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Flowing fluid electrical conductivity logging of a deep borehole during and following drilling: estimation of transmissivity, water salinity and hydraulic head of conductive zones

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Abstract Flowing fluid electrical conductivity (FFEC) logging is a hydrogeologic testing method that is usually conducted in an existing borehole. However, for the 2,500-m deep COSC-1 borehole, drilled at Åre, central Sweden, it was done within the drilling period during a scheduled 1-day break, thus having a negligible impact on the drilling schedule, yet providing important information on depths of hydraulically conductive zones and their transmissivities and salinities. This paper presents a reanalysis of this set of data together with a new FFEC logging data set obtained soon after drilling was completed, also over a period of 1 day, but with a different pumping rate and water-level drawdown. Their joint analysis not only results in better estimates of transmissivity and salinity in the conducting fractures intercepted by the borehole, but also yields the hydraulic head values of these fractures, an important piece of infor- mation for the understanding of hydraulic structure of the subsurface. Two additional FFEC logging tests were done about 1 year later, and are used to confirm and refine this analysis. Results show that from 250 to 2,000 m depths, there are seven distinct hydraulically conductive zones with different hydraulic heads and low transmissivity values. For the final test, conducted with a much smaller water-level drawdown, inflow ceased from some of the conductive zones, confirming that their hydraulic heads are below the hydraulic head measured in the wellbore under non-pumped spaceconditions. The challenges accompanying 1-day FFEC log- ging are summarized, along with lessons learned in address- ing them.

Keywords Hydraulic testing · Fractured rock · Hydraulic head · Well logging · Drilling

Introduction

To understand the hydrogeology of the deep subsurface, infor- mation is required on the spatial distribution (locations and ex- tent) of hydraulically conductive zones, their hydraulic transmis- sivities, as well as their hydraulic heads, temperature, and water salinity or chemical characteristics. These flow zones often arise from hydraulically conductive fractures or faults. Direct data on these conductive fractures can be obtained through downhole tests in deep boreholes. For example, fluid production or injec- tion tests can be conducted at selected depths in the borehole bracketed by two packers and in these bracketed intervals fluid samples can also be collected. As such tests are time-consuming, they are mainly carried out after drilling is completed. Additionally, the depths of potential hydraulically conductive zones, especially zones with low transmissivities, are often not known a priori, making optimal packer placement difficult. Borehole televiewer logging of a borehole can show fractures intercepted by the borehole; however, the majority of these frac- tures are usually not hydraulically conductive—for example, at the Laxemar and Forsmark sites in Sweden, detailed fracture investigations were conducted on cores from several tens of boreholes with depths over 1,000 m, and it was found that only about 10% of the nearly 100,000 fractures inspected were char- acterized as open or partly open and then only 2–3% of all fractures had measurable transmissivity (Rhén et al. 2008; Follin 2008; Follin et al. 2014).

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spaceOne of the very effective ways to specifically study hydraulically conductive fractures intercepted by a borehole is the flowing fluid electrical conductivity (FFEC) logging method (Tsang et al. 1990; Tsang and Doughty 2003; Doughty and Tsang 2005; West and Odling 2007; Doughty et al. 2013; Moir et al. 2014). The method, which will be described in more detail in the next section, is illustrated schematically in Fig. 1. First, borehole water is replaced by freshwater or water with salinity distinctly different from that of the formation water. Then, with the borehole pumped at a low flow rate, the change in salinity or electrical conductivity of borehole water as a function of depth is measured with a moving electrical conductivity/ temperature (EC/Temp) probe. Water-level drawdown in the wellbore is also monitored with a pressure sensor. Profiles of fluid electrical conductivity (FEC) versus depth at different times after the start of pumping can be analyzed to obtain the depths of conducting fractures, their transmissivity, salinity or FEC of the fracture water, and the hydraulic heads in these fractures. Typically, the logging is done over a period of several days or a week in an existing borehole, i.e., after the borehole drilling is finished.

Tsang et al. (2016) proposed the use of FFEC logging dur- ing the drilling of a deep borehole without first replacing borehole water with freshwater, corresponding to starting FFEC logging at a point between the first and second of the three-step process shown in Fig. 1. This is based on two fac- tors—first, the drilling fluid used can have very low electrical conductivity, not much higher than that of freshwater; second, the normal drilling schedule often includes breaks, where 1 day per week is used for the drill crew to rest or for other operational needs. Often, before the break, the drill string is pulled and the well flushed out with freshwater (for example, from a nearby river). Further, an EC/Temp probe, a downhole pump, and a pressure sensor are standard equipment, either already available on a drill site or easily obtainable; thus, FFEC logging can be done in the 1-day breaks with minimum

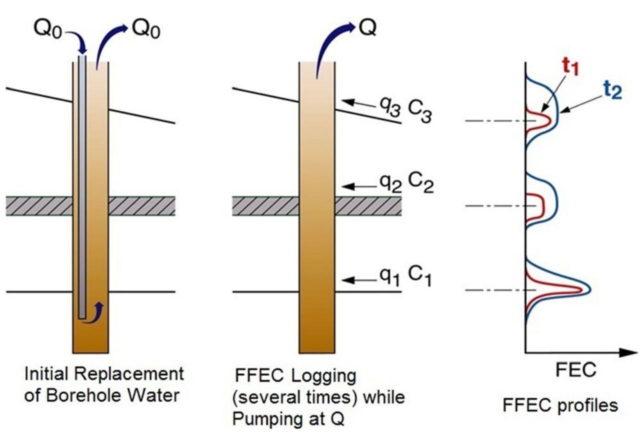

Fig. 1 Schematic of FFEC logging (modified from Tsang et al. 2016)

spaceextra trouble and with no impact on drilling schedule, which provides a new approach to hydraulic testing during drilling.

Tsang et al. (2016) demonstrated that this can be done by applying the method to the drilling of the 2,500-m COSC-1 borehole at Åre, Sweden as part of the Swedish Deep Drilling Program (Gee et al. 2010; Lorenz et al. 2015). The COSC-1 borehole was drilled though the Seve Nappe, which contains low permeability, high grade metamorphic rocks (mostly felsic gneisses) indicative of deep (100 km) crustal levels. Drilling fluid had a low electrical conductivity of ∼200 μS/cm. Based on test data from a 1-day break during the 4 months of drilling, referred to as test 1 in the following, Tsang et al. (2016) were able to identify six hydraulically conductive fractures between the depths of 300 and 1,600 m and estimate their transmissivity and water salinity or FEC. These hydraulically conductive zones correspond to open fractures observed in recovered core samples.

The focus of Tsang et al. (2016) is on introducing the concept of using FFEC logging for hydraulic testing during drilling and on demonstrating by a practical case that important and useful hydrologic information can be obtained. Subsequent to the 1-day test during drilling (test 1) and its data analysis as reported in Tsang et al. (2016), an additional 1-day FFEC logging (test 2) was conducted a week after drilling was completed, using a different pumping rate and water-level drawdown. This enables the estimation of the hydraulic head of each of the conducting fractures (Tsang and Doughty 2003), which is the focus of the present paper. The fracture hydraulic heads are very useful information to understand the hydraulic structure and condition of the deep subsurface.

The paper is organized as follows. In section 'The FFEC logging and data analysis methods', the FFEC logging method is described, together with analysis methods that have been developed for obtaining hydrologic parameters from the log- ging data. Section 'Impact of baseline salinity on FFEC log- ging data analysis' then discusses the impact on data analysis of baseline salinity in the borehole, which may vary because borehole water was not replaced by freshwater during this series of FFEC logging tests. Sections 'Test 1 and test 2 data' and 'BORE II analysis of test 1 and test 2' present the data and application, respectively, of the FFEC method to two 1-day tests (test 1 and test 2) conducted during and shortly after the 4-month drilling period of the 2,500-m COSC-1 borehole. Two confirmatory tests (test 3 and test 4), conducted about 1 year after drilling, are briefly described and analyzed in section 'Test 3 and test 4 data and analysis'—a more complete description of these tests may be found in a separate report (Dobson et al. 2016). After presenting the results from the analyses of the four tests, section 'Discussion' discusses the challenges that arise from conducting FFEC logging during drilling and the lessons learned in addressing them.

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spaceThe FFEC logging and data analysis methods

In the FFEC logging method proposed by Tsang et al. (1990), the wellbore water is first replaced by water of a constant salinity significantly different from that of the formation wa- ter. This may be accomplished by injecting water with a sa- linity distinct from that of the formation water such as munic- ipal tap water, low TDS water from a river or shallow water well, or de-ionized water, through a tube to the bottom of the wellbore at a constant low rate, while simultaneously pumping from near the top of the well at the same rate. In this way, the wellbore water is replaced by injected water without a large change in wellbore hydraulic head, so that neither is the injected water pushed out into the formation nor is the forma- tion water drawn into the well. The FEC of the effluent is monitored at the wellhead until a low, stable FEC value is reached, which typically takes about half a day or overnight for a deep (1–2 km) well.

