Geophysical and geochemical characterization of the groundwater system and the role of Chatham Fault in groundwater movement at the Coles Hill uranium deposit, Virginia, USA

John P. Gannon · Thomas J. Burbey · Robert J. Bodnar · Joseph Aylor

Abstract The largest undeveloped uranium deposit in the United States, at Coles Hill, is located in the Piedmont region of Pittsylvania County, south-central Virginia, and is hosted in crystalline rocks that are adjacent to and immediately west of Chatham Fault, which separates these crystalline rocks from the metasedimentary rocks of the Danville Triassic Basin (in the east). Groundwater at the site flows through a complex network of interconnected fractures controlled by the geology and structural setting. The role of Chatham Fault in near-surface (<≈200m) groundwater flow is examined using electrical resistivity profiling, borehole logging, a pumping test, groundwater age dating and water chemistry to determine if the fault represents a permeability barrier or conduit for groundwater flow. The volumetric flow per unit width flowing eastward across the fault is estimated at 0.069–0.17m^2/day. Geochemical data indicate that groundwater in the granitic crystalline rocks represents a mixture of modern and old water, while the Triassic basin contains a possible deeper and older source of water. In regions with shallow water tables, mine dewatering during operation presents significant mining costs. The study's results yield important information concerning the effect that Chatham Fault would have on groundwater flow during Coles Hill mining operations.

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Introduction

The Coles Hill uranium deposit, located in south-central Virginia near the town of Chatham in Pittsylvania County, was discovered in 1979 by Marline Uranium, Inc. The Coles Hill deposit is located within the Dan River Basin in the Banister River Watershed and is the largest undeveloped uranium deposit in the United States (and 7th largest in the world; Pincock et al. 1982), with the current resource estimated at 54 million kg of U_3O_8 at a cutoff grade of 0.025 wt% contained in two ore bodies.

The Coles Hill uranium deposit is located in the Virginia Piedmont adjacent to the Chatham Fault, a normal fault that was last active in the Mesozoic (Henika 2002) and which separates the crystalline rocks of the Piedmont to the west from the Triassic basin sediments to the east. The hydrogeology of the site is typical of the Virginia Piedmont in that flow occurs primarily in the saprolite and shallow weathered bedrock, or in deeper fractures in unweathered bedrock (Heath 1989). Faulting may also play an important role in influencing groundwater movement and its role is a primary purpose of this investigation.

The Coles Hill deposit shows many features common to other types of uranium deposits (Dahlkamp 1991; Cuney 2009), but does not match completely any of the known types of deposits. As such, the Coles Hill deposit is considered to represent a previously unrecognized style of uranium mineralization referred to as the "Coles Hill type deposit". Marline and Union Carbide began detailed geologic, geochemical and geophysical studies and a major drilling program to characterize the deposit in the early 1980s. However, following the accidents at Three Mile Island and Chernobyl, nuclear energy fell into disfavor, leading to a dramatic drop in uranium prices in the 1980s. At about the same time, the Virginia legislature initiated a moratorium on uranium mining in Virginia (Legislative bill number §45.1-283). Marline and Union Carbide abandoned their development of the deposit. Recently, the property was acquired by Virginia Uranium Inc. (VUI), and a new drilling

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program was initiated to evaluate the potential of mining the uranium deposit at Coles Hill. An independent study commissioned by VUI confirmed the existence of 13.8 million kg of U_3O_8 at an average grade of 0.216 wt% and 54 million kg of U_3O_8 at an average grade of 0.062 wt% U_3O_8 (Santoy Resources 2009), with a value of between $1.4 and $7.6 billion, based on 2009 market prices.

In order for uranium mining to proceed at Coles Hill, the moratorium on uranium mining that currently exists in Virginia must be rescinded. Several studies are currently underway by university researchers, private consultants, and the National Academy of Sciences to gather information related to the effect of mining uranium on the natural environment and local populations and this information may be used to varying extents during deliberations to decide if the moratorium should be overturned in the legislature. Among the more important issues to be considered are the local and regional groundwater systems in the proposed mine area. In particular, the hydrogeologic significance of the Chatham Fault is investigated herein because of the proximity of the deposit to the fault. Initial studies completed by the Marline Corporation and Union Carbide in the 1980s (Lynott 1985) in the south ore deposit began to characterize groundwater flow at Coles Hill, but many questions remained.

At the present time, various options are being investigated for mining the Coles Hill deposit, and these include open pit mining, underground mining, and a combination of open pit and underground mining. The extent to which mining activities at Coles Hill might influence the groundwater system is not completely understood, and in order to predict how groundwater flow might be affected during mining it is critical to first understand the current near-surface groundwater system. In particular, the distribution of groundwater, the abundance, orientation and degree of interconnectivity of fractures, groundwater flow directions, the age of the groundwater and its sources are all critical to developing a robust predictive model for the effect that mining might have on the groundwater system. Of special concern is the role that the Chatham Fault plays in groundwater flow, i.e., does it represent a permeability barrier to groundwater flow or does it represent a conduit for groundwater movement between the crystalline rocks to the west and the metasedimentary rocks to the east. In order to address these issues, a small area located just south of the two ore bodies that includes the Chatham Fault and rocks to either side (referred to henceforth as the “South Spring Study Area”) was investigated to gain a better understanding of how water currently moves in the vicinity of the fault and the nearby ore body.

The purpose of this investigation is to determine the hydrogeologic significance of the Chatham Fault at Coles Hill in order to predict how groundwater flow may be affected during future development of the ore bodies. Although the study is limited to a small area just south of the south ore body, the procedures described herein and the conclusions are thought to be applicable to other parts of the fault in the vicinity of the ore bodies. The results of this study therefore provide a firm foundation for future characterization and assessment of the significance of the Chatham Fault on the hydrogeology of the area surrounding the Coles Hill ore deposit.

Geologic setting

The Coles Hill uranium deposit is located in south-central Virginia between and east of the towns of Chatham and Gretna (Fig. 1) and in the Virginia Piedmont. The Piedmont represents a fault-bounded crustal block that is made up of medium- to-high-grade metaclastic and metaigneous rocks that were later intruded by a variety of plutons (Hibbard et al. 2003; Carter et al. 2006). In the vicinity of Coles Hill, crystalline rocks of the Smith River Allochthon that host the deposit are separated from metasedimentary rocks of the Danville Triassic Basin to the east by the Chatham Fault (Fig. 1), which is a Mesozoic aged northeast striking and southeast dipping (at 60°) normal fault (Henika 1998). Mineralization at Coles Hill occurs exclusively in the crystalline rocks to the west of the Chatham Fault. However, because the Chatham Fault dips to the SE at about 60°, the surface projection of the ore bodies extends well to the east of the Chatham Fault and into the Danville Basin. Thus, if open-pit mining methods are used to extract uranium at Coles Hill, the Chatham Fault would run through the open pit and rocks on both sides of the Chatham Fault will be exposed during mining. Mining activity at the site may therefore affect the groundwater flow in the crystalline Piedmont rocks, the Chatham Fault zone, and in the Danville Triassic Basin.

The Chatham Fault divides the crystalline Piedmont rocks to the west from the Danville Triassic Basin metasedimentary rocks to the east. The Chatham Fault shows two distinct periods of evolution. The fault is thought to have originated as a Paleozoic thrust fault associated with the collision of North America with a large volcanic province that migrated westward (Lineberger 1983; Gates 1997). The Chatham Fault was then reactivated by Post-Alleghenian rifting, forming the current Triassic Danville Basin (Lineberger 1983; Gates 1997). Today, the Chatham Fault is characterized by a silicified breccia and cataclasite zone in the Leatherwood Granite that separates the crystalline rocks of the Smith River Allochthon and Piedmont from the metasedimentary rocks of the Danville Triassic Basin to the east (Henika 1998). The cataclasite is estimated from cores to be approximately 40 m thick, with 1–5 m of noncohesive Chatham Fault gouge forming the boundary between the fault zone and the Triassic basin (Jerden 2001). This fault gouge is made up of an unconsolidated matrix of green and gray clay containing angular pieces of quartz and feldspar (Jerden 2001).

