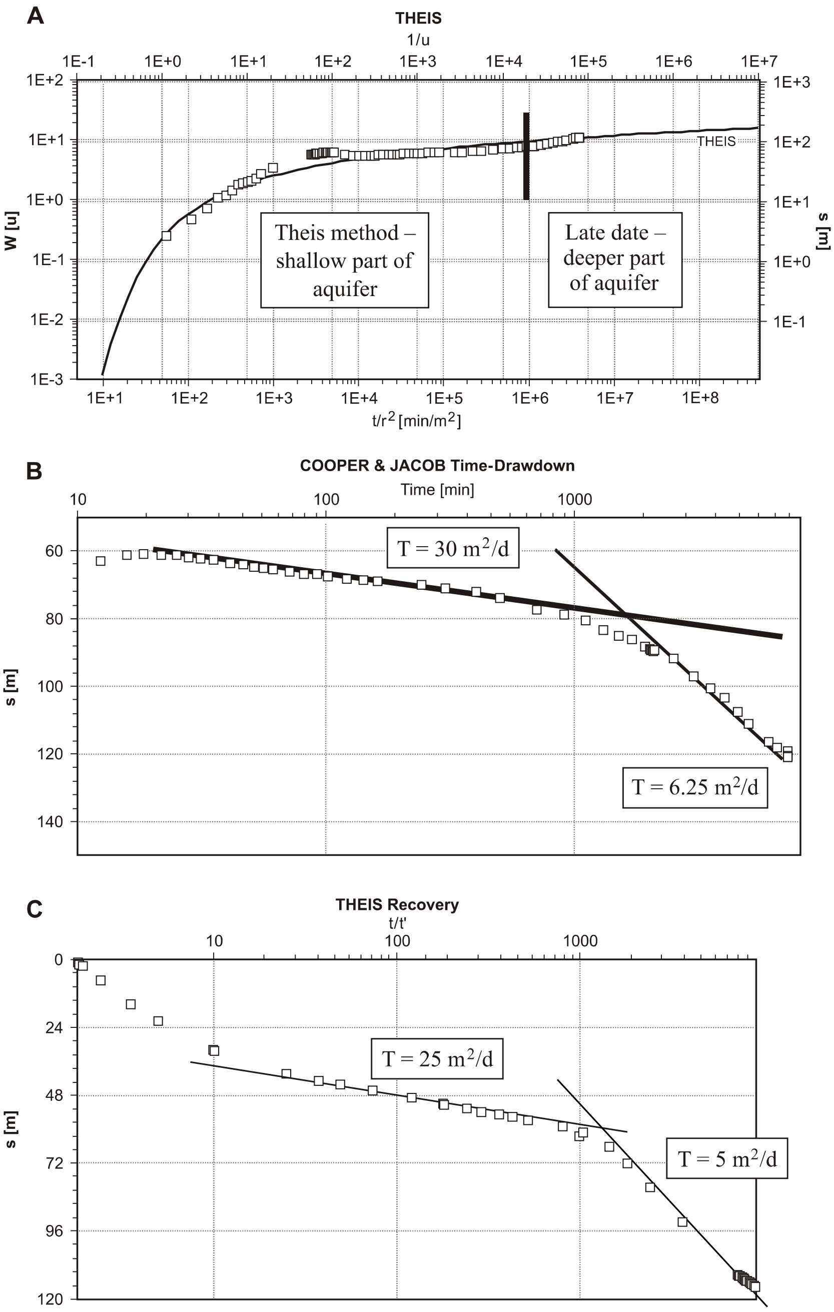

Fig. 6. A: Aquifer pumping test interpretation; data for Well 2 completed in Leeds Creek Member of Twin Creek Limestone; Theis interpretation for single porosity model: $T = 7.4\ \mathrm{m}^2/\mathrm{d}$, $K = 3.5 \times 10^{-2}$ m/d, $Ss = 4.5 \times 10^{-4}\ \mathrm{m}^{-1}$. B: Cooper–Jacob interpretation with different parameters for shallow and deeper levels: $T_{shallow} = 30\ \mathrm{m}^2$/day, $T_{deep} = 6\ \mathrm{m}^2$/d. C: recovery interpretation $T_{shallow} = 25\ \mathrm{m}^2$/d; $K = 0.2$ m/d, $T_{deep} = 5\ \mathrm{m}^2$/d, $K_{deep} = 0.03$ m/d