If the final stable effluent FEC is substantially different from the FEC of the injected replacement water, it indicates that native fluid has entered the wellbore during the borehole- water-replacement phase. This may occur because wellbore hydraulic head could have unintentionally dropped during borehole water replacement, or if natural regional groundwa- ter flow is intercepted by the well. It can also occur if different hydraulically conductive features intercepted by the wellbore have different hydraulic heads, which sets up an internal

spacebelow (upstream) that point. Here C can be expressed in NaCl ionic concentration in g/L, or in terms of its fluid elec- trical conductivity with units of μS/cm. When a peak grows and shows skewing, it is possible to infer q and C indepen- dently, but for early times or small flow rates, when the peak grows symmetrically, only the product qC can be determined. A convenient method for determining the qC product for iso- lated peaks is the so-called mass integral analysis, wherein the area under each peak is calculated as a function of time, with the slope of the resulting line giving qC (Doughty et al. 2008). A simple code BORE II (Doughty and Tsang 2000) has been developed to solve the one-dimensional (1D) advection-dispersion equation for flow up the wellbore, with sources and sinks used to represent inflow and outflow zones. Matching the FFEC profiles calculated by BORE II to the profiles col- lected in the field involves choosing values of q and C for each peak by trial and error until an acceptable match to all the FFEC profiles is obtained. The parameter to describe vertical Bdispersion^ (the sum of diffusion and mixing due to probe movement) along the wellbore is also adjusted to obtain the best fit.

The inflow rates q and the water-level drawdown h_D (a positive number) in the borehole due to the constant-rate pumping during logging may be used in the Thiem (1906) equation to calculate the transmissivity values T of the inflow zones. For each inflow zone

spacewellbore flow, with formation water entering the wellbore through the features with higher hydraulic head and borehole

$$q = \frac{2\pi T}{\ln\left(\frac{r_{out}}{r_{wb}}\right)}\left(h + h_D\right) \quad (1)$$

spacewater exiting to the formation through features with lower hydraulic head.

After the wellbore water is replaced by water of salinity distinct from that of the formation water, a baseline FEC pro- file is collected by moving an electrical-conductivity/temper- ature (EC/Temp) probe up and down the wellbore. Then the well is pumped at a constant rate and formation water enters the wellbore and mixes with wellbore water at the inflow depths. FFEC profiles are measured along the wellbore at a series of times after the start of pumping (Fig. 1). The pump and a pressure sensor are emplaced at the shallow part of the well below the anticipated drawdown of the water table. The FFEC profiles thus obtained will display peaks in FEC values at depths where water enters into the well. The peaks will spread around the inflow points in the wellbore because of mixing caused by the moving probe and solute diffusion; these effects can be combined into a dispersion term. Peaks will also be skewed in the direction of water flow at their locations in the borehole. The position of the inflow zones can be determined with an accuracy on the order of 10 cm.

The height of each peak depends on the inflow rate q, the salinity C of the formation water from the particular flow zone, and the local vertical flow rate along the borehole q_{up}, which is the sum of all inflow rates for flow zones located

where r_{wb} is well bore radius, r_{out} is an assumed outer radius where the pressure response to pumping drops to zero, and h is the hydraulic head of the inflow zone with reference to the initial hydraulic head of the wellbore with no pumping (i.e., the average hydraulic head of all flow zones intercepting the borehole). If the hydraulic heads of all the flow zones intersecting the borehole are assumed to be equal, then they are simply equal to the initial hydraulic head in the borehole, and h =0 in Eq. (1). Under these conditions, T for each inflow zone can be determined from Eq. (1) using the q for that inflow zone obtained by fitting FFEC profiles from a single test. Note that the method does not require a specialized probe, but just a typical EC/Temp probe, a pressure sensor, and a downhole pump.

If the logging procedure is repeated using one (or two) more higher or lower pumping rates at the top of the well, multi-rate analysis of the data yields the hydraulic heads h of the flow zones at the different depths, which could be different from one another (Tsang and Doughty 2003). Let us assume that two pumping rates are used with two water-level draw- down values h_{D1} and h_{D2} (positive numbers), and separate analyses of the FFEC logs give inflow rates q_1 and q_2

space

spacerespectively, for an inflow zone at a particular depth with a hydraulic head h.

Subtracting Eq. (1) for the second test from Eq. (1) for the first test and solving for T yields

ðq −q Þln(r_{out} \

spacefluid into the borehole from all zones (all Δh values are pos- itive), so there will be three peaks in the FFEC profiles. For weakly pumped conditions, fluid flows into the borehole from zones 2 and 3 ($\Delta h > 0$), but out of the borehole for zone 1 ($\Delta h < 0$). Zone 1 will not produce a peak in the FFEC profile,
but may exhibit other signatures (Doughty and Tsang 2005).

space1 2

T ¼

ðh_{D1}−h_{D2}

spacer_{wb}

ð2Þ

Þ2π

spaceFor non-pumped conditions, fluid flows into the borehole for zone 3 and out of the borehole for zones 1 and 2, setting up an

spaceDividing Eq. (1) for the first test by Eq. (1) for the second test and solving for h yields

spaceinternal flow. Internal flow that occurs during wellbore water replacement could impact the baseline FEC profile, producing discrete peaks or step changes at zones with positive h

space h ¼ $\frac{q_2 h_{D1} - q_1 h_{D2}}{q_1 - q_2}$

spaceð3Þ

space(Doughty et al. 2005). Internal flow also impacts FFEC pro- files subsequently obtained while pumping, in that zones with negative h but positive Δh may not show peaks right away, if

spaceEquations (2) and (3) are a significant improvement over the original method for determining T and h using the multi- rate analysis methc Doughty 2003), which in- volved comparing one peak with the total wellbore responses (tl flow rates for all peaks, which ideally are eq pumping rates Q_1 and Q_2). However, if there analyzable peaks or inflow
from a non-logged portion of the well, then ∑ method cannot be used. In contrast, Eqs. (2 treat one peak at a time, making it poss information from non-ideal tests.

Recall that h is defined as the hydraulic head of a flow zone relative to the initial (non-pumping) hydraulic head in the wellbore. Thus, under non-pumped conditions, for zones with positive h values, there is a driving force for fluid flow from the formation into the borehole and, for zones with negative h values, there is a driving force for fluid flow from the borehole into the formation, and there could be internal flow in the wellbore between different zones. When the well is pumped, resulting in a drawdown h_D, the driving force for flow into the
well is $\Delta h = h - (-h_D)$, with positive values of Δh producing flow into the borehole. Figure 2 is a schematic diagram show- ing strongly pumped, weakly pumped, and non-pumped con- ditions for three flow zones with different h values. For strong- ly pumped conditions, the drawdown h_D is sufficient to pull
spacelow-salinity wellbore fluid entered those zones before pumping began.

The multi-rate analysis procedure typically lasts for a few days to a week, with five or six FFEC profiles collected at each of two or three pumping rates, and has proved to be an effective method to yield estimates of transmissivity, water salinity and hydraulic head of the inflow zones all along the borehole (Doughty et al. 2005, 2008, 2013).

Impact of baseline salinity on FFEC logging data analysis

The present paper is concerned with FFEC logging conducted during drilling, with data obtained in just 1 day, without a prior carefully controlled borehole water replacement by freshwa- ter. In such cases, it is likely that the baseline FEC levels before logging begins will vary from one test to another. While this complicates some aspects of the analysis such as precluding application of the mass integral analysis, it can provide useful information. Simple mixing rules may be used to estimate peak height relative to baseline level (i.e., how much of a peak is visible) at steady state. Assume there are two tests with baseline levels C_{01} and C_{02}, an isolated flow zone with salinity C and inflow rates for the two tests of q_1 and

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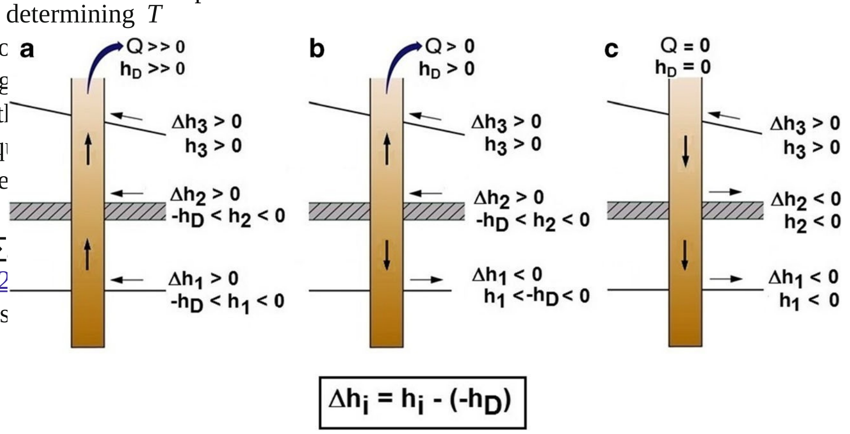


tic of inflow, outflow, and wellbore flow for a strongly pumped, b

weakly pumped, and c non-pumped conditions, when flow zones have different hydraulic head values *h* and different driving forces for

flow into or out of the borehole Δ*h* space

spaceq_2, and upflow from below the flow zone for the two tests of q_{up1} and q_{up2} (i.e., q_{up} is the sum of the inflow rates below the zone of interest). At steady state, the peak heights observed for the first and second tests would be