The Danville Basin contains primarily arkosic conglomerates with a siltstone matrix (Thayer 1970); however, these rock types are also interfingered with shales, siltstones, and carbonaceous black mudstones (Thayer 1970; Henika and Thayer 1983). Bedding in the Triassic basin sediments dips northwestward toward the fault plane, at angles that increase to about 40–50° near the fault (Lineberger 1983). The Triassic rocks near the fault contain fractures that are hydraulically open in some cases and sealed by precipitated minerals in others (Jerden

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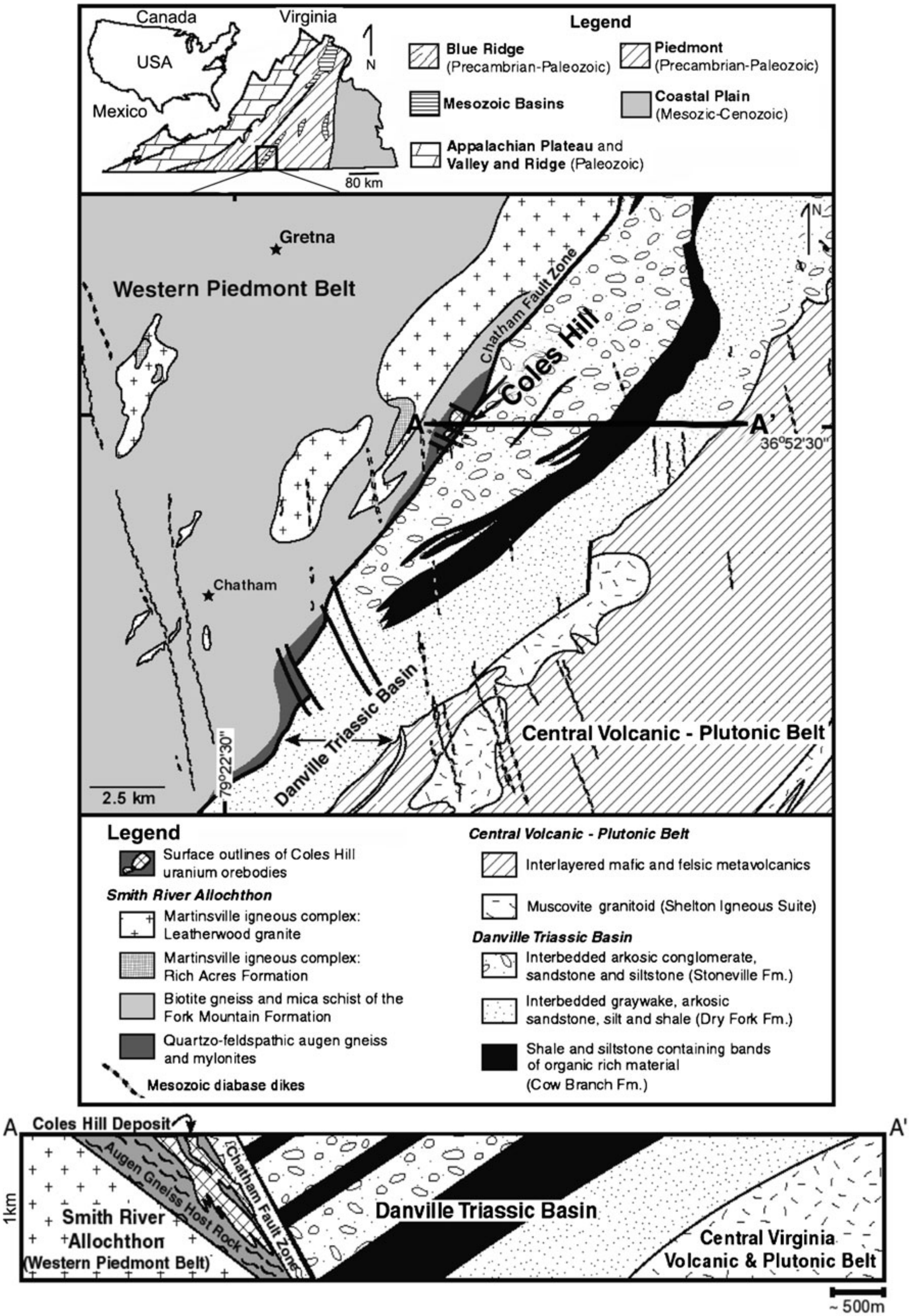

Fig. 1 Location map, geologic map and cross section of the area surrounding the Coles Hill uranium deposit (From Jerden 2001, adapted from Henika 1998)

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2001). The open fractures observed from cores have apertures ranging from 1–10 mm (Jerden 2001) and along with bedding planes, provide the chief pathways for groundwater flow in the Triassic basin.

Hydrogeologic setting

The hydrogeology of the Piedmont is typically described as a simplified two-layered system consisting of a highly heterogeneous regolith overlying a variably fractured crystalline bedrock aquifer (Daniel 1996). The uppermost regolith, or soil zone, supplies water from precipitation to the highly weathered and fractured zone of bedrock referred to as saprolite, which represents the lower regolith (Fig. 2). Shallow groundwater typically occurs in the saprolite except during periods of prolonged drought or during the summer months when evapo-transpiration can exceed precipitation. Below the regolith, water occurs in the less weathered fractures in crystalline bedrock. In general, these fractures tend to decrease in frequency as a function of depth (Daniel 1996). However, significant quantities of groundwater can be attributed to recharge and flow along minimally weathered fractures or joints associated with currently or recently active geologic structures such as faults and lineaments (Seaton and Burbey 2000, 2005).

At Coles Hill the simple two-layered groundwater flow system is modified by the Chatham Fault, which juxtaposes two different rock units with potentially different hydrogeologic characteristics and fracture densities (Fig. 2). Adding additional complexity to the hydrogeologic setting are a number of northwest striking, steeply dipping, cross faults (lineaments) that intersect the Chatham Fault at nearly right angles (Marline Uranium 1983). These cross faults could enhance flow across the Chatham Fault if fractures associated with these faults occur along strike of the fault traces.

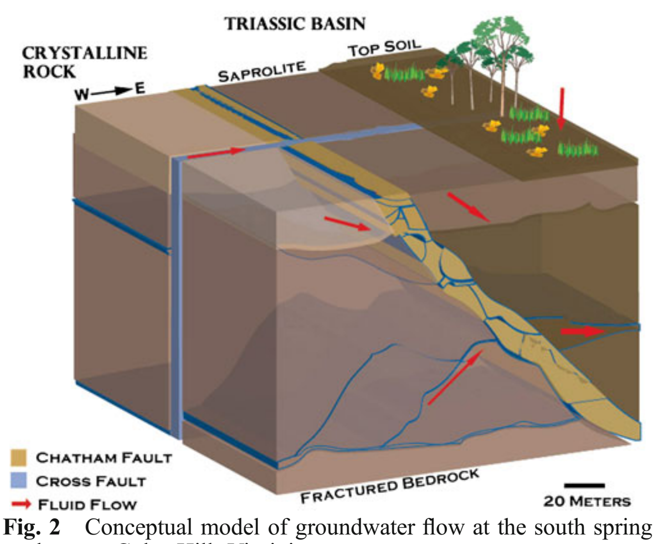

Fig. 2 Conceptual model of groundwater flow at the south spring study area, Coles Hill, Virginia

A basic pumping test was conducted by Marline Uranium, Inc. (Gibbs & Hill, Inc, consulting report, unpublished data, 1985), but the results did not provide sufficient evidence to characterize any of the individual hydrogeologic units of the area. The test was performed using wells that intersected the Chatham fault, the Triassic basin, and the Leatherwood Granite in the region between the two ore bodies (about 200 m NE of the current study area). These wells (which no longer exist) were cased through the saprolite but no effort was made to isolate the different rock types from one another to analyze their differing responses to pumping (Gibbs & Hill, Inc, consulting report, unpublished data, 1985). Because the Chatham Fault, Leatherwood Granite, and Triassic basin rocks present in the wells were not isolated, and because only a basic Theis analysis was performed on the data, the transmissivity calculated from the pumping test provided little information about the hydraulic properties of these separate units or of the area as a whole. The only transmissivity values provided were for wells in the Triassic basin (see the following discussion on aquifer testing and Tables 1 and 2).

A number of methods were employed to quantify the hydrogeological characteristics of the Chatham Fault and to gain a better understanding of the role the fault plays in the current groundwater flow system in the vicinity of the Coles Hill deposit. The main question addressed in this study was what effect, if any, the Chatham Fault has on the quantity, chemistry, and direction of groundwater flow near the ore body. This information is needed to predict the extent to which the Chatham Fault might affect the local groundwater system in the future if the deposit is mined.

Methods and results

Electrical resistivity profiling

Electrical resistivity profiling was used to locate areas of potential fluid saturation (Seaton and Burbey 2002). Data were collected and processed using an AGI SuperSting 8-channel resistivity imaging system. The type of survey configuration utilized in this study was dipole-dipole. The dipole-dipole method was chosen due to its depth of penetration (20% of profile length) and ability to resolve fluid-filled vertically oriented fractures (Seaton and Burbey 2002). These characteristics make the dipole-dipole method favorable for a fractured rock environment such as occurs at Coles Hill.

Data collected with the 64 electrode AGI SuperSting were inverted using Loke's RES2DINV (Loke 2006) to obtain a resistivity value, which invokes a smoothness-constrained least-squares inversion technique to estimate resistivity values. A 10-m spacing between electrodes was used for all resistivity profiles (640-m total profile length). However, because of large spatial variations in near-surface resistivity values, electrode spacing was halved for some of the profiles (for example, COL12) to provide greater near-surface resolution.