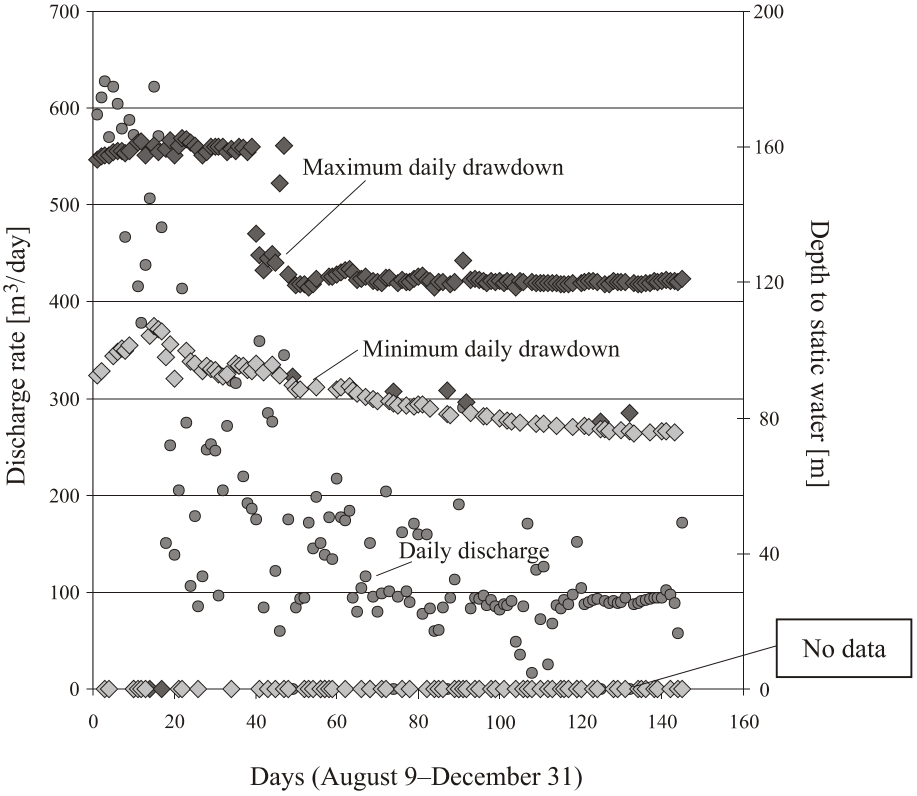

Fig. 7. Water levels and discharges for Well 2 from August to December 2000

(Fig. 6C), comparable to results from drawdown data. Interestingly, the transition from higher to lower transmissivity occurs when the water level reaches a depth of about 60 m during recovery, and a depth of about 80 m during drawdown. The small inconsistency between drawdown and recovery data may be related to well inefficiency. Drawdown data were also analyzed using the double porosity model of Moench (1984), but neither the pseudo-steady-state-flow nor transient approaches yielded a better fit than for the Theis model.

Geologic observations also provide constraints on acceptable models. The Leeds Creek Member consists mostly of very fine-grained limestone that has very limited grain-scale porosity. Pencil fracturing, related to thin partings (mostly < 1 mm wide) along bedding and cleavage, has spacings on the order of 1 cm in surface exposures. Some partings may be related to near-surface stress relaxation and weathering, and so average fracture spacing at depth may be wider. The permeability for a fracture network that behaves like an equivalent porous media is given by:

$$k = F\,(1/12)\,w^3\,(p),$$

where F varies from 0 for completely isolated fractures to 1 for infinite, connected fractures, w is the average effective aperture, and p is a measure of fracture density related to spacing and length distributions (Oda, 1985). At low confining pressures, permeability is expected to be on the order

