Application of direct-fitting, mass integral, and multirate methods to analysis of flowing fluid electric conductivity logs from Horonobe, Japan

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1. Introduction

Knowledge of the locations and hydraulic properties of conductive features is needed to understand flow and transport through fractured rocks, which is required for a variety of practical applications, including geologic storage of nuclear waste, toxic chemicals and carbon dioxide, and exploitation of natural resources such as petroleum and geothermal fluids. Boreholes drilled deep into the rock are often used to obtain this information. Various downhole methods for studying fracture flow have been developed over the past few decades. Coring and geophysical methods may be able to locate the fractures, but they are unlikely to provide direct information on fracture flow properties. Straddle-packer pump testing yields fracture flow properties, but it is very time consuming and expensive. Flow-logging techniques are an attractive alternative: They measure flow directly and are efficient to deploy in the field. Several varieties of flow logging exist, including spinner surveys [Molz et al., 1989], heat pulse flowmeters [Paillet and Pedler, 1996; Paillet, 1998; Öhberg and Rouhiainen, 2000], tracer dilution analysis [Brainerd and Robbins, 2004], and the flowing fluid electric conductivity (FFEC) logging method, sometimes referred to as hydrophysical logging, the technique used in the present study.

To initiate the FFEC logging method, wellbore fluid is replaced with water of constant salinity different from that of the formation water, a process known as recirculation. Then FEC profiles in the wellbore are measured at a series of times while the well is pumped at a constant rate. Locations where native fluid enters the wellbore show peaks in the FFEC logs. By fitting the growth and movement of these peaks with a numerical model, one can infer inflow strengths and salinities of individual permeable features intersected by the borehole. Since Tsang et al. [1990] introduced the method, it has been widely applied in deep wells down to 1500 m or more [Kelley et al., 1991; Guyommet et al., 1993; Doughty et al., 2005], in inclined...
boreholes drilled in the underground Grimsel Test Laboratory [Marschall and Vonvoris, 1995], and extensively in shallower wells down to about 100 m [Evans et al., 1992; Pedler et al., 1992; Bauer and LoCoco, 1996; Paillet and Pedler, 1996; Karasaki et al., 2000]. Continued development of analytical and numerical data analysis techniques [Löw et al., 1994; Evans, 1995; Tsang and Doughty, 2003; Doughty and Tsang, 2005] have broadened the range of applicability and enhanced the ease of use of the method. Note that FFEC logging requires little or no specialized equipment or expertise, and may be carried out more quickly than most other methods, making it a valuable tool for efficient subsurface characterization.

Data analysis techniques include three main methods: (1) direct fitting of the time series of FFEC profiles, which yields the locations, inflow strengths, and salinities of permeable features [Tsang et al., 1990]; (2) the mass integral method, in which each FFEC profile is integrated over the entire logged interval to provide an estimate of salt mass in place as a function of time [Doughty and Tsang, 2005]; and (3) multirate FFEC logging, in which FFEC logging is repeated using two different well-pumping rates, which enables the transmissivities and inherent (far-field) hydraulic heads of the different permeable features to be determined [Tsang and Doughty, 2003]. Using multiple pumping rates to infer transmissivity and inherent hydraulic head of individual fractures has also been investigated in conjunction with use of a heat pulse flowmeter [Paillet, 1998, 2000] and tracer dilution analysis [Brainerd and Robbins, 2004].