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Table 1 Well information used in this investigation (see Fig. 3)

Well name	Total depth (m)	Casing depth (m)	Hydraulic fractures (m below LS)	LS elevation (m ASL)	Initial hydraulic head (m ASL)
Johns1	80	10	14, 61–67	188.15	a
Johns2	183	14.2	53, 91	188.98	176.85
Johns3	12	None	Saprolite	188.98	b
Cow1	183	12	50, 72	185.93	176.41
VAUTrail	80	11.8	45–53, 55	181.36	175.09

NA not available, *LS* land surface, *ASL* above sea level

[a] Casing not sealed in bedrock. Head reflects saprolite, not bedrock aquifer

[b] Well open only to saprolite, no bedrock head value available

A spring emanating adjacent to the Chatham Fault south of the ore body was considered to be an ideal location to investigate the hydrologic nature of the fault and adjacent geologic units for reasons outlined in the following. The spring is located along a local topographic high 5–15 m to the west of the Chatham Fault, in a depression west of Coles Road, near the projected intersection of the Chatham Fault with one of the cross faults identified previously by Marline, Inc. (Fig. 3; identified as TrailSpr). Three existing wells are located within 100 m of the spring (Fig. 3, Table 1). One of the wells is located in the Leatherwood Granite, west of Coles Road (Johns1, 80 m deep), a second well is located east of Coles Road, north-east from Johns1 and east of the fault in the Triassic Basin (VAUTrail, 80 m deep), and the third is an unnamed dug well 13.6 m deep on the west side of the Chatham fault (in the crystalline rocks) and in close proximity to Johns1, west of Coles Road ('Dug well' in Fig. 3). The concentration of wells and a spring at the site made it a favorable area for conducting resistivity surveys to provide some corroboration of data by comparing the resistivity profiles over these existing wells with borehole logs obtained from the available wells (discussed in the next section). Low resistivity regions in the profiles (<100 ohm-m) may be indicative of either fluid-filled structures (faults or fracture networks) or clay-rich fault gouge. Geophysical logs and the many drill cores extracted from the area do not reveal fault gouge. Thus, the low resistivity regions along the profiles (Fig. 4) are more likely related to fluid saturation.

Resistivity survey COL13 (line A–A', Fig. 3) was oriented to cross the Chatham Fault in order to investigate the potential fluid saturation of the fault zone. After processing, the survey indicated a region of low resistivity associated with the Chatham Fault (Fig. 4). Near the surface, the Coles Hill site is highly heterogeneous (Fig. 4). The low resistivity region associated with the fault was also observed in other resistivity surveys conducted throughout the site (COL12, COL15, Fig. 4), suggesting the fault remains both structurally and hydraulically consistent throughout the study area.

Based on the resistivity profiles obtained at the south spring area, the optimal locations for two additional wells were chosen. Originally, one well was to be located on the cross fault in the study area, but due to drill hole location restrictions, this was not possible. Instead, a well was drilled 10 m west of the spring (Johns2; Fig. 3) in an attempt to intercept fractures related to the fault. The second new well (Cow1; Fig. 3) was sited to intersect the Chatham Fault near its intersection with a local cross fault (Fig. 3) in order to evaluate the hydrogeologic nature of the Chatham Fault near cross faults, which are common in the Coles Hill area; however, restrictions to where the well could be placed may have precluded interception of the cross fault. COL14 (Fig. 4) reveals a resistivity transition in the vicinity of the cross fault in this area, which may be indicative of increased fluid content, particularly at depths greater than 75 m.

Geophysical well logging

Geophysical well logging was performed in four wells at the south spring area (VAUTrail, Johns1, Johns2, Cow1; Figs. 3, 5a and b, Table 1) to locate and further characterize low resistivity zones that have been interpreted to be zones with abundant fluid-filled fractures. A

Table 2 Pumping test results for wells Cow1_lower and Johns2 for pumping well VAUTrail pumped at 6.3×10^{-4} m^3/s (10 gpm) for 24 h

Pumping well	Obs. well	Dist. (m)	Total drawdown pumped well (m)	Total drawdown obs. well (m)	T (m^2/s)	*S*	*n*
VAUTrail	Cow1_upper	65.5	11.35	.45	1×10^{-4}	3.98×10^{-4}	2.18
VAUTrail	Johns2	176.8	11.35	.3	3.98×10^{-5}	1.05×10^{-4}	2.24
Gibbs & Hill, Inc. (1985) test wells no longer exist		18	47	.88	2.6×10^{-5} to 1.3×10^{-4}	ND	2[a]

ND not determined, *T* transmissivity, *S* storativity, *n* flow dimension, *Dist.* distance between pumping well and observation well

[a] *n* was not determined but is inherent in the Theis method used in this study

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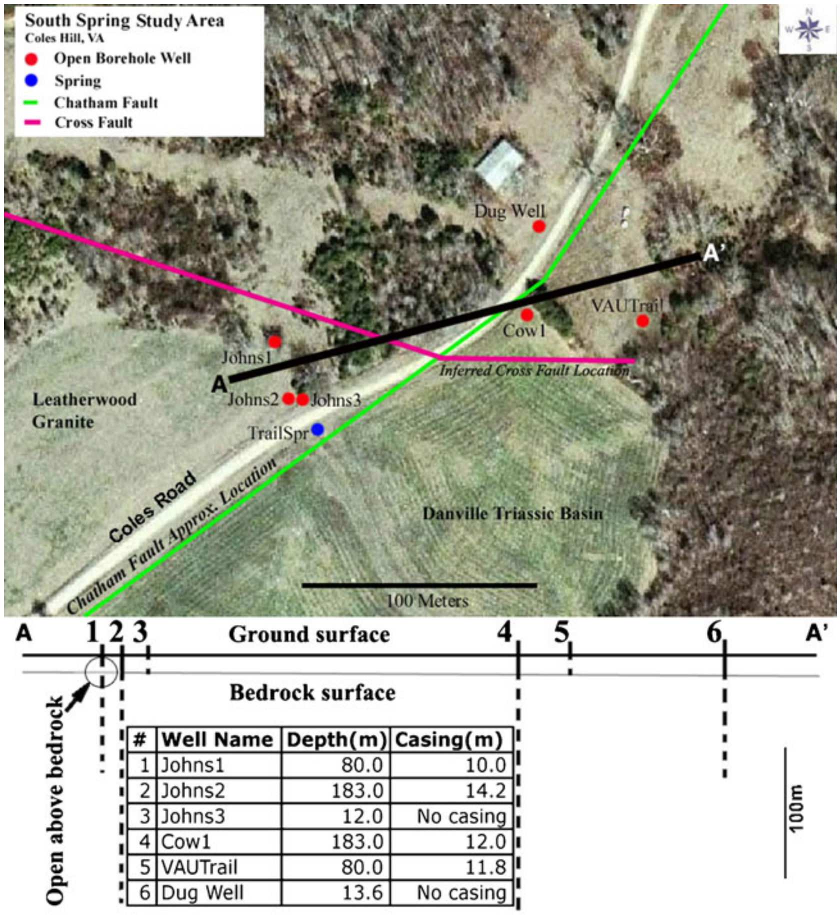

#	Well Name	Depth(m)	Casing(m)
1	Johns1	80.0	10.0
2	Johns2	183.0	14.2
3	Johns3	12.0	No casing
4	Cow1	183.0	12.0
5	VAUTrail	80.0	11.8
6	Dug Well	13.6	No casing

Fig. 3 Well and spring locations at the south spring study area. Wells logged include VAUTrail, Cow1, Johns1 and Johns2. Also shown is the location of spring *TrailSpr*, the inferred location of a nearby cross fault, and the location of electrical resistivity profile A–A' shown in Fig. 4

suite of well logs was obtained using the Mount Sopris MGX II logging system and included caliper, spontaneous potential, fluid resistivity and temperature, short and long normal resistivity, single point resistance, heat pulse flowmeter, natural gamma radiation, and optical televiewer logs. A detailed description and use of these tools for physical characterization is found in Hearst et al. (2000).