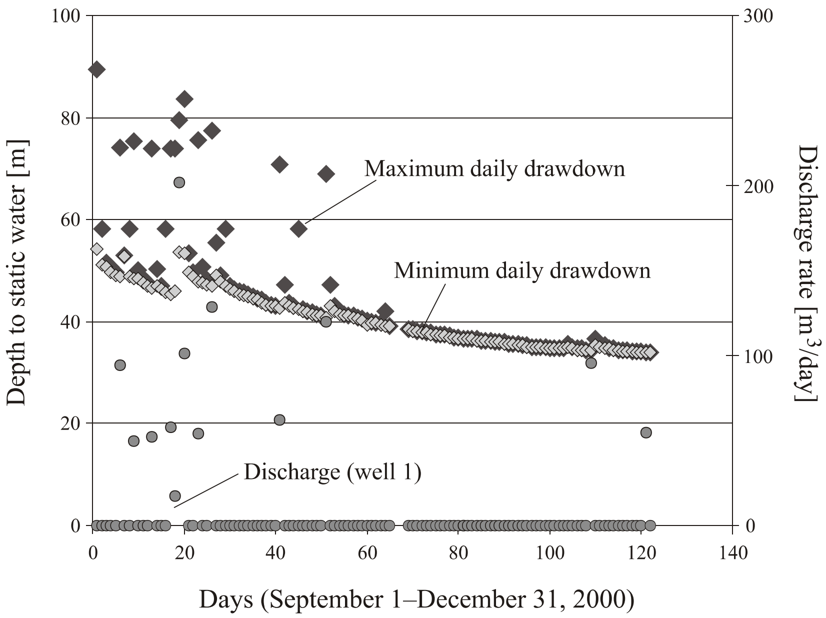

Fig. 8. Water levels and every daily discharges for Well 1 from September to December 2000

of 10^{-11} to 10^{-13} m^2, based on a fracture density of 10^1 to10^2 /m (corresponding to an average spacing of 1 to 10 cm for open fractures in the subsurface), an effective aperture of 10^{-4} m (reflecting fractures with less than 1mm openings, which have surface roughness that reduces effective width), and 0.1 to 1 for F (reflecting variably isolated fractures). The calculated hydraulic conductivity of 0.2 m/day from the pump test corresponds to a permeability on the order of 10^{-13} m^2, consistent with the lower range calculated from fracture characteristics, suggesting that some fractures are closed and isolated. To estimate permeability at depth, we use the empirical relation of Evans and others (1997):

$$k = k_0 \exp(-\gamma P),$$

where k_0 is permeability at $P = 0.1$ MPa, P is effective pressure in MPa ($P = P_{rock} - P_{fluid}$), and γ varies from about 0.1 to 0.2 for most fractured rocks. At a depth of 100 m, $P = 2.5$ MPa if fluid pressure = 0, and permeability is reduced by about 25 to 40%. Thus, if fracture density is similar with depth, then permeability and hydraulic conductivity are expected to decrease slightly during pumping. However, the hydraulic conductivity estimated from drawdown and recovery data for deeper levels is about 80% less than estimated for shallow levels, indicating other factors are involved.

Grain-scale porosity is very low, and fracture porosity is also likely small, probably about 1 to 3% (corresponding to a spacing of 1 to 10 cm for fractures with 0.3 to 1 mm openings), resulting in limited storage for this aquifer. Elastic specific storage Ss, is given by:

$$Ss = \rho g (\alpha + n\beta),$$

where ρ is density of water, α is the compressibility of the aquifer skeleton (on the order of 10^{-11} m^2/N for rock), *n* is porosity, and β is the compressibility of water (= $5*10^{-10}$ m^2/N), yielding elastic specific storage *Ss* of 10^{-7}. Approximate values of specific storage estimated from the aquifer tests indicate semiconfined conditions.