Cq þ $C_{01}q$

spacepump depth with its cable guided through tubing attached to the side of the pump. In this way the EC/Temp probe can be lowered to scan the borehole from about 100 m depth (the extent of the cased part of the borehole below which the bore- hole is uncased) to the borehole bottom. Because of the design

spaceC_1 ¼
space1
q_1 þ q_{up1}
spaceup1
spaceð4Þ

spaceof the EC/Temp probe, only the FFEC data recorded during the downward scan of the probe were used in subsequent data

space*C* ¼ Cq_2 þ $C_{02}q_{up2}$
2
spaceð5Þ

spaceanalysis. The downward speed of the probe was about 10 m/

spaceq_2 þ q

space
up2

spacemin, and the return of the probe back to the top of borehole was at a higher speed of about 20 m/min, which means that it

spaceIf C_{rel} is defined as peak height relative to baseline, and C_{rat} is defined as the ratio of C_{rel} for the two tests, then at steady state

! Cq_2 þ $C_{02}q_{up2}$ −C

spacetook about 3.75 h to complete each logging scan from 100 to 1,600 m and back during test 1. For test 2, the logging tool scanned from 100 to 2,000 m (the maximum depth the tool was rated for), with a 4.75 h round trip. In each of the 1-day FFEC logging operations, three FFEC versus depth profiles

space C C_{rel2}

spaceC_2−C_{02} !

spaceq_2 þ q

space$_{up2}$

space^{02} 6Þ ¼ were obtained. ¼ ¼

space $_{rat}$ C_{rel1} C_1−C_{01}

Simple algebra yields

space Cq_1 þ $C_{01}q_{up1}$

q_1 þ q_{up1}

space

−C_{01}

spaceð For test 1, a number of field problems were encountered that were unrelated to the FFEC method such as accidental sliding of the pump in the borehole by 2 m, entangling of pump and logging cables, and interruption of electric power supply at the drill site. Also the initial estimate of pump rate

space $_{02}$$C$−$C$ C_1 $_{up1}$ þ q !

spacewas too high so that the water-level drawdown reached the

ð7

Þ

depth of the pump, resulting in a fluctuating pumping rate;

C_{rat} ¼ 2

space$C$−C_{01} q_1

spaceq_2 þ q_{up2}

spacenevertheless, an average flow rate of 3.5 L/min out of the borehole was obtained during logging at a drawdown of

spaceFor short-term logging periods with low inflow rates, the observed peaks are nowhere near steady state, and BORE II modeling shows that early-time C_{rat} can be much smaller than steady-state C_{rat}; thus, Eq. (7) provides an upper limit for the observed C_{rat}.

If C is large compared to C_{01} and C_{02}, then the first term in parentheses will be near one, and C_{rat} will just depend on inflow rates. However, if $C_{02} > C_{01}$, and C is not much bigger than C_{02}, then the first term could be quite small, greatly decreasing C_{rat}; hence, analyzing tests with different baseline levels can provide information on C values. For peaks that do not show skewing, this is a powerful addition to the analysis method. If baseline concentration is not uniform with depth, then the C_0 value just below the peak of interest could be used in Eq. (7) for an approximate analysis. The second term shows the expected direct dependence of C_{rat} on q_1 and q_2, whereas the third term shows how a large upflow from below can decrease peak height above baseline.

Test 1 and test 2 data

As described in the ΒIntroduction^ section, two 1-day FFEC logging tests were performed when the drilling of COSC-1 borehole reached depths of 1,600 and 2,500 m, denoted test 1 and test 2, respectively. The pump and pressure sensor were emplaced 70 m below the water table, which was close to the land surface. The EC/Temp probe was initially set below the space70 m. For the second test, the drawdown was set at 50 m, but pumping was also interrupted several times due to opera- tional problems, and flow rate out of the borehole was highly variable, averaging 2.5 L/min during logging. Figures 3 and 4 show wellbore pressure and pumping rate for test 1 and test 2, respectively.

For both tests, a baseline FEC logging profile was obtained under non-pumped conditions, then two more profiles were obtained during pumping, at about 3 and 11 h after pumping started. Figures 5 and 6 present the FFEC logs for test 1 and test 2, respectively. In these plots the FEC values have been corrected to 20 °C-equivalent values (Tsang et al. 1990) using temperature along the borehole (T_b) measured at the same time with the EC/Temp probe:

FECð20^{o}CÞ ¼ FECðT_bÞ=½1 þ SðT_b– 20^{o}CÞ] ð8Þ

where $S = 0.024\ °C^{-1}$.

The FEC values in these plots can be related to salinity or NaCl concentration C through an approximate formula (Tsang et al. 1990) valid for the range of FEC values encountered in this paper:

1 FECðμS=cmÞ≈1870Cðg=LÞ ð9Þ

In this paper, C and FEC values are used interchangeably with this conversion in mind.

Figures 5 and 6 show that the FFEC data are erratic at depths above 250 m, which correspond to the depths affected space

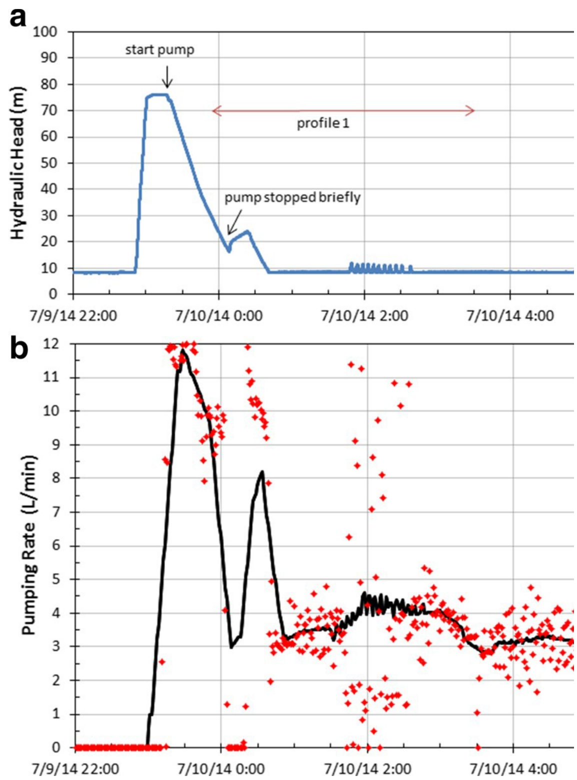


Fig. 3 Test 1 operating conditions: a wellbore hydraulic head (relative to pressure sensor located at a depth of 70 m), with logging periods shown, and b
pumping rate (symbols), with 25-min moving average shown (line). Date and time formats: month/day/year; hour:min

spaceby aforementioned unrelated operational problems. From 250 m down to 1,600 m, the test 1 FFEC profiles show distinct peaks at seven locations, indicating inflows at depths of 288, 338, 508, 553, 696, 1,214, and 1,243 m. Thus, this simple 1- day test already yields very useful information—i.e., the iden- tification of the depths at a high resolution of hydraulically conductive zones with both large and small flow rates. It is at these depths where post-drilling double packer tests and water sampling should be done. All of the peaks look symmetric, indicating that inflow rates are too small to produce significant skewing of peaks up the wellbore within the 1-day period allocated for FFEC logging during drilling.

No additional peaks were identified between depths of 1,600 and 2,000 m during test 2. Comparison of the FFEC profiles for test 2 (Fig. 6) and test 1 (Fig. 5) show the follow- ing important differences.

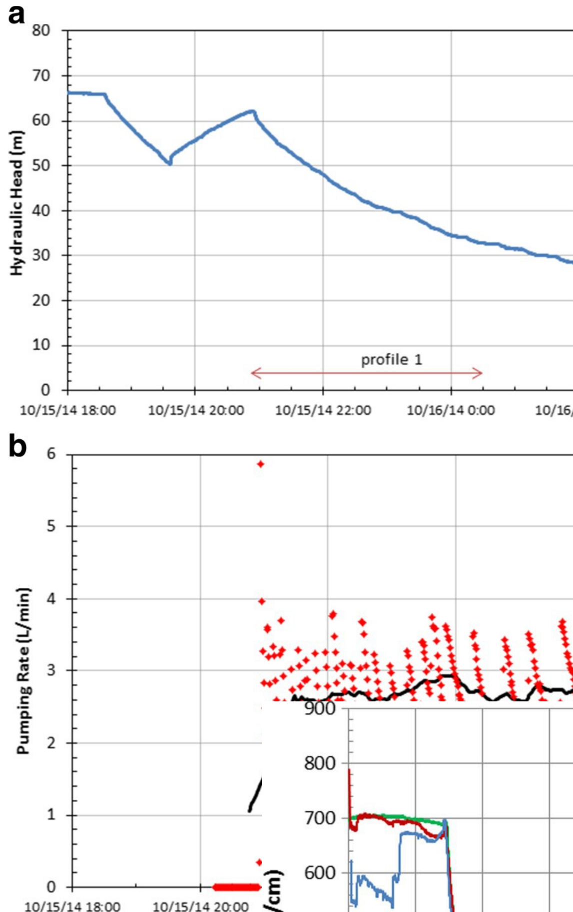
- The baseline FEC profile is much higher in test 2 than in test 1, which precludes use of the mass integral analysis for determining the qC product for each peak. Thus, a detailed fit using BORE II must be done, as is described in the next section.
- Peaks 1–3 (at depths of 696, 1,214, and 1,243 m) are much smaller than the corresponding test 1 peaks, and peak 4 (553 m) and peak 5 (508 m) have disappeared entirely, suggesting that the h values of these flow zones are neg- ative (Eq. 3).
- spacePeak 6 (338 m) shows a larger peak for test 2 than for test 1 ($C_{rat} > 1$ in Eq. 7), consistent with inflows for peaks 1–5 being much smaller for test 2 than for test 1 ($q_{up2} << q_{up1}$ in Eq. 7), and a positive h value for this flow zone ($q_2 \sim q_1$ in Eq. 7).
- At a depth of 288 m, the small peak 7 in test 1 has become a local minimum in test 2, suggesting that the C value for this zone is in between the baseline values for the two tests, C_{01} and C_{02}.