The VAUTrail well is located entirely in the Danville Triassic Basin 65 m east of the surface projection of the Chatham Fault, which approximately follows Coles Road in the south study area. While the VAUTrail well is close to and east of the eastward dipping Chatham Fault, there is no evidence from the well logs (Fig. 5b) that the well intersects the Chatham Fault at depth. The geometry of the fault would suggest it passes beneath the VAUTrail well location at a depth of approximately 112 m. The logs from the well do, however, reveal the presence of a fracture producing significant flow as indicated by the heat pulse flowmeter. This prominent fracture occurs at a depth of 55 m where inflow during both ambient and pumping conditions was significant. At this depth the 8-inch normal resistivity log shows a dramatic decrease in measured resistivity (Fig. 5b), while the caliper log shows a fracture (the drilled borehole diameter is 15.24 cm). The optical televiewer log shows a 1.2-m-long steeply dipping fracture trending slightly E–NE to slightly W–SW, approximately orthogonal to the Chatham Fault. The dip of the fracture is calculated to be 83° from the optical televiewer log. A small amount of outflow occurs during pumping at a depth between 53 and 45 m, suggesting the presence of a fracture of lower transmissivity here, with a lower hydraulic head than the main fracture at 55 m (Fig. 5b).

Johns1 is located in the Leatherwood Granite ~50 m west of the Chatham Fault (Fig. 3). The logs from Johns1 (Fig. 5b) corroborate the resistivity profile that was obtained approximately 10 m to the south of this well, which shows it to be a minimally fractured granitic rock.

Johns2 is located 10–15 m closer to the Chatham Fault than Johns1 (Fig. 3) and intersects a low electrical resistivity zone (COL13; Fig. 4). The geophysical logs indicate few fractures, some of which have minimal flow associated with them (Fig. 5a). Total production from the well bore is less than 2 L/min and the production zones are fractures located at depths of 53 and 91 m according to the heat-pulse flowmeter log (as a small amount of inflow was observed coming into the borehole at these depths during pumping conditions). The caliper log also shows a fracture zone at a depth between 91 and 98 m and this also represents a zone of

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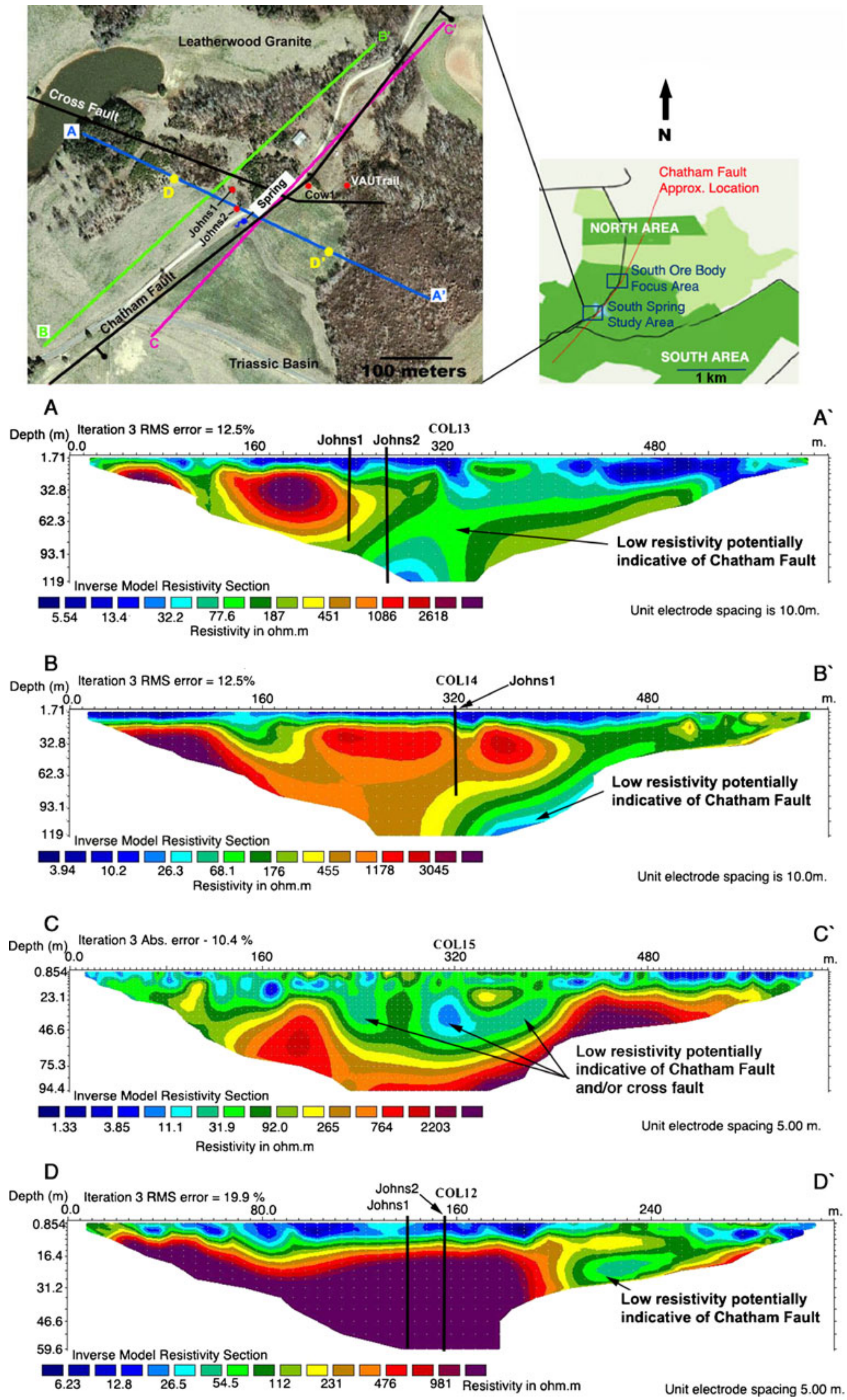

Fig. 4 Locations and profiles of South Spring Study Area resistivity transects

low resistivity in the log suggesting that this is likely the most significant fracture intersecting the borehole. A small amount of outflow was observed at a depth of 22 m (Fig. 5a). No ambient flow was detected in this well. The flowmeter log was terminated at 150 m because of a lack of evidence of fractures below this depth.

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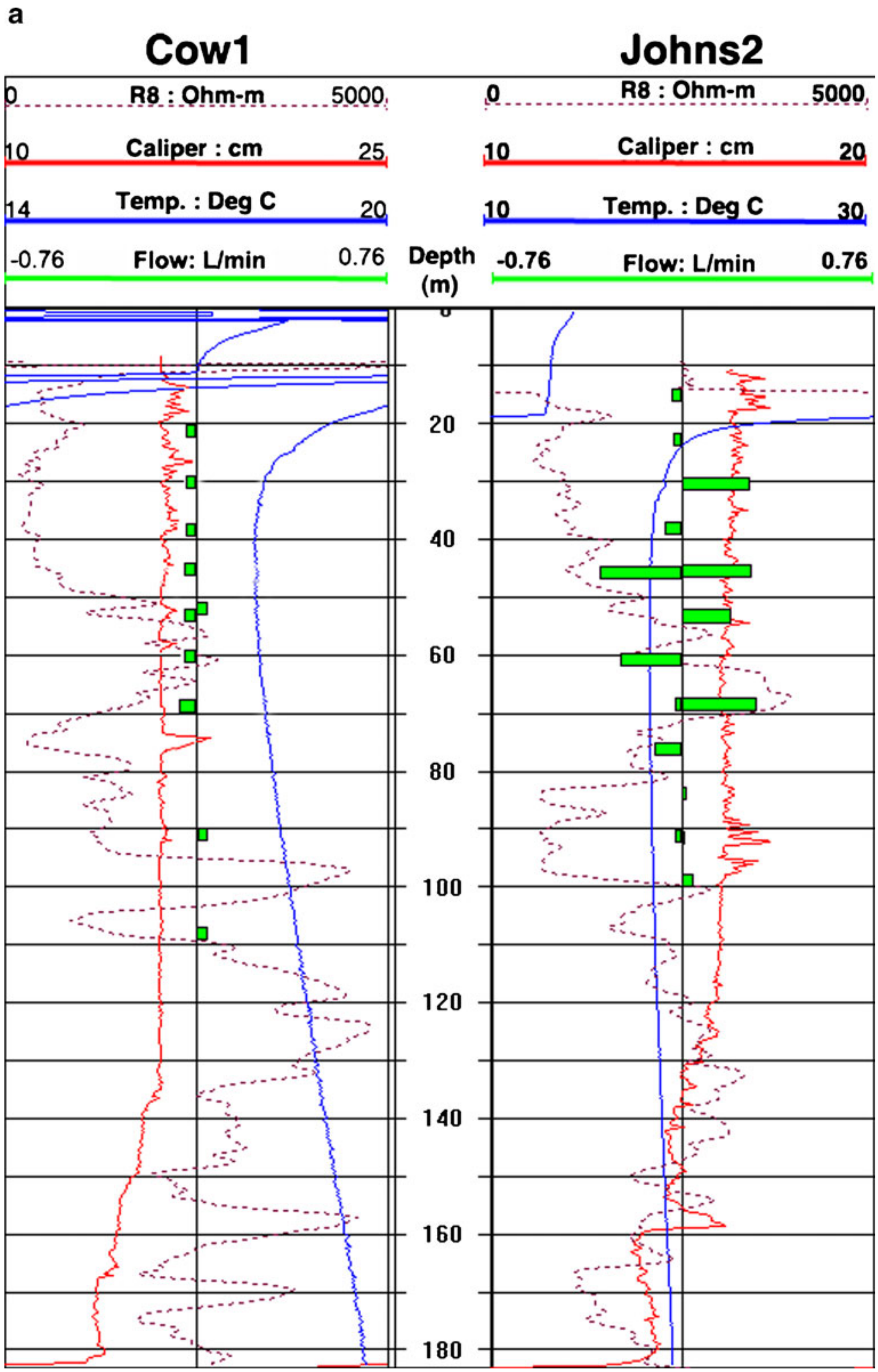