Long-term monitoring of average discharge and water levels in Wells 1 and 2 from August through December 2000 provide additional insights into aquifer characteristics, including estimates of safe yield for this part of the Upper Twin Creek Formation in this area (Fig. 7). When Well 2 was pumped at an average discharge rate of 600 m^3/day during peak summer demand, water levels at minimum drawdown (reflecting partial recovery between daily pumping periods) were declining at a rate of 3 m/day, and the maximum drawdown levels were also declining. This pattern recorded significant groundwater mining, and water restrictions were imposed. When Well 2 was pumped at intermediate average rates of about 200 to 500 m^3/day, following restrictions, the water levels at minimum and maximum drawdown approached quasi-steady-state conditions. When the average pumping rate was further reduced to about 100 m^3/day, water levels at minimum drawdown started to recover at a rate of about 0.3 m/day, indicating that recharge to the aquifer, probably from leakage along loosing parts of nearby streams, exceeded discharge. Much greater values of the maximum daily drawdowns in both Wells 1 and 2 (Figs. 7 and 8) for deeper portions of the aquifer confirm results of the aquifer pumping test, suggesting significantly smaller transmissivity at greater depths.

PROPERTIES FOR NUGGET HYDROSTRATIGRAPHIC UNIT

Results of the five-day long aquifer test for a well completed in part of the Nugget Sandstone in the nearby Summit Park area (Fig. 1) were used to interpret hydrologic properties of this formation. The well was drilled near the crest of the Summit Park anticline, which has a moderately northeast plunging fold axis and is cored by the Summit Park fault (Keighley *et al*., 1997). The Nugget Sandstone locally displays closer spaced fractures and some minor faults near the fold core, where exposed southwest of the well. The well is open to the Nugget Sandstone from a depth of 210 m to about 400 m; the upper part of the well is sealed where it goes through the overlying Twin Creek Limestone. Interpretation of the aquifer test revealed that the Nugget Sandstone reacts very differently to aquifer stress in comparison to the Upper Twin Creek Limestone. The Theis method did not produce a satisfactory fit to drawdown data, possibly indicating double-porosity flow in the aquifer (Fig. 9). Interpretation of early drawdown using the double-porosity, pseudo-steady flow model produced the following best fit results: $T_{fracture} = 3.8$ m^2/d, $T_{matrix} = 1.4$ m^2/d and $Ss = 1.4 \times 10^{-5}$ m^{-1}, using the following rock and fracture system parameters: average aperture — 0.001 m, block thickness 0.02 m, $Ss'/Ss = 200$, $K_{block}/K_{fracture} = 0.4$. A double-porosity transient-flow model for slab-shaped blocks produced the following results: $T_{fracture} = 2.6$ m^2/d, $T_{matrix} = 1.0$ m^2/d and $Ss = 5.7 \times 10^{-5}$ m^{-1}, using the same fracture parameters except $Ss'/Ss = 50$. During the later part of the aquifer test, the drawdown increased more slowly, indicating additional flow of water to the well from more permeable part of the aquifer. Estimated transmissivity using the Cooper–Jacob method increased from 3 m^2/day to about 20 m^2/day for late time data. Calculated values of transmissivity for early data may reflect greater cementation near the fold core, possibly associated with intervals of fluvial facies or sealing near fractures, values of transmissivity for late time data, representative of the aquifer at distances more than 100 m from the pumping well, are similar to the values reported from other wells in the area (Holmes *et al*., 1996), and may reflect presence of