All of these features are amenable to analysis with BORE II and will be described in the following section.

BORE II analysis of test 1 and test 2

The baseline FEC profiles are used as the initial conditions for the BORE II calculations. The baseline FEC profiles were measured over the course of several hours prior to the start of pumping, but to use them as an initial condition implicitly assumes that they were measured instantaneously at $t = 0$, when the pump was turned on. This is a reasonable assump- tion if the baseline FEC profile represents steady-state condi- tions in the wellbore, which is supported for depths below 250 m by the subsequent FFEC profiles, which change in time only at the discrete flow zones.

space



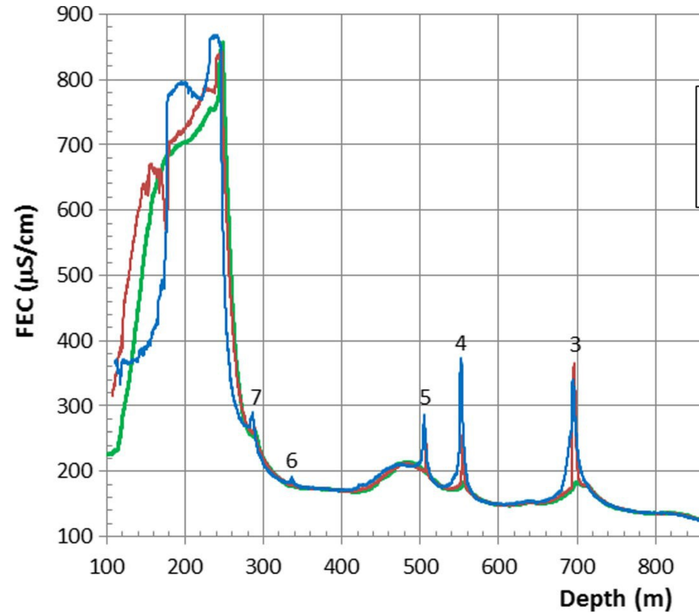


Fig. 5 FFEC profiles measured during test 1. Peaks are identified by number, from deep to shallow

space

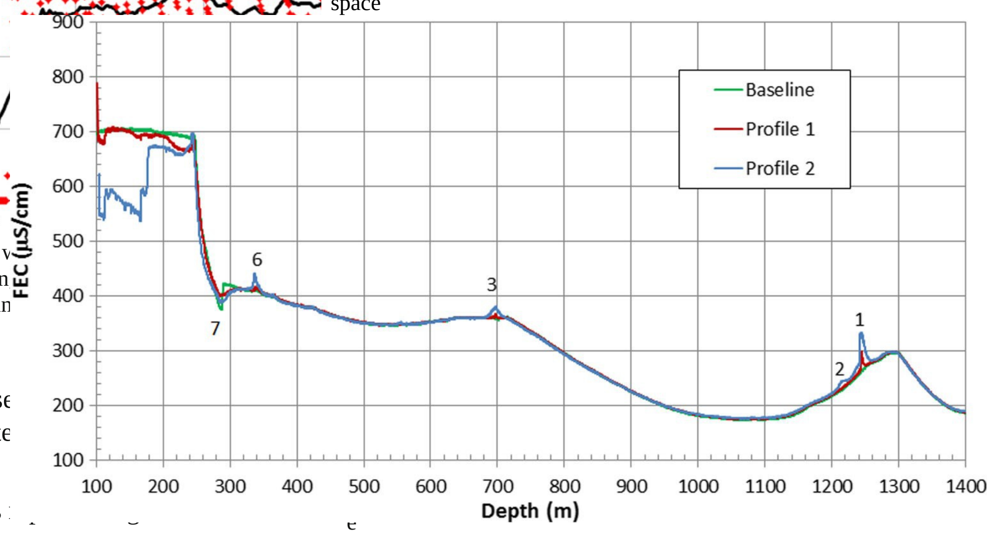


Fig. 4 Test 2 operating conditions: a v
logging periods shown, and b pumpin
moving average shown (line). Date an
hour:min

spaceNormally, when the base
result of a careful borehole-wate
local minima and

spacemaxima are interpreted as
with positive
h values and relatively low and high *C* values, respectively.

space

es measured during test

2

Matching the skewing constrains the sum of the q values for all the peaks below that point. Table 1 shows the q, C, and t_0 values obtained for both approaches. Note that the sum of the q values, 110–127 ml/min, is far less than the

spacerate at which the well is being pumped, ∼3.5 L/min, indicating that the seven feed points between 250 and 1,600 m do not represent the only inflow to the borehole. This is consistent with the large FEC values obtained for the 100–250 m depth range, but as mentioned before, operational problems precludes analy- sis of these data. The differences in q and C between the low-C and high-C approaches provide a rough idea of the uncertainty associated with these parameters, which is illustrated in Fig. 8. Table 1 also shows the q, t_0, and C values obtained by an independent analysis of the test 1 FFEC data (Tsang et al. 2016). For the three deepest peaks, the q and C values for the independent analysis are close to or within the range of the low- C and high-C approaches, but for the shallowest

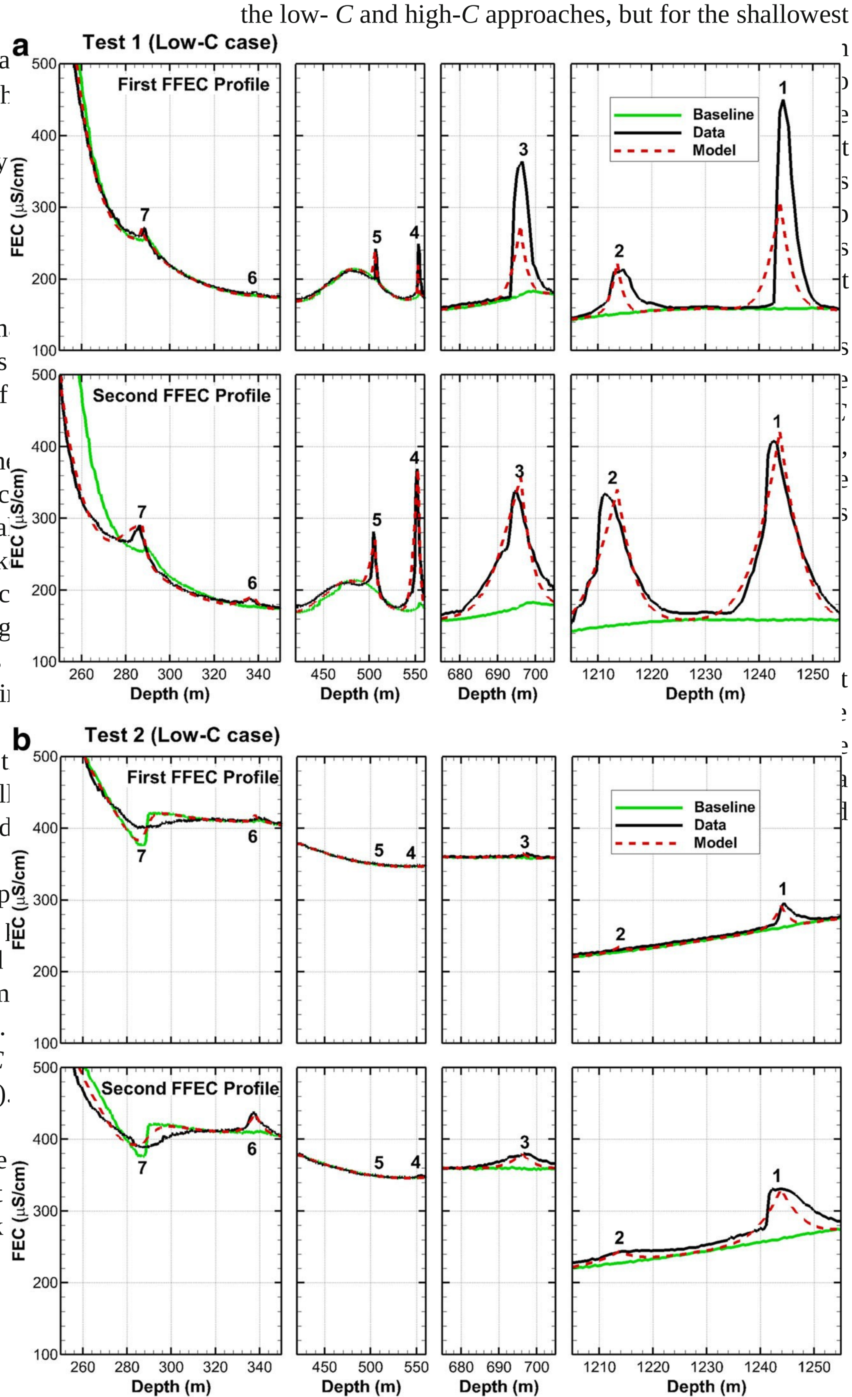
spaceHowever, for the present tests, the ba follow the washing out of the borehole, wh under unknown conditions, making this uncertain, as evidenced by the variability baseline profiles for test 1 and test 2.