Fig. 5 Eight-inch normal resistivity, fluid temperature, caliper, and heat pulse flow meter logs for **a** Cow1 and Johns2 wells, and **b** VAUTrail and Johns1 wells. Also shown on **b** is an optical televiewer image of the wall at a depth of about 55–56 m that is associated with high fluid flow rates

Cow1 is located 5–10 m east of the Chatham Fault and east of Coles Road and is collared in Triassic metasediments (Fig. 3). At depths between 10 and 30 m, the caliper, optical televiewer, resistivity, fluid temperature, and heat pulse flowmeter logs all indicate a highly fractured zone with some flow (Fig. 5). This zone was further confirmed to be the Chatham Fault after analysis of cuttings from the drilling process (W.

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Henika, Virginia Tech, personal communication, 2009). Below a depth of 30 m, the well passes into Leatherwood Granite similar to that observed in Johns1 and Johns2. The logs confirm the presence of few fractures with small amounts of flow (Fig. 5a). The largest fracture encountered with the caliper log is at 73–75 m. This coincides with a zone of low resistivity. A very small amount of inflow occurred during pumping at depths of 95 and 57 m, while outflow occurred at 72 and 50 m. No flow was observed during ambient conditions. It appears that the most significant hydraulically connected fracture below the Chatham Fault in the Leatherwood granite occurs between the depths of 73 and 75 m in the Cow1 well, but the transmissivity of this fracture is very low based on the heat pulse flowmeter log.

The interchanging zones of inflow and outflow observed in these data are evidence that a complicated head relation exists between the measured zones. Additionally, the small amounts of flow observed indicate low transmissivity in all measured zones.

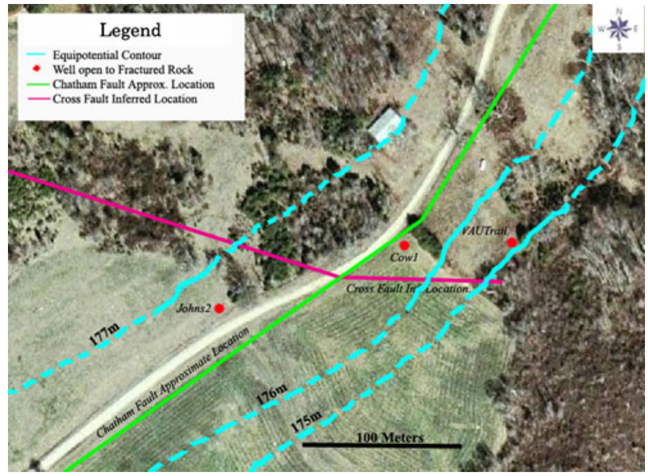

Fig. 6 Inferred composite potentiometric surface of fractured rock aquifer at the south spring area of Coles Hill

Water levels

Static water levels were recorded for a number of wells (Table 1) and for the spring at the south spring area to evaluate the natural hydraulic gradient of the area. The measured composite hydraulic heads from the available wells suggest that the gradient is very low but trending from west to east towards the Triassic basin. On the west side of the fault in the Leatherwood Granite, static water levels were measured in Johns2 and Johns3. Johns2 is cased through the saprolite and only open to fractures in the granite while Johns3 is an open borehole, which is drilled only to the top of bedrock at a depth of 12 m. The water level in Johns 2 is 7.7 m lower than the water level in Johns 3. The water level in Johns3 is lower than Trail Spring, which suggests that the spring is not sourced from the saprolite at this location. If there is a connection between the bedrock and saprolite, the hydraulic gradient is downward toward the fractured-rock aquifer. The Cow1 well intersects the Chatham Fault zone, and also has a water level 6.39 m below that of the spring. The VAUTrail well in the Triassic basin has a water level 1.32 m lower than that of the Cow1, which intersects the Chatham Fault. Figure 6 is a composite estimated potentiometric surface for the deep fractured rock aquifer at the site. A composite head distribution is used because flowmeter logs suggest that the heads at each well site are complex. These composite heads suggest that the deep fractured aquifer is not a source of water to the spring.

Pumping test

A pumping test was performed at the VAUTrail well (Fig. 6) to test for fracture connectivity between this well and observation wells Cow1 and Johns2 (Fig. 6), and to estimate the hydraulic properties of any connected fractures by observing the time-drawdown response at these two observation wells. The VAUTrail well was pumped for a period of 24 h at a rate of 38.75 L/min. Cow1 is located 65.5 m from VAUTrail (Fig. 6) and extends through the fault zone into the underlying Leatherwood Granite. A packer was placed at the transition between the Chatham Fault material and the underlying granite at a depth of 32.9 m below land surface in order to monitor water levels in each zone independently. The upper zone located in the Chatham Fault is referred to henceforth as Cow1_upper, while the lower zone located in the Leatherwood granite is referred to as Cow1_lower. After equilibration of the heads in each zone, transducers were installed to monitor both zones during the pumping test. Johns2 is located 176.8 m from VAUTrail (Fig. 6) and was monitored with a transducer. All transducers collected water-level data at 1-min increments during the 24-h test.

At the end of the 24-h pumping test, the resulting total drawdowns were recorded in the wells (Table 2). Figure 7 shows the results of the pumping test from these two wells. The head in the Chatham Fault in Cow1_upper began responding to pumping after about 37 min, while the head in the more distant granitic rocks of Johns2 began responding after 110 min of pumping (Fig. 7). The transducer in Cow1_lower failed and no data were collected at this site.

Transmissivity and storativity are calculated (Table 2) using the time-drawdown response for both wells using the Barker method (Barker 1988). The assumptions of the Barker method include scale-dependant permeability and storativity in heterogeneous (fractured) rocks. These assumptions describe the Coles Hill site better than those assuming scale independent parameters, which are unrealistic in the fractured and faulted environment of this site. In accordance with the Barker method, the responses of the two wells are fitted to various types of curves describing flow in an n-dimensional sphere where $1<n<3$

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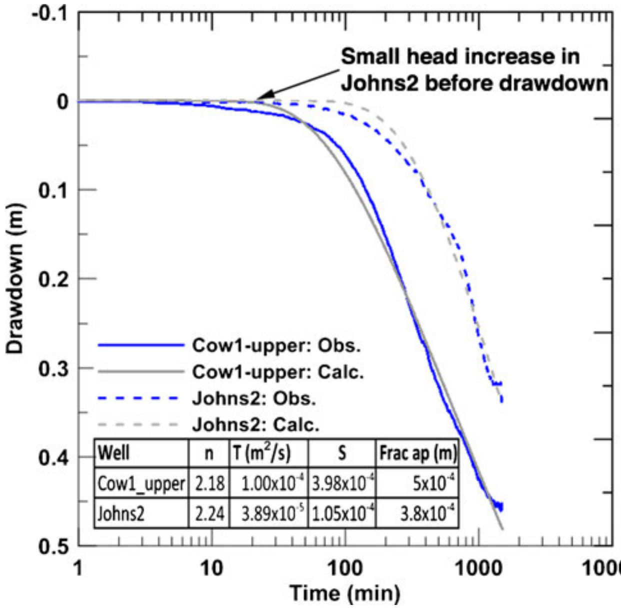

Fig. 7 Pumping test results and analytical solution calculations at Cow1_upper and Johns2 in response to pumping VAUTrail. *T* transmissivity, *S* storage coefficient, *Frac ap* fracture aperture

(Barker 1988). The analytical solution for the drawdown according to the Barker method as presented by Le Borgne et al. (2004), is:

$$s(r,t) = h_o(r)\Gamma\left(\frac{n}{2} - 1, \frac{t_c(r)}{t}\right) \tag{1}$$

where Γ is the (complementary) incomplete gamma function given by

$$\Gamma(v,u) = \int_u^\infty e^{-t} t^{v-1} dt, \tag{2}$$

and where *s(r,t)* is the drawdown at distance *r* and time *t*. The characteristic time t_c and characteristic amplitude h_o are used to calculate the transmissivity (*T*) and storativity (*S*) as follows:

$$t_c = \frac{Sr^2}{4T} \tag{3}$$

$$h_o = \frac{Qr^{2-n}}{4\pi^{\frac{n}{2}} T}. \tag{4}$$

Characteristic time is the time elapsed from the start of the pump test to the inflection point of the drawdown curve (Le Borgne et al. 2004).