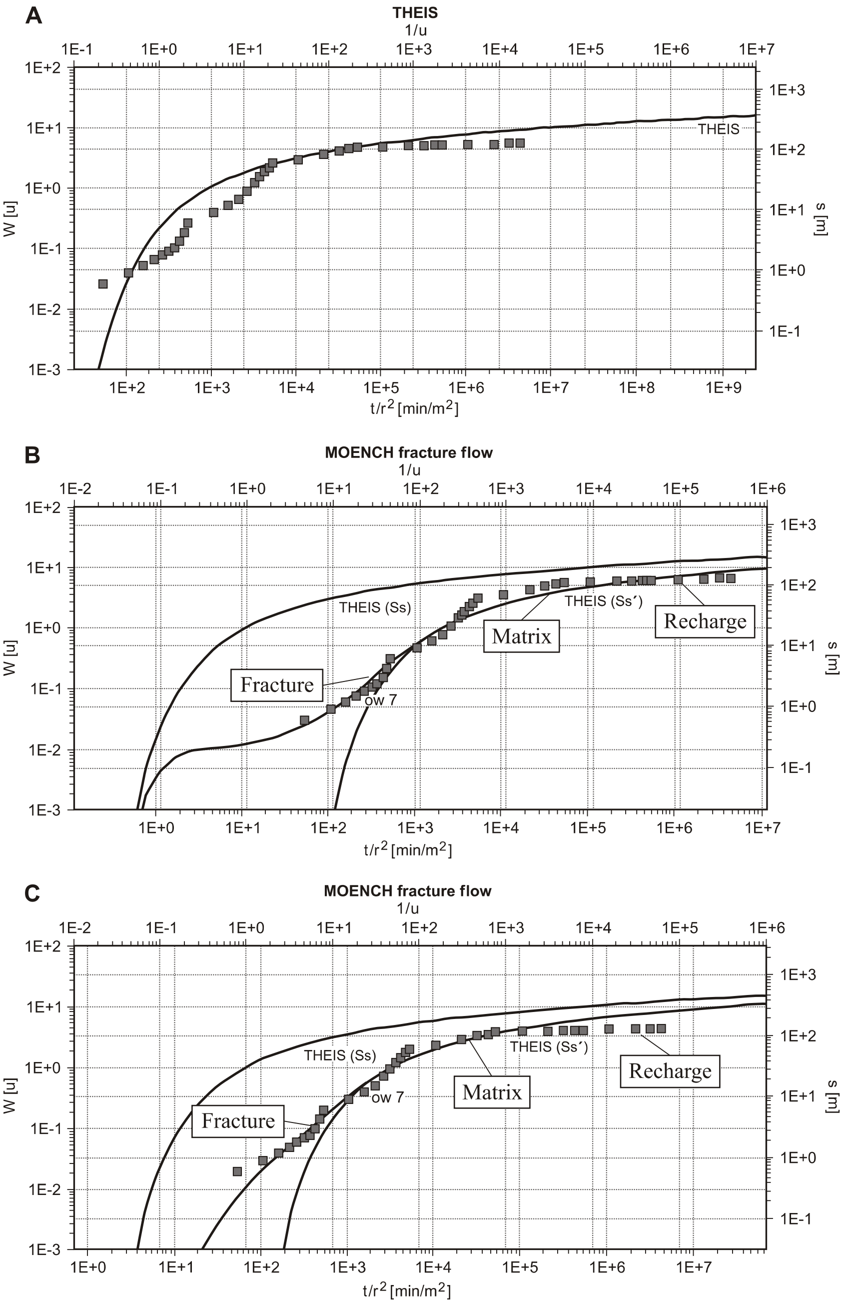

Fig. 9. A: Aquifer pumping test interpretation; data for Summit Park well completed in Nugget Sandstone; Theis interpretation for single porosity model did not produce a satisfactory fit. B: Double-porosity pseudo-steady flow model: $T_{fracture}$ = 3.8 m^2/d, $K_{fracture}$ = 1.7 x 10^{-2} m/d, Ss = 1.4 x 10^{-5} m^{-1} (aperture = 0.001 m, block thickness = 0.02 m, Ss'/Ss = 200, $K_{block}/K_{fracture}$ = 0.4). C: Double-porosity transient-flow slab-shaped blocks model, $T_{fracture}$ = 2.6 m^2/d, $K_{fracture}$ = 1.2 x 10^{-2} m/d, Ss = 5.7 x 10^{-5} m^{-1} (Ss'/Ss = 50, $K_{block}/K_{fracture}$ = 0.4, aperture = 0.001 m, block thickness = 0.02 m). Parts of curves related to fluid flow mostly from fractures, local matrix, and recharge boundaries in more permeable eolian facies are labeled