Analysis of test 1

The first step of the BORE II analysis is to m profiles for test 1 by picking q and C values by trial and error. Because of the lack of consequent difficulty of determining independently, this fitting ex- ercise is don two different approaches. In the first approac of C is used as the starting guess for each pea to make the corresponding q large, and C is k possible during the fitting process. In the sec high values of C are used as the starting g tends to make the corresponding q values values are kept as large as possible durin process.

The dispersion coefficient and t_0, the t formation fluid begins to flow into the well peak, are also chosen by trial and error, and same for the low-C and high-C approaches. not show normal growth: at peak 1 at a dep and at peak 3 at a depth of 696 m, the 3-h high as the 11-h peak, which is attributed variable pumping rate. No t_0 can be determ peaks, and just the late-time peak is matched.

Figure 7 shows the match for the low-C high-C approach yields a comparable match). can be matched reasonably well. At two profiles, slight skewing provides some information on q: at the sharp upslope just and at the gradual downslope between peak



II fit to the FFEC profiles for *a* test 1 and *b* test 2, using the low-*C* approach

space

well. Table 1 shows the q and t_0 values obtained for test 2. Note that peaks 4 and 5 have disappeared (i.e., $q \leq 0$) but peak 6 has a larger q value than for test 1. These features will be discussed further in the multi-rate analysis described in the following.

What was peak7 at 288 m in test1 is nowa minimum in all the test 2 profiles. It is hypothesized that the *C* value for this peak is ∼380 μS/cm, which is higher than the test 1 baseline value at that depth (so produces a peak) but lower than the test 2 baseline value (so produces a minimum). Subsequent FFEC logging at this borehole in test 3 and test 4 (described in the following) with

space

even larger baseline FEC values produces FFEC profiles that persist in showing a minimum at 288 m, supporting this hypoth- esis. It turns out that the large difference in baseline FEC for the different tests, originally considered a shortcoming, can actually provide constraints on the *C* values of individual peaks, which is very useful information for low-flow peaks that do not show appreciable skewing. Unfortunately, the test 2 profiles do not show the development of a negative peak at 288 m in a manner that can be matched with BORE II, so the *q* value for peak 7 is very uncertain.

space

Table 1 Parameters obtained for each hydraulically conductive zone from BORE II fitting of test 1 and test 2 FFEC data using the low-*C* and high-*C* approaches: depth, flow rate (q_1, q_2), starting time for formation flow (t_{01}, t_{02}), and salinity (*C*, same for both tests)

Test 1
Test 2
multi-rate analysis test 1/test 2

Low-*C* approach | High-*C* approach | Both approaches | Independent analysis | Low-*C* approach

spaceHigh-*C* approach
spaceBoth approaches
spacePeak No. Depth (m)
spaceq_1 (ml/min)
space*C* (μS/cm)
spaceq_1 (ml/min)
space*C* (μS/cm)
spacet_{01} (h) q_1 (ml/min)
space*C* (μS/cm)
spacet_{01} (hr)
spaceq_2 (ml/min) q_2 (ml/min) t_{02} (h) *h* (m) *T* (m²/s)

1	1,243	14	1,700	11	2,200	
	0	10	2,244	0	4.0	
	3.1	1.5	−42	7×10^{-9} – 9×		
10^{-9}						
2	1,214	18	1,150	41	620	
	2.3	28	935	1.67	1.4	
	3.6	1.5	−48	2×10^{-8} – 3×		
10^{-8}						
3	696	21	1,000	14	1,400	
	0	22	1,309	0	2.9	
	1.9	1.5	−47	1×10^{-8} – 2×		
10^{-8}						
4	553	13	1,800	7.7	2,900	2.0
5	508	4.8	1,800	3.5	2,800	0
6	338	1.7[a]	1,200	0.55[b]	2,900	1.5
7	288	55	380	54	380	1.0
Sum	–	127.5	–	109.9	–	–

Values of q_1, t_{01}, and *C* obtained by an independent analysis of test 1 (Tsang et al. 2016) are also shown. For multi-rate analysis, low-*C* and high-*C* approaches yield the same value of *h* and the range of *T* values shown. Same value of t_0 is used for both low-*C* and high-*C* approaches

[a] Increased to 2.7 for mul

ti-rate analysis[b]

Increased to 0.85 for multi-rate an

alysis[c]

Upper limit[d]

Decreased to 1.9 for multi-rate a

nalysis

e

Decreased to 0.61 for multi-rate analysis

f

P

lace-holder result

[g] Very uncertain

space

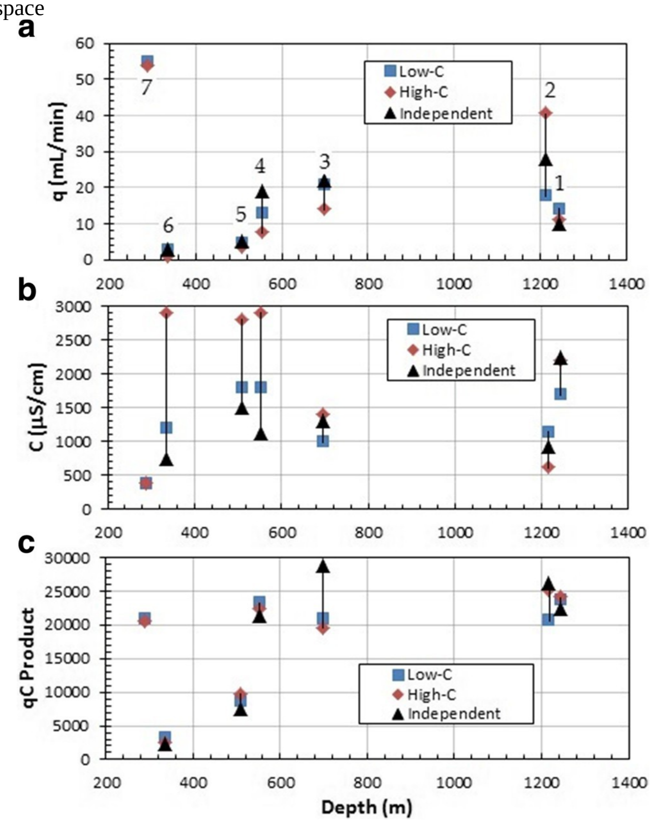


Fig. 8 Comparison of results for test 1 for low-*C* approach, high-*C* approach, and independent analysis of Tsang et al. (2016), for a *q*, b *C*, and c *qC* product

Multi-rate analysis of test 1 and test 2

Next, the *q* values from test 1 and test 2 are used in Eq. (2) to calculate *T* and in Eq. (3) to calculate *h* for each hydraulically conductive zone. For the *T* calculation, r_{wb} = 0.048 m (corre- sponding to a wellbore diameter of 9.6 cm) and r_{out} = 48 m, which is an estimate used by Tsang et al.

(2016). Equation (2) is not very sensitive to r_{out}, so in the absence of actual infor- mation about the extent of the pressure response, using r_{out} = 1,000 r_{wb} is believed to be a reasonable approach. Table 1 shows the results of the multi-rate analysis. For all peaks, nearly the same *h* values are obtained for the low-*C* and high-*C* approaches, which greatly increases confidence in the results, given all the limitations of 1-day logging, includ- ing no controlled borehole water replacement, highly variable pumping rate, few FFEC profiles obtained, and minimal skewing observed.

Note that the *h* values for peaks 1–3 are all negative, and have magnitudes close to h_{D2} = 50 m; thus, for test 2 there is little driving force for flow from the hydraulically conductive zone into the wellbore, resulting in small peaks. For peaks 4 and 5, which are absent in test 2, *q* = 0 is assumed, and Eq. (3)
yields $|h|= h_{D2}$ = 50 m. This is actually an upper limit for *h*, which could be anywhere between −70 and −50 m (*h* must be greater than −70 m because these zones produced peaks in test
space1, for which h_{D1} = 70 m). If *h* < −50, then there will be outflow from the wellbore to the flow zone during test 2. The *q* and *h* values for peaks 4 and 5 will be determined more accurately when test 3 and test 4 data are analyzed in the next section.