Curve matching of the Cow1_upper and Johns2 water-level responses from pumping were fit using Eqs. 3 and 4 and the resulting parameter calculations are displayed in Table 2. The calculated transmissivity values are nearly identical to those calculated by Gibbs & Hill (consulting report, unpublished data 1985) for an area within the Triassic basin and 200 m north of the study site. The *n* values for both Johns2 and Cow1_Upper are close to 2.0, which would be equivalent to a Theis-type cylindrical flow system. The Theis method was used to evaluate transmissivity in the earlier tests by Gibbs & Hill (consulting report, unpublished data 1985). The transmissivity values of the two wells in this investigation lead to calculated hydraulic fracture apertures of 5×10^{-4} m and 3.8×10^{-4} m for Cow1_upper and Johns2, respectively (Singhal and Gupta 2010).

The pumping test results suggest that Johns2 is drilled into a somewhat less transmissive zone with lower available storage than the upper portion of the Cow1 well. This interpretation is supported by observation of the Mandel-Cryer effect, which is observed as a slight increase in hydraulic head in Johns2 just before the decrease in head level associated with the pumping test drawdown (Gibson et al. 1963; Verruijt 1969; Wang 2000; Fig. 7), This effect is associated with fractures exhibiting low transmissivity and storativity. Pumping at VAUTrail caused a contraction of the fracture. Strain compatibility requires that a pore pressure buildup occurs at the leading edge of the pressure wave extending outward from the pumping well. A buildup in pore pressure is therefore observed at Johns2 prior to a decrease in pressure. The large duration of this effect (between 20 and 100 min after the start of pumping) implies that the fracture probably has an aperture of microns or perhaps 10's of microns, which is inferred based on the long duration for pore pressures to dissipate to static levels. The aperture suggested by the observation of the Mandel-Cryer effect is not in agreement with the aperture calculated from the pumping test results. This discrepancy is addressed in the forthcoming Discussion section. The estimated transmissivity and storativity from the Barker method along with the drawdown response suggests a very low-density fracture system with small apertures connecting wells VAUTrail, Johns2, and the upper section of Cow1.

Water chemistry and age dating

Water samples were collected from VAUTrail, Johns2, and Cow1. Cow1 was packed off and sampled in the Chatham Fault zone and in the underlying granitic rocks. These samples were analyzed for field parameters, major cations and anions (Fig. 8), and dissolved gases, to determine recharge temperatures, and chlorofluorocarbons (CFCs) and sulfur hexafluoride (SF_6) concentrations, and tritium-helium ratios ($^3H/^3He$) as environmental tracers (Table 3; Figs. 9, 10, 11). Samples were collected by members of the US Geological Survey Virginia Water Resources Center and with methods adhering to the standards set forth at USGS (2009).

Major ion chemistry from all the well sites reflects a calcium–magnesium bicarbonate dominated groundwater. Piper plots of the ion chemistry suggest the wells all have

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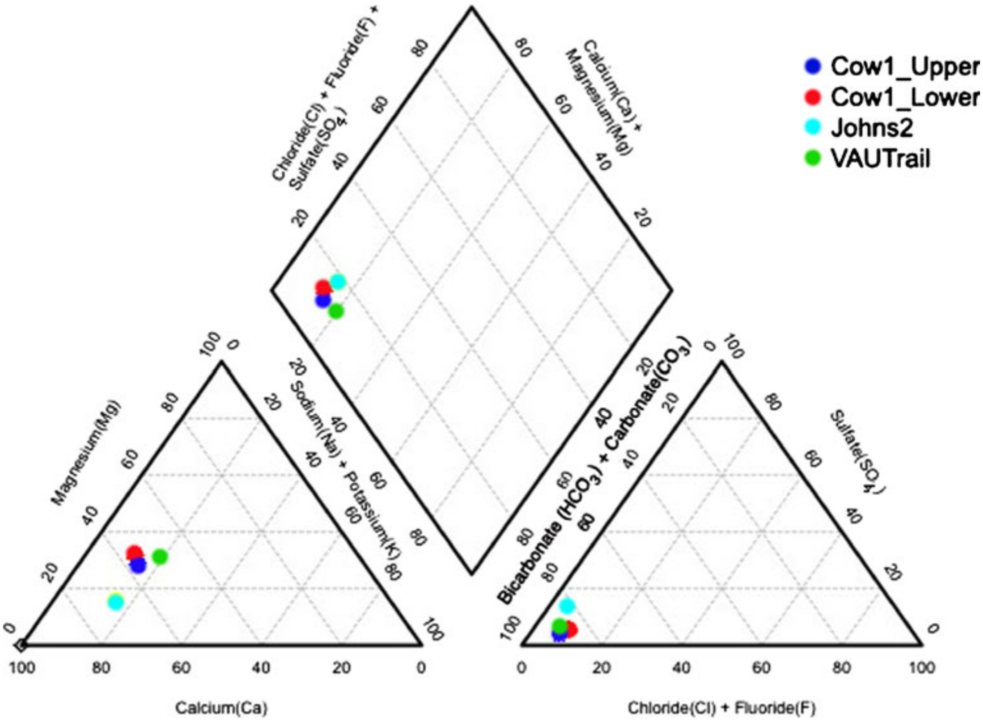

Fig. 8 Piper plot of water chemistry data from sampled wells at Coles Hill

Table 3 Water chemistry and field parameters for wells sampled at Coles Hill. The samples from Cow1_Upper were deemed to be contaminated (from a gas leak in a packer) and were not included in the analyses. *pptv* parts per trillion per volume

Sample name	Temp °C	pH	DO (mg/L)	Alk mg/L $CaCO_3$	N_2 (mg/L)	Ar (mg/L)	Recharge Temp (°C)
VAUTrail	15.2	7.6	1.3	199	24.35	0.8007	8.3
Cow1 Lower	15.5	7.5	2.3	137	23.01	0.7026	15.2
Cow1 Upper	16.0	7.0	0.8	109	0.00	0.0000	-
Johns2	15.3	7.4	4.8	128	20.63	0.6804	14.9
Anion analysis	(mg/L in solution)						
Sample name	F	Cl	Br	NO_3–N	SO_4		
VAUTrail	0.0448	10.1631	0.183		10.3994		
Cow1 Lower	0.2533	7.2636	0.4932	0.0401	7.3794		
Cow1 Upper	0.2108	5.955	0.06	0.4419	4.2305		
Johns2	0.1614	3.8827	0.0603	0.3544	19.91		
Cation analysis	(mg/L in solution)						
Sample name	Ca	K	Mg	Mn	Na	Si	Sr
VAUTrail	46.367	2.825	17.274	0.043	17.606	23.247	0.596
Cow1 Lower	37.742	1.122	11.886	0.087	9.291	21.931	0.398
Cow1 Upper	29.392	1.029	8.538	0.255	7.769	16.437	0.171
Johns2	43.269	1.322	6.177	0.078	9.396	24.905	0.299
Dating	Tritium		Tritium, error	^{4}He	Ne	%He	
Sample name	^{3}H_pCi/L	^{3}H_TU	^{3}H_pCi/L	^{3}H_TU	(10^{-8} ccSTP)	(10^{-8} ccSTP/g)	Terrigenic
VAUTrail	6.4	2	0.45	0.1	188.63	35.44	95.22
Cow1 Lower	19.5	6.1	0.7	0.2	6.39	22.62	13.31
Cow1 Upper	20.6	6.4	0.76	0.2			
Johns2	14.1	4.4	0.57	0.2	6.59	23.7	11.29
			CFC–11	CFC-12	CFC-113	SF_6	
Sample name	D^3He (uncor)	(+/– 1stdev(%))	pptv	pptv	pptv	pptv	
VAUTrail	–57.52	3.5	5.3	2	1.6	0.07	
Johns2	–2.44	0.28	72.7	281.3	34	11.41	
Cow1_lower	13.85	0.3	59.8	187.5	24.6	3.00	
Apparent piston flow age (years)							
Sample name	CFC-11	CFC-12	CFC-113	SF_6			
VAUTrail	53.4	63.9	48.9	48.90			
Johns2	37.9	31.9	26.4	16.40			
Cow1_lower	39.4	36.4	28.9	-			