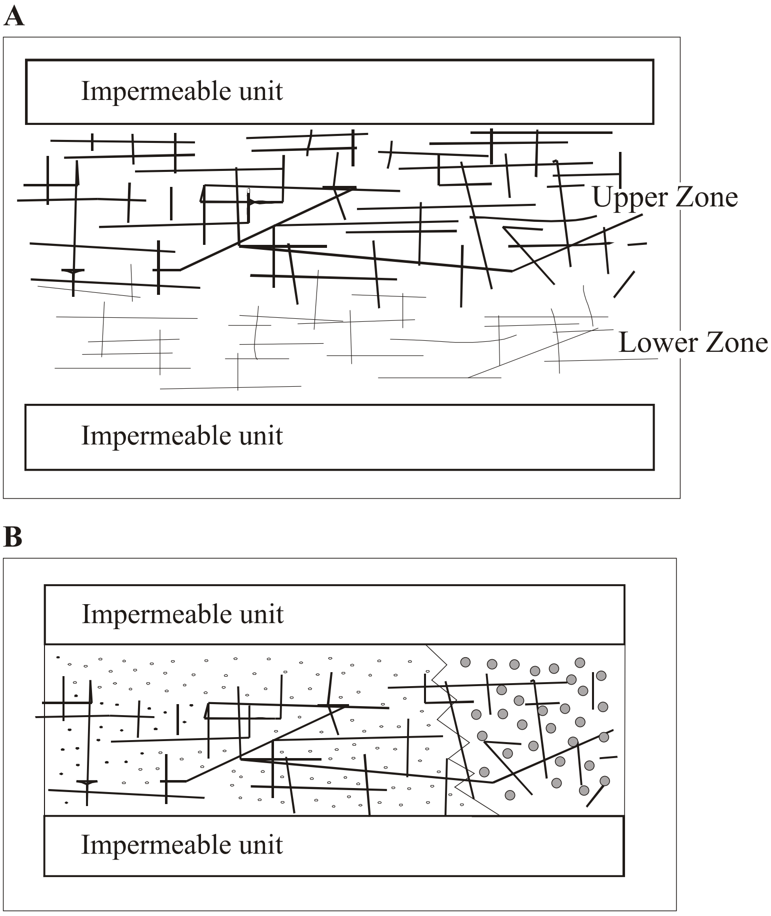

Fig. 10. Diagram illustrating conceptual model for matrix and large-scale fluid flow. A: the Upper Twin Creek aquifer; partings along bedding and cleavage produce widespread fracturing, with overall wider apertures at shallower levels. B: the Nugget aquifer; more significant porosity varies laterally with facies

more permeable eolian intervals. These results lead to the conceptual model of the Nugget aquifer presented in Figure 10. The double-porosity model indicates significant contributions of both fracture, secondary porosity and primary matrix porosity to flow in the aquifer, and additionally increased flow caused by a part of the aquifer with higher transmissivity.

Additional data are available from oil fields where the Nugget is an important reservoir. Average intrinsic permeabilities of most core samples from the eolian facies are on the order of 10^{-15} to 10^{-14} m^2, whereas average intrinsic permeabilities of most core samples from the fluvial facies are on the order of 10^{-16} m^2 (Lindquist, 1988). These permeabilities correspond to average hydraulic conductivities for water on the order of 10^{-2} to 10^{-3} m/day for the eolian facies, which are broadly consistent with higher conductivities estimated from pump test data, and 10^{-4} m/day for the fluvial facies. Higher values for eolian facies indicate that matrix storage is important over longer time intervals, but fractures provide important short-term pathways.

CONCLUSIONS

Conceptual models of fractured aquifers in the Upper Emigration Canyon area developed in this study improve understanding of the ground water flow system in a part of the Sevier thrust belt in the Wasatch Mountains, Utah. Geologic mapping, long-term monitoring of water levels, and long-term (5-day) aquifer pumping tests were used to develop two models of fracture flow representing the Upper Twin Creek aquifer and the Nugget aquifer respectively. A single-porosity model with a dense network of fractures, rock matrix with very low permeability, and decreasing transmissivity with depth, represents the Upper Twin Creek Limestone. Transmissivity of the lower part of the aquifer (6 m^2/day) is much lower than in the upper part of the aquifer (30 m^2/day), partly related to greater closure and isolation of fractures at depth. The safe yield determined for the aquifer in the Emigration Canyon based on the long-term monitoring is 300 m^3/day. The Nugget Sandstone is better described by a double-porosity model with lateral changes of transmissivity in the aquifer. Pseudo-steady state flow model and transient-steady flow models revealed similar aquifer parameters and geometric fracture characteristics, with transmissivity of about 3 m^2/day, increasing to values 20 m^2/day at lateral distance of greater than 100 meters from the pumping well.

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