For the simple steady-state flow presumed in the

peak 6, Figs. 5 and 6 show that at the final logging times, the test 2 peak height above baseline is 2.5 times bigger than that for test 1, which provides a lower bound for steady-state C_{rat}. Table 2 summarizes the three multiplicative terms in Eq. (7) that de- termine steady-state C_{rat}, for four *C* values. The middle two *C* values are the peak 6 values obtained from the low-*C* and high-*C* fitting approaches. The lowest and highest *C* values are included to illustrate the dependence of C_{rat} on a larger range of *C*. The key requirements for obtaining C_{rat} > 1 are *C*
>> C_{01} and *C* >> C_{02}, so that the first term of Eq. (7) is not too small; $q_2 \sim q_1$ so that the second term is not too small; and $q_{up2} << q_{up1}$, $q_2 << q_{up2}$, and $q_1 << q_{up1}$ so that the third term is large. The large decrease in the height of

Table 2 The use of C_{rat} to constrain *C* and *h* for peak 6. The terms in Eq. (7) for steady-state C_{rat} are shown in *italic*, using baseline values C_{01} = 178 µS/cm and C_{02} = 408 µS/cm, from assuming that $q_2/q_1 = h_{D2}/h_{D1}$ = 50/70 = 0.71

	Smaller *C*	Low-*C* approach	High-*C* approach	Larger *C*
C (µS/cm)	500	1,200	2,900	5,000
$(C–C_{02})/(C–C_{01})$	*0.29*	*0.77*	*0.92*	*0.95*
q_1 (ml/min)	4.0	2.7	0.85	0.20
q_2 (ml/min)	2.9	1.9	0. 61	0.14
q_2/q_1	*0.71*	*0.71*	*0.71*	*0.71*
q_{up1} (ml/min)	71	71	77	77
q_{up2} (ml/min)	8.3	8.3	8.6	8.6
q_{up1}/q_{up2}	8.5	8.5	8.9	8.9
$(q_1 + q_{up1})/(q_2 + q_{up2})$	*6.7*	*7.2*	*8.4*	*8.8*
Steady-state C_{rat}	*1.4*	*4.0*	*5.5*	*6.0*

The C_{rat} value observed in the field for test 1 and test 2 is about 2.5 – the steady-state C_{rat} shown in the *bottom row* must be larger than that

peaks 1–5 between test 1 and test 2 ensures that $q_{up2} << q_{up1}$, and the small size of peak 6 means the q_{up} terms dominate the third term. Table 2 indicates that for the low-*C* and high-*C* approaches, steady- state C_{rat} values are 4.0 and 5.5, respectively, both greater than the observed C_{rat} of 2.5, verifying that it is indeed plausible for
peak 6 to be larger in test 2 than in test 1 for the assumed *C* and
h values.

Additional results for smaller (500 µS/cm) and larger (5,000 µS/cm) values of *C* are also given in Table 2, to provide insight into the impact of *C* on C_{rat}. For *C* (500 µS/cm) not much bigger than C_{02} (408 µS/cm), the first term in Eq. (7) becomes quite small (0.29), producing too small a value of C_{rat} (1.4). In contrast, a very large value of *C* (5,000 µS/cm) does not increase the first term appreciably (0.95 compared to
0.92), so C_{rat} does not change much (6.0 compared to 5.5). Thus, for estimating the *C* value for peak 6, values of C ≤ 500 µS/cm can be eliminated from consideration, and there is no need to hypothesize very high values of *C* ≥ 5,000 µS/cm to produce the 2.5 times larger peak observed in test 2 compared to test 1.

As described in the previous section, the q_2 value for peak 7 is very uncertain. Hence, the *T* and *h* values for peak 7 are very uncertain too. Normally, the *h* values obtained with the multi-
space

spacerate analysis are compared to the t_0 values obtained from the individual fits as a consistency check: large t_0 values should be associated with negative *h* values because low-salinity wellbore fluid flowed into the formation during borehole wa- ter replacement. This relationship holds for the peaks for which a t_0 could be obtained, but the highly variable pumping rate means that not much significance can be associated with this result.

Test 3 and test 4 data and analysis

Test 3 and test 4 were conducted about 1 year after the drilling of the COSC-1 borehole was completed. For test 3, the draw- down was set at 50 m, and for test 4 drawdown was set at 10 m. Although these water levels were reasonably well main- tained during logging, the pumping rate still fluctuated some- what (Dobson et al. 2016). Operational problems precluded doing borehole water replacement prior to logging, so baseline FEC levels were even higher than for test 2. For test 3, there is a baseline log, three logs obtained during pumping, and a log obtained after the pump was turned off. For test 4, eight logs were obtained during pumping, but the final two only went to a depth of 400 m.

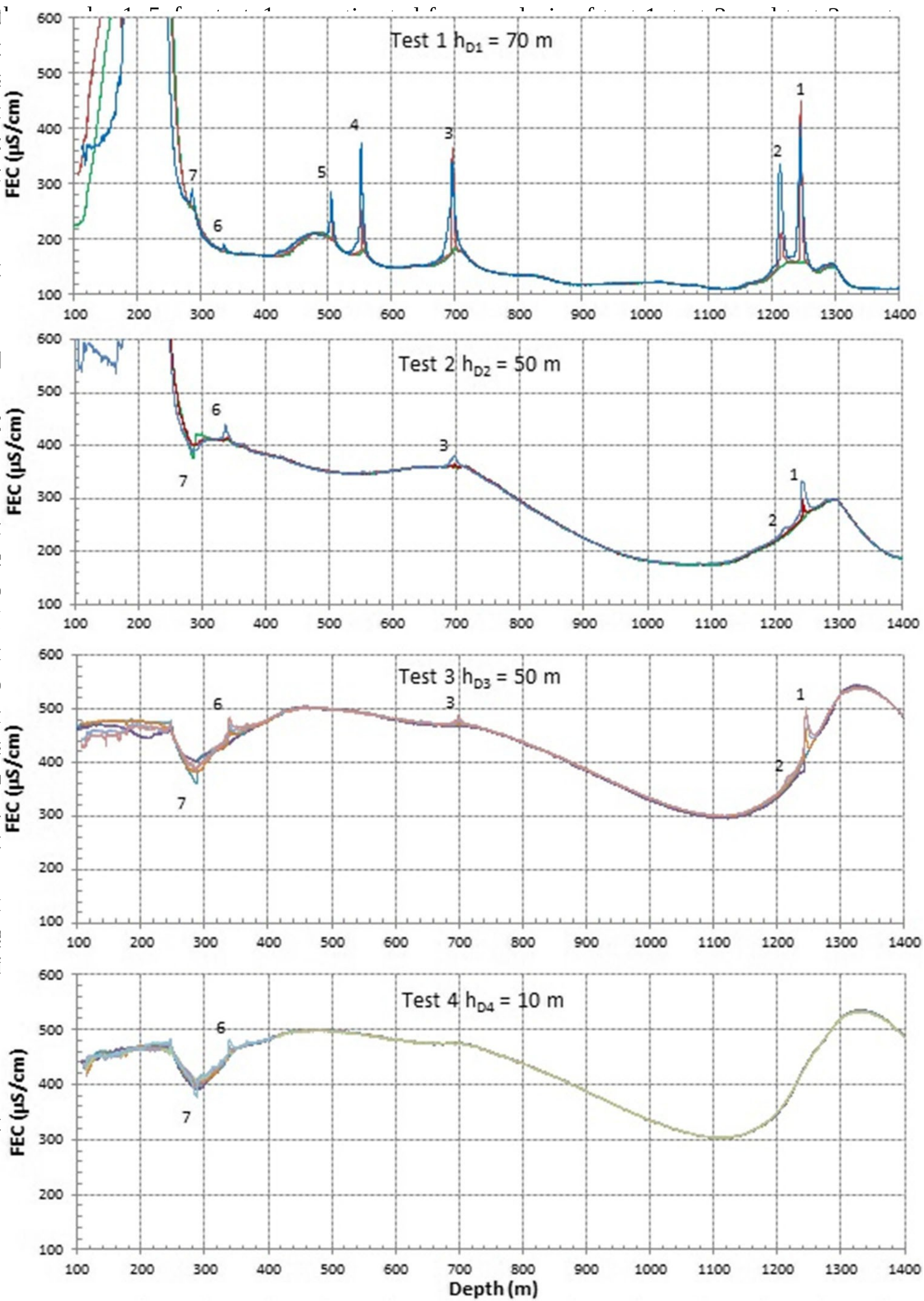
Figure 9 shows the FFEC logs for all four tests together, to provide an overall look at the data. Peaks 1–5 for test 2 are disproportionally smaller t
consider- ing the difference in
shown in Table 1, this indicates
1–5 are negative. The peaks for
for test 2, which is expecte
specified for both tests are 50 r
all absent, which is consistent
zones shown in Table 1;
all are lower than −10 m, so a
insuffi-
cient to induce inflow into the
for both test 3 and test 4, enal
estimate
h. The persistence of the FE
suggests

spacethe inflow of low-*C* water
draw- down values and under
implying that *h* for zone 7 is po
BORE II is used to fit th
and indicates that slightly hig
match test 3 than test 2 for n
is actu- ally larger than h_{D2}. Th
for test 2 (Fig. 4) could also
out of the formation is
pumping rate, with th
wellbore storage, which wo
smaller inflow rates for t
values test 2 and test 3
determine the effective diffe
producing h_{D2} = 48 m, just slig
m. Additional small changes
to improve the match to F
described in a separate report
4 shows only one growing
readily fit with BORE II, enab
test 3 and test 4 to determine t

6 (Table 3), which are an improvement on the conservative estimates ob- tained from the test 1/test 2 multi-rate analysis (Table 1).

Test 4 does not show normal peak growth for peak 7, so it cannot be analyzed quantitatively. Any small value of q_4 can be used for a qualitative match, so one that gives a consistent *h* value with the test 1/test 2 multi-rate analysis is used.