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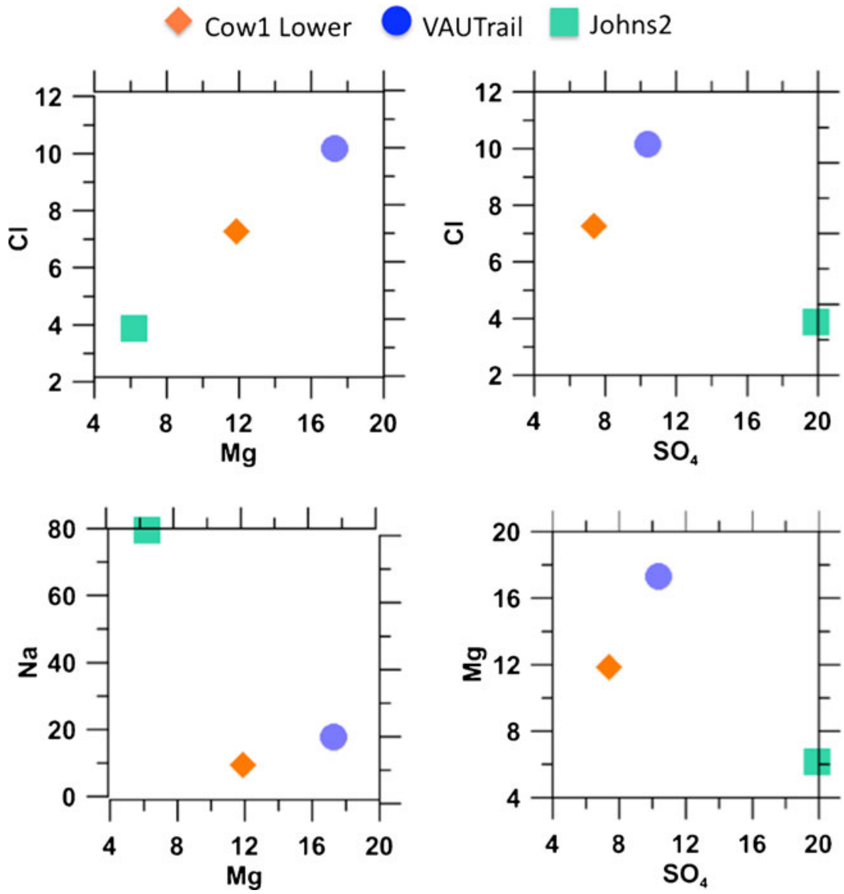

Fig. 9 Ion-ion plots of water chemistry data from sampled wells at Coles Hill. Values provided in mm/L

similar chemistry (Fig. 8). However, several ion-ion plots produced from the chemistry data appear to show that Johns2 differs somewhat from Cow1_lower and VAUTrail (Fig. 9) in that Johns2 contains more Na and SO_4 ions, and less Mg and Cl ions. CFC and SF_6 concentrations were measured to determine a recharge date for the water

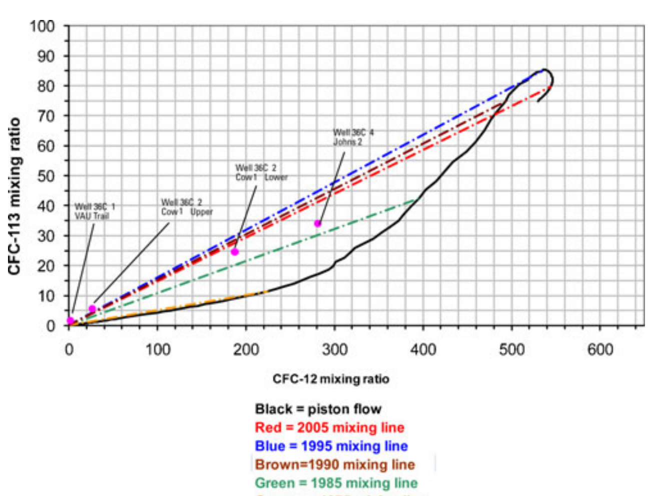

Fig. 10 Mixing ratios of Coles Hill samples plotted against piston flow and mixing lines for pre-CFC water and different years (D.L. Nelms, US Geological Survey, personal communication, 2009)

samples (Cook and Herczeg 2000; Cook and Solomon 1997; Busenberg and Plummer 2000).

After recharge enters the fractured-rock aquifer system, groundwater ages can be estimated using a mixing model (Cook and Herczeg 2000; Plummer et al. 2003) in which groundwater of one age containing a certain CFC concentration is mixing with older water, recharged before the CFCs were present in the atmosphere, that is pre-1950s water (Plummer et al. 2003). In the binary mixing model used in this investigation, which compares CFC-12 to CFC-113 (Fig. 10), the age of the water containing CFCs can be determined by plotting two of the tracers against one another (Plummer et al. 2003). A data point falling on the solid black line would be indicative of piston flow, where groundwater of only one age is present in the sample, whereas water compositions falling on any of the colored lines would be indicative of the presence of water of that corresponding line's age along with pre CFC water (Plummer et al. 2001). The position of the point on this line along the abscissa indicates the percentage of young post-CFC water present in the mixture (Plummer et al. 2003). A point plotted exactly half way along one of the mixing lines would therefore contain 50% water from the date of the mixing line and 50% pre-CFC water (Plummer et al. 2003).

The samples from the fault zone (Cow1_upper) were found to be contaminated and degassed due to a packer leak (D.L. Nelms, US Geological Survey, personal

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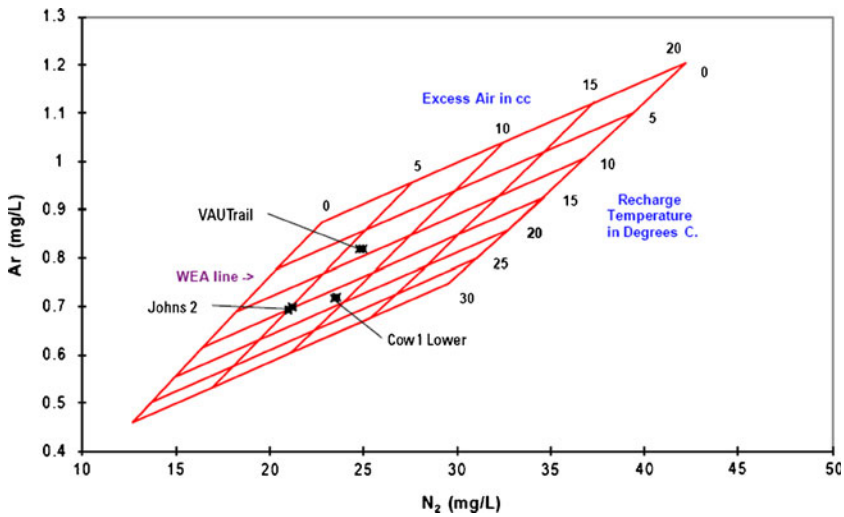

Fig. 11 Plot of N_2 vs. Ar, gas concentrations normalized to sea level for Coles Hill (D.L. Nelms, US Geological Survey, personal communication, 2009)

communication, 2009). The CFC concentrations in the VAUTrail well indicate that it contains very little modern water (Fig. 10). In addition, VAUTrail contains very low SF_6 and tritium concentrations, while beyond the limits of the method for SF_6, and the water appears to be at the very old end of the young water spectrum (D.L. Nelms, US Geological Survey, personal communication, 2009). Cow1_lower and Johns2, both located in the Piedmont crystalline rocks, show signs of young and old water mixing (Fig. 10). Cow1_lower appears to contain 42% water dated at 21.9 years, while Johns2 was calculated to contain 70% water dated to 23.4 years. If the Chatham Fault zone provides pathways to deeper, older fracture networks, the lower content of young water in Cow1_lower may be explained by its proximity to the Chatham Fault zone. Both samples from the Piedmont crystalline rocks have anomalous SF_6 concentrations that may be explained by a terrigenic SF_6 source (D.L. Nelms, US Geological Survey, personal communication, 2009).

$^3H/^3He$ ratios were also examined in order to further validate the dates calculated from the CFC data (Table 3). This method utilizes the radioactive decay of ^3H to ^3He to calculate the age of the groundwater sampled. When H decay occurs in an environment open to the atmosphere such as the unsaturated zone, ^3He is lost to the atmosphere (Cook and Solomon 1997). However, once isolated from the atmosphere, the concentration of ^3He in groundwater will begin to increase (Cook and Solomon 1997). It is by examining the ratio of ^3H to ^3He that dating of this groundwater is possible. Using this ratio, the age of the groundwater is defined as

$$t = \lambda^{-1}\ln\left(^3\mathrm{He}*/^3\mathrm{H}+1\right)$$

where t is the age of the groundwater, λ is the decay constant of ^3H, and ^3H and $^3He^*$ are measured in tritium units (TU; Cook and Solomon 1997). TU for ^3H is representative of one tritium atom in 10^{18} atoms of hydrogen and for ^3He is approximately 0.402 pcm/kg (Cook and Solomon 1997). ^3He can also be present as a result of processes other than radioactive decay of ^3H (Cook and Solomon 1997). At Coles Hill large amounts of terrigenic ^4He were detected and were accounted for in calculations. The utilization of $^3H/^3He$ led to ages of 16.9 +/– 0.5 years for Cow1_lower and 7.1 +/− 0.6 years for Johns2 (Table 3). Extremely high terrigenic ^4He prohibited dating of the VAUTrail well, but even taking into consideration the large amount of terrigenic ^4He, the water from VAUTrail appears to be much older than the water in the other two wells. The older calculated ages from the CFC data are indicative of degradation of the CFCs and illustrate the importance of using multiple dating techniques (D.L. Nelms, US Geological Survey, personal communication, 2010).