Direct-fitting and multirate analyses for FFEC logging were recently carried out successfully for a 500-m-deep borehole in fractured granitic rock in the Tono region of Japan [Doughty et al., 2005]. The analyses identified 19 hydrologically conducting fractures, which showed a range of values for transmissivity, salinity, and hydraulic head. FFEC results compared well with static FEC profiles and independent chemical, geological, and hydrogeological data. The present paper describes a field application of the multirate FFEC logging method, using data from a 1000-m-deep well known as Well HDB-11, in fractured sedimentary rock in the Horonobe area of Japan. This case differs from the Tono application [Doughty et al., 2005] in several significant ways. Not only is the rock sedimentary instead of granitic, but also a number of complications are associated with the logging data, including (1) a section of the borehole having a variable wellbore diameter; (2) the presence of a free water surface in the borehole (i.e., the logged zone is not isolated with packers); (3) flow of low-salinity water into fractures during the initial recirculation period; (4) periods of unknown pumping rate during FFEC logging; (5) a small increase in salinity all along the borehole during FFEC logging, possibly arising from flow through the unfractured rock matrix itself or the diffusion of salt from residual mud used in drilling the well; (6) a gradual borehole water level decline during FFEC logging; (7) possible unknown inflows into the borehole from unmonitored borehole sections; and (8) sets of FFEC profiles that are not all internally consistent. Whereas the Tono application demonstrated the first field application of the multirate FFEC logging method, the Horonobe application examines the robustness of the method under nonideal conditions.

### 2. Methodology

This section gives a summary of data collection and analysis methods. Details of the data collection method are given by Doughty et al. [2005]. Details of the analysis method are given by Tsang et al. [1990], Tsang and Doughty [2003], Doughty and Tsang [2005], and Doughty et al. [2005].

#### 2.1. Data Collection

In the FFEC logging method, the wellbore water is first replaced by water of a constant salinity different from that of the formation water, a process known as recirculation. Deionization of native water is one convenient means to produce replacement water with a salinity contrast, but shallow groundwater may also be used if it has a salinity distinct from that of the formation of interest. For simplicity, replacement water is always referred to as deionized (DI) water below. Recirculation is done by injecting DI water through a tube to the bottom of the wellbore at a low rate, while simultaneously pumping from the top of the well at the same rate. The goal is to completely replace the wellbore water with DI water without altering wellbore hydraulic head, so that no DI water is pushed out into the formation or is any formation water pulled into the well. The FEC of the effluent is monitored throughout the recirculation period, which continues until a low stable FEC value is reached. If the final, stable, effluent FEC is substantially higher than the DI water FEC, it indicates that native fluid is entering the wellbore during recirculation. This may occur because wellbore hydraulic head was unintentionally dropped during recirculation. It can also occur if different permeable features intercepted by the wellbore have different inherent hydraulic heads, which sets up an unavoidable internal wellbore flow, with formation water entering the wellbore through features with higher hydraulic head and DI water entering the formation through features with lower hydraulic head.

Next, the well is shut in (i.e., injection and pumping are stopped) and the DI water tube is removed. Then the well is pumped from the top at a constant low flow rate \( Q_1 \) (e.g., several or tens of liters per minute), while an electric conductivity probe is lowered into the wellbore to scan the FEC as a function of depth. This produces what is known as a flowing FEC (or FFEC) log or profile. With constant pumping conditions, a series of five or six FFEC logs are typically obtained over a 1- or 2-day period. Optionally, the entire procedure may be repeated using a different pumping rate \( Q_2 \), typically half or double the original rate \( Q_1 \). Throughout the process, the water level in the well should be monitored.

#### 2.2. Data Analysis

At depth locations where native water enters the wellbore (inflow feed points), the FFEC logs display peaks. These peaks grow with time and are skewed in the direction of water flow. By analyzing these logs as described below, it is possible to obtain the inflow rates and salinities of groundwater inflow from the individual feed points. Although locations where water leaves the wellbore (outflow feed points) do not produce distinct peaks in the FFEC
logs, they can sometimes be identified by their impact on other peaks using a mass integral method [Doughty and Tsang, 2005]. By performing FFEC logging using different pumping rates, a procedure called multirate FFEC logging [Tsang and Doughty, 2003], the transmissivities and inherent hydraulic heads of the permeable features giving rise to the feed points can also be determined.