There is now an *h* value and a *T* value associated with every zone (Table 3), so Eq. (1) can be used to predict inflow or outflow for any applied value of $h_{D.}$ In particu- lar, the outflow rates for peaks 1–5 for test 4 with h_{D4} = 10 can be determined. If these outflow rates are used in a BORE II simulation for test 4, there is significant down- ward skewing of the profiles, as shown in Fig. 10. Repeated logging over a period of 45 h during test 4 (Fig. 9) indicates no visible changes of the FFEC profiles except at peaks 6 and 7. This suggests that the *h* values



same scale, for qualitative assessment

space

negative for peaks 1–5, resulting in too great an outflow for test 4. By trial and error, the maximum outflow for peaks 1–5 that produces minimal downward skewing is determined (Table 3). These new q_4 values can be used with the q_3 values to obtain new *h* values using Eq. (3), also shown in Table 3.

As a final consistency check, these new *h* values should not produce any visible downward skewing under quiescent con- ditions ($h_D = 0$), and in fact, using them in a BORE II simula- tion produces minimal downward skewing. The positive *h*

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values for peak 6 and peak 7 produce inflow when $h_D = 0$, but the rates are small enough to not produce distinctive peaks. In summary, the main value added from the analysis of test 3 and test 4 is to provide additional information on the nega- tive *h* values of peaks 1–5. Because these negative head values produce inflow to the borehole when drawdown is large and outflow to the formation when drawdown is small, the wide range of drawdowns from test 1 to test 4 produces very dif- ferent FFEC profiles, enabling better constraint on the *h* values. Additionally, test 3 and test 4 enable a quantitative

spaceTable 3 Parameters obtained from the multi-rate analyses of test 1/test 2/test 3 and test 3/test 4

Peak No.	Depth (m)	Test 1, q_1 (ml/min)	Test 2, q_2 (ml/min)	Test 3, q_3 (ml/min)	Test 4, q_4 (ml/min)	*C* (μS/cm
1	1,243	14	4	4.7	−2.6	1,700
2	1,214	17	1.4	1.8	−3.4	1,150
3	696	40	8	9.8	−8.7	600
4	553	10	0	0.1	−0.4	2,350

5	508	4.5	0	0.1	−0.4
6	338	1.7	2.6	2.7	1.6
7	288	55	40	10	3.4

Drawdowns assumed for each test are test 1: h_{D1} = 70 m, test 2: h_{D2} = 48 m, test 3: h_{D3} = 50 m, test 4: h_{D4} = 10 m

spacemulti-rate analysis of peak 6 to be done. Finally, the non- standard behavior of p parameters ob- tained for it are

Discussion

Table 3 indicates that all the zor negative *h* values. By definition the transmissivity-weighted sun thus shallower heads must be p peaks analyzed yield positive baseline FEC values for the dep 5 and 6) are consistent with positive *h* values, since positive *h* results in inflow to the borehole during non-pumped conditions. This distribution of decreasing *h* with depth indicates the potential for downward flow under natural conditions, which makes sense for the mountainous terrain.

Tables 1 and 3 show *h* and *T* values inferred from various multi-rate analyses. A general indication of the uncertainty in *h* and *T* can be obtained by comparing these values, as shown in Fig. 11. Another source of uncertainty in *T* is the value of r_{out} used in Eq. (2). Increasing or decreasing the assumed value of r_{out} by a factor of ten results in a modest increase or decrease in *T* by less than a factor of 1.5, which is small

spacecompared to the range of *T* shown in Fig. 11. The different symbols provide reasonable uncertainty bounds for peaks 1– 6, but for peak 7 the uncertainty should be even larger, due to the inability to quantitatively fit the FFEC profiles of peak 7 during test 3 and test 4.

The independent results from an analysis of test 1 data by Tsang et al. (2016) are also shown in Fig. 11. Since their analysis considered only one test, they could not do a multi- rate analysis, and they assumed all hydraulically conductive zones had the same hydraulic head, *h* = 0. For the deep peaks with negative *h*, Eq. (1) indicates that assuming *h* =0 would result in too strong a driving force for flow, and thus yield too low a value of *T*. For peak 6 with positive *h*, the opposite would be true. While this trend is apparent in Fig. 11, the *T* values obtained by Tsang et al. (2016) are generally close to the range of values obtained by the present multi-rate analysis.

Analyzing FFEC logs obtained during a 1-day break during drilling is challenging for a number of reasons, as enumerated in the subsequent. Each of these challenges has been ad- dressed in the present study, leading to a corresponding lesson learned, and these lessons learned may be useful for future application and analysis of FFEC logging.

Challenge 1. The time available for logging is limited, meaning few profiles can be obtained. The key

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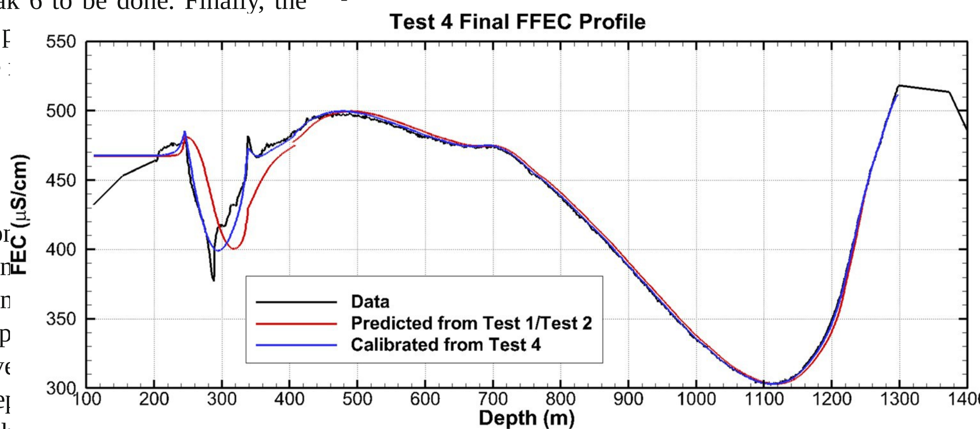

fit to final FFEC profile for test 4. W

hen the h values obtained from the test 1/test 2 multi-rate analysis are used to predict the outflows for peaks 1–5 for test 4, the downward skewing is too great (*red curve*). Decreasing the outflow

for peaks 1–5 until downward skewing is minimal (*blue curve*) yiel

d s
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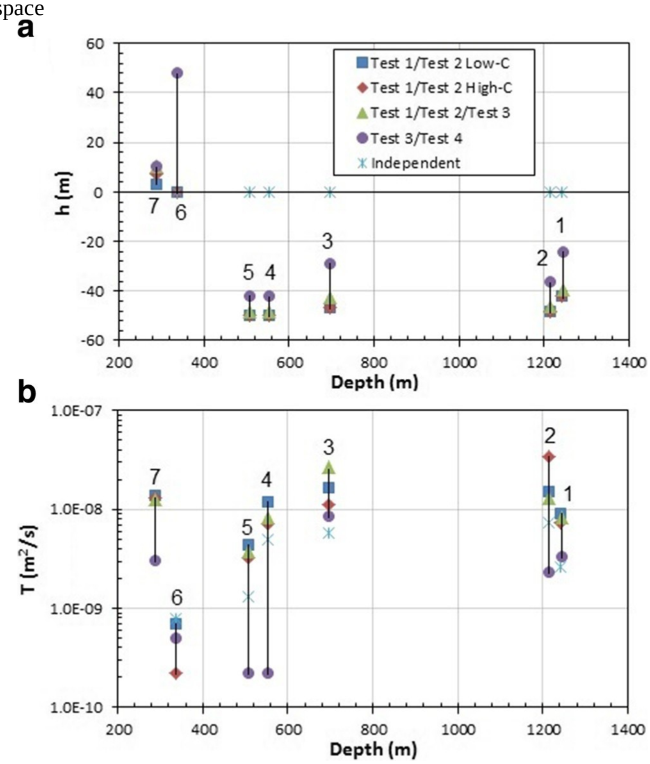

Fig. 11 The a *h* and b *T* values obtained from various multi-rate analyses

information in FFEC logging analysis comes from chang- es between successive profiles, and there is always noise in the data, so obtaining multiple successive profiles is optimal for getting a clear signal. Furthermore, when in- flow rates are small, peaks in the FFEC logs are small and symmetric. That is, there is little or no peak skewing up the borehole in the short time available for logging, which means it is difficult to determine inflow rate *q* and flow zone salinity *C* for each peak independently.

Lesson 1. The fact that few profiles are available means it is easier to fit the FFEC logs, and hence there is greater uncertainty associated with the returned parameters for inflow rate *q* and salinity *C* for each hydraulically con- ductive zone. The lack of peak skewing also makes the determination of *q* and *C* independently subject to greater uncertainty. These difficulties can be addressed by doing the fitting twice, with different constraints on *C*. This exercise provided a measure of the uncertainty of *C*, which could be used to estimate the uncertainty of flow- zone transmissivity *T*. Significantly, in this case the same values for the hydraulic head *h* of the flow zones were obtained with the different *C* constraints, greatly increas- ing confidence in the validity of the results and the ro- bustness of the multi-rate analysis method.