The water chemistry results show that Johns2 and Cow1_lower contain water of similar age. The VAUTrail well samples, however, appear to contain a larger old water component and have higher alkalinity and lower dissolved oxygen (DO). Recharge temperatures were also calculated for these samples by plotting N_2 and Ar concentrations (Fig. 11; Plummer et al. 2001; D.L. Nelms, US Geological Survey, personal communication, 2009). The VAUTrail sample is shown to have a lower recharge temperature than the samples from Cow1_lower and Johns2. According to the age dating results, dissolved oxygen (DO), alkalinity, and estimated recharge temperature, the water from VAUTrail may not be sourced in the granitic rocks. However, the Piper plot and ion-ion plot (Figs. 8 and 9), suggest that the Cow1_lower water is a mixture of water from multiple sources.

Discussion

Quantity of groundwater flow across the Chatham Fault

Evidence for fluid-filled fractures in the Chatham Fault and adjacent rocks was provided by electrical resistivity profiles conducted over the site (Fig. 4), and by the

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geophysical well logs of the wells at the south spring study area (Fig. 5). Fracture apertures are generally found to be small (<1 cm) with the exception of one large fracture in the VAUTrail well east of the fault zone, which appears to have an aperture of 2–3 cm. The generally small apertures and very low fracture density of rocks on both sides of the Chatham Fault suggest that only small quantities of groundwater flow are available to flow across the fault and through the area in general. This conclusion is confirmed by heat-pulse flowmeter logs and aquifer testing.

The low hydraulic gradient coupled with the overall small number of conductive fractures observed at the site is another indication of the likelihood for only small amounts of flow through the bedrock in the study area. The low transmissivity and storativity observed from the pumping test confirms that while some fractures are hydraulically connected, the quantity of water moving through the system is small. The observation of a prolonged Mandel-Cryer effect in Johns 2, a strain induced rise in head level prior to traditional water-level declines from pumping, is further evidence of a weakly connected system with small quantities of flow and low hydraulic diffusivity. Finally, the calculated differences in fracture apertures between the observed long-term (>10 min) Mandel-Cryer effect and from the pumping test may imply that the fault is acting as a barrier to flow by causing pumping-induced strain along the fault well in advance of the hydraulic pore-pressure response. The difference in calculated apertures is too large to be attributed to a difference in hydraulic and mechanical aperture (Renshaw 1995). Additionally, a Mandel Cryer effect is not seen in the Cow1_upper well, despite its apparent similarly sized aperture. These findings suggest that significant quantities of flow would not be encountered at Coles Hill during mine development and that minimal flow across the Chatham Fault would occur. If sustained flows of up to 0.15 m^3/m are encountered, they may be isolated in the vicinity of the cross faults.

Chemistry of groundwater

The age dating performed on samples from the study area revealed an age difference between the groundwaters on either side of the fault. CFC, SF6 and $^3H/^3He$ age dating shows that water from the VAUTrail well, located in the Triassic basin, contains a higher percentage of old (pre-CFC) water than water from the crystalline rocks to the west of the Chatham Fault. Recharge temperature determined from N_2 and Ar concentrations, as well as differences in dissolved oxygen and alkalinity, further differentiates groundwater from the granitic rocks and that from the Triassic basin.

The apparent distinction of groundwater from the west and east sides of the fault is complicated, however, by the ion chemistry of the samples from wells. Piper and ion-ion plots (Figs. 8 and 9) suggest that the groundwaters from the Cow1_lower and VAUTrail locations are similar. Furthermore, Cow1_lower contains a percentage of old water that is between the percentages found in VAUTrail and Johns2 wells.

These results, along with the fact that the VAUTrail well contains a high amount of terrigenic helium, suggest that the source of water for this well may be from a source in the crystalline rocks at greater depth instead of from the Triassic basin to the east. The VAUTrail well is in the Triassic basin and the hydraulically active fracture intersecting this well at a depth of 55 m is within the Triassic metasediments based on well logging data, but the high angle fracture (89°) intersecting the well may very well extend downward to the fault boundary and across the fault into the crystalline rock beneath. This could explain the similar water chemistries of VAUTrail and Cow1_lower (Figs. 8 and 9). Additional wells further east within the Triassic basin would be necessary to more adequately constrain the sources of water in this region and the connection between the crystalline rocks in the west to the Triassic basin metasediments to the east.

Direction and quantity of flow

The small hydraulic gradient (about 0.02 m/m) across the Chatham Fault (Fig. 6) is the only observational evidence found to describe the direction of flow at the site. The estimated gradient is based on only three wells and is therefore not suitable to describe a general flow direction for the area. Apparent mixing of waters from the crystalline Piedmont and Triassic metasediments sides of the Chatham Fault in Cow1_lower is not seen, but one cannot conclude a general flow direction from the results available. However, there are no drastic changes in head related to the fault in any area, which is likely evidence that the fault does not play a controlling role in local groundwater movement. This is an area for further investigation and will require additional well data to verify.

Aquifer test data provide a range of transmissivities across the fault from 1×10^{-4} to about 4×10^{-5} m^2/s. Using the estimated hydraulic gradient of 0.02 yields a range of volumetric flows per unit width of 0.068–0.17 m^2/day. If one assumes that this rate is consistent along the length of the Chatham fault extending from the south spring study area to the northern margin of the north ore body (approximately 800 m), then the volumetric flow across the Chatham Fault in the vicinity of the ore bodies would range from ~54 to 136 m^3/day, which represents a very small volume of water.

If the findings in this investigation are found to be consistent along the Chatham Fault to the north in the vicinity of the ore bodies, then it is unlikely that the direction and volume of flow would have a significant impact on future development of a mine. Any pumping that would occur during mine dewatering would likely create a large localized hydraulic gradient in a radial direction toward the excavated area.

It has been confirmed that there is some flow across the Chatham Fault. However, there is a sharp chemical and groundwater age gradient at the fault, the observed flow is

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very low magnitude (0.068–0.17 m^2/day), and the hydraulic gradient in the area is very low (0.02 m/m) with no substantial effects from the fault. All of this suggests that the fault may be inhibiting flow, but small quantities of localized flow are likely to occur across the fault through a small number of hydraulically active fractures. If the flow across the fault is consistent with the flow rates observed in this investigation then the volumetric flow rates across the fault in the vicinity of the ore body would be highly manageable (<150 m^3/day). The fault would therefore not likely pose problems for the development of a mine in the Coles Hill area.

Conclusions

In this study electrical resistivity surveys, geophysical well bore logging, water level mapping, groundwater age dating, groundwater chemistry, and pumping tests were employed in order to determine the effect of the Chatham Fault on the quantity, chemistry, and direction of flow in the vicinity of the Coles Hill uranium deposit in the Virginia Piedmont. The purpose of this investigation was to provide some preliminary understanding of the hydrogeologic influence of the Chatham Fault on the groundwater system at Coles Hill in order to better predict how future mining operations might be affected by the quantity and direction of groundwater in the vicinity of the ore bodies.

The results of the study are constrained to only a small region along the Chatham Fault and it is not clear if the findings of this investigation can be extended to the entire length of the fault in the vicinity of the ore bodies at Coles Hill. However, the results suggest that the fault is minimally permeable, and the quantities of flow across the fault in the study area are not likely to exceed 0.2 m^2/day, which is a manageable quantity in regard to mining operations. The investigated portion of the Chatham Fault appears to provide enough resistance to flow to preserve a hydrochemical and groundwater age gradient over a relatively short distance from west to east across the fault. On the other hand, the fault allows enough flow to preserve connectivity between the wells in the area as evidenced by groundwater mixing that occurs in close proximity to the structure itself.

If a larger scale study of the Chatham Fault were to corroborate the results of this investigation, it could be concluded that flow volume would not likely exceed 150 m^3/day. This volume would not present any major challenges to a mining operation. The fault would likely act similarly to the host bedrock in the area, with generally small amounts of flow and possible intermittent larger fractures producing variable volumes of water that are not significantly different than the surrounding host rock. Additionally, this study has illustrated how a combination of geophysical methods, traditional pumping tests, and examination of environmental tracers may be utilized to examine the hydrogeologic role of a fault in a fractured rock environment.

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