[10] The numerical models BORE [Hale and Tsang, 1988] and the enhanced version BORE II [Doughty and Tsang, 2000] calculate the time evolution of ion concentration (salinity) in the wellbore during FFEC logging by solving the one-dimensional advection-dispersion equation, given a pumping rate \( Q \) and a set of feed point locations \( z_i \), strengths \( q_i \), and salinities \( C_i \) (i.e., the forward problem).

Fluid flow in the wellbore is considered quasi steady; that is, fluid is assumed to be incompressible so it responds instantly to changes in pumping rate or feed point strength. Internal wellbore flow occurring during recirculation results in nonuniform salinity along the borehole, which may be accounted for in two ways. First, a nonuniform conductivity profile \( C_0(z) \) may be specified as the initial condition for the model. Second, a starting time \( t_0 \) may be specified for each feed point, to indicate the time after which fluid entering the wellbore has salinity \( C_i \), to reflect DI water that entered the formation during recirculation. Density differences between the original wellbore fluid (DI or low-salinity water, which may contain traces of drilling mud) and formation fluid flowing into the wellbore are neglected. Another version of the code, VHBOR[C Hale and Tsang, 1994], does consider compressible flow with compositional density differences, but it is not used here. The governing equations for BORE II are presented by Doughty and Tsang [2005].

[11] The general procedure for using BORE II is to assign feed point locations \( z_i \) by identifying individual peaks in the early time FFEC profiles, then to assign feed point properties \( (q_i, C_i, t_0) \) by trial and error until an acceptable match between modeled and observed FFEC profiles is obtained (i.e., an inverse problem). This procedure is known as direct fitting. Integrating the FFEC profiles over the entire logged interval or a desired subinterval (the mass integral method) provides an estimate of salt mass in the borehole interval under study as a function of time, which provides a useful constraint for the analysis. If FFEC logs were only collected using one pumping rate \( Q \), then the analysis would end here.

[12] However, if multiple sets of FFEC logs were collected using different pumping rates \( Q \), then the inverse procedure is repeated for each value of \( Q \), with the inverse problems constrained by requiring that the same set of \( z_i \) and \( C_i \) values be used for each one. Assuming that two sets of FFEC logs were collected with pumping rates \( Q_1 \) and \( Q_2 \), and that the strengths of individual feed points \( i \), as evaluated by BORE II, are \( q_i^{(1)} \) and \( q_i^{(2)} \) respectively, then Tsang and Doughty [2003] and Doughty and Tsang [2005] showed that

\[
\frac{T_i}{T_{tot}} = \frac{q_i^{(1)} - q_i^{(2)}}{Q_1 - Q_2} \tag{1}
\]

\[
I \Delta P_i = \left( \frac{q_i^{(1)}}{T_i/T_{tot}} - 1 \right) Q_1 \tag{2}
\]

where \( T_i/T_{tot} \) is the fraction of the total transmissivity of the logged interval corresponding to the fracture or permeable zone represented by the \( i \)th feed point (\( \Sigma T_i/T_{tot} = 1 \)) and \( \Delta P_i = P_i - P_{avg} \) where \( P_i \) is the inherent hydraulic head of fracture \( i \) and \( P_{avg} \) is the stabilized hydraulic head in the wellbore when it is shut-in for an extended time. \( I \) is a ratio known as the productivity index (in the petroleum literature) or specific capacity (in hydrology), which is defined as the ratio of pumping rate to steady state drawdown during a well test. \( I \) characterizes the entire permeable formation intersected by the wellbore in an average sense under steady state flow conditions. In the FFEC context, we may approximate \( I \) as

\[
I = \frac{Q_1}{P_{avg} - P_{wb}^{(1)}}, \tag{3}
\]

where \( P_{wb}^{(1)} \) is the hydraulic head in the wellbore (presumed constant) during the FFEC logging at \( Q = Q_1 \).