Challenge 2. Washing out the borehole prior to FFEC logging is not as well-controlled an operation as borehole

spacewater replacement, especially in the case of conductive fractures having different hydraulic heads, which could have two adverse consequences. First, borehole fluid may enter the flow zones during washing out; it returns to the borehole during logging while pumping, thus early-time logs do not represent formation fluid. Second, the base- line profile does not reflect internal flow in the borehole under non-pumped conditions.

Lesson 2. Baseline FEC profiles that result from poorly controlled washing out of the borehole can be used as initial conditions for FFEC logging, if they represent steady conditions in the borehole. Their use complicates the analysis, requiring detailed fitting instead of the sim- pler mass integral analysis to infer the *qC* product of each peak. For data analysis, a t_0 value was introduced for each inflow zone to mark the onset of formation fluid entering the borehole, and it turned out that the t_0 values were not difficult to estimate from the data for properly executed FFEC logging tests. On the other hand, having different baseline levels of FEC may enable identification of the salinity of inflow zones that are close to the FEC baseline values.

Challenge 3. Because of the short time available for test- ing, it may not be possible to determine the optimal pumping rate to use during logging, resulting in a variable pumping rate, which makes FFEC log analysis much more difficult.

Lesson 3. For the highly variable pumping rates used, a perfect match to all aspects of all profiles cannot be ex- pected, and the totality of the logging operations must be taken into account in choosing what to emphasize in the fitting process. For this reason, it is important to measure drawdown and pumping rate throughout the FFEC logging operation. The short duration of FFEC logging during drilling requires that the available time be used as efficiently as possible, which can be expedited by doing a preliminary analysis of the data in real time. Monitoring FFEC peak growth or lack thereof can determine whether or not additional profiles should be obtained. Monitoring drawdown and pumping rate can determine optimal values to select. A very feasible solution of the problem is to use three different 1-day breaks in the drilling schedule: the first to establish the optimal pumping rate to use and to monitor how long it takes for drawdown to stabilize to determine the timing of profiles; the second for logging at $h_{D1;}$ and the third for logging at $h_{D2} \sim h_{D1}/2$. If new hydraulically active fractures are encountered as the borehole depth increases between each break, the drawdown obtained for a given pumping rate may decrease, requiring a flexible, adaptive approach to

spaceoperations. This three 1-day FFEC logging testing proce- dure during drilling is highly recommended.

The preceding points show, on the one hand, lessons learned for an effective analysis of FFEC logging data during drilling, and on the other hand, lessons learned for improving the procedure for the 1-day FFEC testing such as better control of pumping rate and maximizing the drawdown value with the proper positioning of the pump in the borehole. The improve- ments for field test procedures should be possible to accom- plish without much trouble. The overall lesson is that with careful planning and thoughtful execution, much useful information can be obtained from FFEC logging, even when log- ging is conducted during drilling.

Summary and conclusions

The FFEC logging-during-drilling tests, test 1 and test 2, pro- duced key information about the hydraulically conductive fea- tures intercepting COSC-1 borehole between 250 and 2,000 m depth, which was confirmed and refined by follow-up tests, test 3 and test 4. Seven hydraulically conductive zones were identified, each localized over a small depth zone, suggesting that they are individual fractures. Flow rate q and salinity C of each zone were determined by fitting the FFEC profiles for test 1 and test 2 independently with the code BORE II. Then a multi-rate analysis was used to obtain the transmissivity T and hydraulic head h of the zones by combining results of the two tests, which were conducted with different drawdowns. Comparison with profiles obtained from test 3, conducted with a similar drawdown, but different baseline FEC to test 2, enabled refinement of flow zone properties. Test 4 was conducted with such a small drawdown that most peaks were absent, but multi-rate analysis with test 3 enabled estimates of the outflows from the borehole to the hydraulically conductive zones. Conducting multiple analyses and comparing the re- sults provided estimates of uncertainty associated with the zone properties.

Compared to the previous analysis of test 1 by Tsang et al. (2016), the present paper has made the following advances:
(1) determination of a distinct h value for each hydraulically conductive zone; (2) use of different baseline FEC levels to help constrain the C values for several zones; (3) confirmation and refinement of the results of tests conducted during the drilling period by follow-up tests conducted a year later; and
(4) joint re-analysis of data from all four tests, considering distinct h values, to provide the most constraints possible on the results.

All the inferred fracture properties—flow rate, salinity, transmissivity, and hydraulic head—varied greatly among the hydraulically conductive zones, as is typical of a poorly connected fracture network in low-permeability rock. Salinity

spacevalues are relatively low and hydraulic head variability sug- gests downward groundwater flow; both features are consis- tent with the mountainous setting of the COSC-1 borehole.

Despite the challenges discussed in the previous section, useful and critically important information from FFEC logging during 1-day breaks in drilling was obtained, with no impact on the drilling schedule and at minimal cost, as all the equipment needed was already available on site as part of the drilling operation.

The most basic information obtained is the depth of hydraulically conductive zones, which can be determined very accurately, typically within 10 cm, assuming that the depth value has been properly calibrated against other geophysical logging data. Given that the vast majority (about 97%) of fractures observed in core and logs are non-conductive, iden- tifying the conductive features is of utmost importance, both for its own sake and to guide deployment of further borehole characterization techniques such as fluid sampling and packer tests.

Next, inflow and outflow rates from the conductive zones and salinity of the formation fluid can be determined with reasonable accuracy by calibrating against BORE II models, which are also very useful information for designing further characterization studies. Finally, combining tests with differ- ent applied drawdowns enables estimates of the hydraulic head and transmissivity of individual fractures. There is great- er uncertainty associated with these estimates, but they are data not easy to obtain in any field tests and are critically valuable for understanding the overall pattern of groundwater flow through fractured rock.

Given the high value of the information that can be obtain- ed, and the relative ease of conducting the tests, it is strongly recommended that FFEC logging during drilling be consid- ered whenever suitable breaks in the drilling schedule occur. They can provide a wealth of information on the hydrology of the fractured rock in themselves, and offer essential guidance for designing and deploying more expensive, time-consuming characterization studies to be conducted after drilling is com- pleted. As a further recommendation, it will be most useful to conduct a post-drilling, regular FFEC logging test lasting about 1 week that includes an initial replacement of borehole water. Such a test would greatly improve the accuracy of hy- drologic data obtained from the deep borehole.

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$$T = \frac{(q_1 - q_2)\ln\left(\frac{r_{out}}{r_{wb}}\right)}{(h_{D1} - h_{D2})2\pi}$$

Dividing Eq. (1) for the first test by Eq. (1
test and solving for h yields

$$h = \frac{q_2 h_{D1} - q_1 h_{D2}}{q_1 - q_2}$$

$$C_1 = \frac{Cq_1 + C_{01}q_{up1}}{q_1 + q_{up1}}$$

$$C_2 = \frac{Cq_2 + C_{02}q_{up2}}{q_2 + q_{up2}}$$

If C_{rel} is defined as peak height relative to base
is defined as the ratio of C_{rel} for the two tests, t
state

$$C_{rat} = \frac{C_{rel2}}{C_{rel1}} = \frac{C_2 - C_{02}}{C_1 - C_{01}} = \frac{\left(\frac{Cq_2 + C_{02}q_{up2}}{q_2 + q_{up2}}\right) -}{\left(\frac{Cq_1 + C_{01}q_{up1}}{q_1 + q_{up1}}\right) -}$$

Simple algebra yields

$$C_{rat} = \left(\frac{C - C_{02}}{C - C_{01}}\right)\left(\frac{q_2}{q_1}\right)\left(\frac{q_1 + q_{up1}}{q_2 + q_{up2}}\right)$$

$$FEC(20^oC) = FEC(T_b)/[1 + S(T_b - 20^oC)]$$

where $S = 0.024\ °C^{-1}$.

The FEC values in these plots can be related t
NaCl concentration C through an approximate for
et al. 1990) valid for the range of FEC values en
this paper:

$$1\ FEC(\mu S/cm) \approx 1870C(g/L) \quad (9)$$

Table 1 Parameters obtained for each hydraulically conductive zor
formation flow (t_{01}, t_{02}), and salinity (C, same for both tests)

		Test 1			
		Low-C approach		High-C approach	
Peak No.	Depth (m)	q_1 (ml/min)	C (µS/cm)	q_1 (ml/min)	C (µS/cm)
1	1,243	14	1,700	11	2,200
2	1,214	18	1,150	41	620
3	696	21	1,000	14	1,400
4	553	13	1,800	7.7	2,900
5	508	4.8	1,800	3.5	2,800
6	338	1.7[a]	1,200	0.55[b]	2,900
7	288	55	380	54	380
Sum	–	127.5	–	109.9	–

Values of q_1, t_{01}, and C obtained by an independent analysis of test 1 (T
shown. Same value of t_0 is used for both low-C and high-C approach

[a] Increased to 2.7 for multi-rate analysis

[b] Increased to 0.85 for multi-rate analysis

[c] Upper limit

[d] Decreased to 1.9 for multi-rate analysis

[e] Decreased to 0.61 for multi-rate analysis

[f] Place-holder result

[g] Very uncertain

$$q = \frac{2\pi T}{\ln\left(\frac{r_{out}}{r_{wb}}\right)}(h + h_D)$$