[13] The derivation of equations (1) and (2) assumes that the flow geometries within all the hydraulically conductive fractures intersecting the borehole are the same (e.g., all radial flow or all linear flow). The inherent (also known as far-field) hydraulic head \( P_i \) is the ambient or undisturbed hydraulic head in a fracture (or permeable layer) that the borehole intersects, and it is the value that would be measured under nonpumping conditions with packers inflated in the wellbore on either side of the fracture to isolate it for a substantial time period to attain steady state pressure conditions. In contrast, \( P_{avg} \) is the value that would be measured under nonpumping conditions when the wellbore has been open to all feed points in the logged interval for a substantial time period. \( P_{avg} \) can be calculated as a transmissivity-weighted average over all \( P_i \) values: \( P_{avg} = \Sigma(T_iP_i)/T_{tot} \). The head difference \( \Delta P_i = P_i - P_{avg} \) provides a measure of the driving force for fluid flow between hydraulically conducting fractures and the wellbore under nonpumping or shut-in conditions, which gives rise to internal wellbore flow. Note that from the definition of \( P_{avg} \) above, if all the \( P_i \) values are the same, then \( P_i = P_{avg} \), and so all \( \Delta P_i = 0 \), and there will be no internal wellbore flow under nonpumping conditions. In this case, equation (2) shows that feed point strength \( q_i \) is proportional to fracture transmissivity \( T_i \), making it possible to determine \( T_i/T_{tot} \) by matching FFEC profiles for just one pumping rate \( Q \).

[14] The quantities on the left-hand sides of equations (1) and (2) are the fundamental results of a multirate analysis, and they depend only on the \( q_i \) values obtained by matching FFEC logs for various \( Q \) values. If \( T_{tot}, I, \) and \( P_{avg} \) are known (e.g., from a conventional well test of the entire well section), then the \( T_i \) and \( P_i \) values themselves can be directly calculated from these two equations. Additionally, because \( T_i \) and \( P_i \) appear in ratios in equations (1) and (2), if one particular set of \( T_i \) and \( P_i \) are measured (e.g., from a well test on a packed-off interval across fracture \( j \)), then all the additional \( T_j \) and \( P_j \) values can also be determined.

[15] The multirate analysis requires two sets of FFEC logs at two pumping rates (at \( Q \) and \( 2Q \), for example), but if three sets of logs for three pumping rates, \( Q_1, Q_2, \) and \( Q_3 \), are available, then three sets of results can be obtained by analyzing three combinations of data sets: \( (Q_1, Q_2), (Q_2, Q_3), \) and \( (Q_1, Q_3) \).
and \( Q_3 \), and \( (Q_3 \ and \ Q_4) \). This permits internal checking, a means to evaluate measurement errors, and an estimate on the confidence level of the analysis results. One interesting option (not considered here) is to use \( Q = 0 \) for the first pumping rate, which has the advantage of investigating internal flow directly. If one logs at \( Q_1 = 0 \) and no peaks develop, then it immediately follows that there is no internal wellbore flow, and consequently that all \( P_i \) are the same. Then equation (1) may be used while logging at some \( Q_2 > 0 \) to determine \( T/T_{\text{tot}} \) (a procedure first suggested by Molz et al. [1989]). The disadvantage of logging with \( Q = 0 \) is that if there is internal flow, half the flow will be outflow, which is usually invisible on a FFEC profile, and hence much more difficult to analyze [Doughty and Tsang, 2005; Doughty et al., 2005].

3. Horonobe Well HDB-11 Data

[16] Horonobe, located in the northermost part of Hokkaido, Japan (Figure 1), is the site of an underground research laboratory (URL), where hydrogeochemical investigations are being conducted to develop technologies and methodologies that may in the future be applied during the geological disposal of high-level radioactive waste in sedimentary rock in Japan [Hama et al., 2007]. The main subsurface investigation area is about 3 km \( \times \) 3 km square, including the URL construction site, which is located about 15 km east of the present coastline of the Japan Sea. The gentle topography in the study area is thought to be a periglacial landform. Horonobe overlies Neogene sedimentary sequences (in ascending order, Souya coal-bearing Formation, Masuhoro Formation, Wakkanai Formation, Koetoi Formation, and Yuchi Formation), which are underlain by an igneous and Palaeogene-to-Cretaceous sedimentary basement. The Wakkanai and Koetoi formations, composed of Neogene argillaceous sedimentary rocks, are intercepted by Well HDB-11 and are also the host rocks for the URL.

[17] Hydrologic properties reported for the URL host rocks [Hama et al., 2007] include porosities up to 60% and hydraulic conductivities ranging from \( 2 \times 10^{-9} \) to \( 4 \times 10^{-8} \) m/s for the Koetoi Formation, and porosities of 30–40% and hydraulic conductivities ranging from \( 3 \times 10^{-10} \) to \( 8 \times 10^{-9} \) m/s for the deeper Wakkanai Formation. Hydraulic conductivity of the intact diatomaceous mudstone has been reported to be as low as \( 10^{-12} \)–\( 10^{-11} \) m/s [Shigeta et al., 2003], and thus the larger observed values of hydraulic conductivity are attributed to fluid flow through fractures or fracture zones.

[18] The area is tectonically active, and microearthquake swarms have occasionally occurred in and around Horonobe. The eastern margin of the Japan Sea is a well-defined seismic zone, especially for microearthquakes. The Omagari Fault, a NW-SE trending fault with surface trace inferred to be about 1 km east of Well HDB-11, was active until early Quaternary times and is believed to have a maximum vertical displacement of over 1000 m. Present-day active faults are thought to occur to the west of the Omagari Fault. In addition, historical coal mines were present in Horonobe, and oil/gas exploration work (including deep borehole investigations) has been conducted in the region. Further details of the Horonobe URL site are given by Hama et al. [2007].

[19] Well HDB-11 was drilled in four stages. FFEC logs were taken after the second stage of drilling from 150 to 450 m through the Koetoi Formation (hereinafter denoted the shallow zone), and after the third stage of drilling from 450 to 800 m through the Wakkanai Formation (hereinafter denoted the deep zone). During logging of each zone, the well was cased from the surface to the top of the logged zone, leaving the logged zone uncased.

[20] Figure 2 shows the caliper log for Well HDB-11. Over the depth interval of the shallow zone (Koetoi Formation, 150–450 m below ground surface (bgs)) the wellbore diameter is nearly constant at 164 mm. Over the depth interval of the deep zone (Wakkanai Formation, 450–800 m bgs) the wellbore diameter is more variable: Below 550 m depth, it is nearly constant at 162 mm, but above 550 m it gradually increases to 240 mm. This diameter increase will cause peaks in FFEC profiles to move upward more slowly. Thus if the change in borehole diameter is not accounted for, data analysis will result in feed point strengths that are underestimated over the depth interval 450–550 m.

[21] FFEC logging was repeated three times for both the shallow and deep zones, using different pumping rates, for a total of six tests. Prior to each logging period, recirculation occurred, in which groundwater with very low electrical conductivity (9 mS/m) was pumped from a nearby shallow well and injected into Well HDB-11 just below the bottom of the zone to be logged (10–15 m above the bottom of the well), while water was simultaneously pumped out of the top of the well at the same rate, using a submersible pump located near the ground surface. The total volume of water

![Figure 2. Caliper log for Well HDB-11.](image-url)
replaced during each recirculation period was 1.5 to 4 times the borehole volume. By the end of each recirculation period, the electric conductivity of the effluent had stabilized at less than 40 mS/m. There was a short quiescent period between recirculation and logging during which the well was shut in. Then, during the logging periods, water was pumped out of the top of the well using the same submersible pump used during recirculation.

[22] For the three shallow-zone tests, logging was conducted using pumping rates of 2 L/min, 10 L/min, and 19.1 L/min. Figure 3 shows the resulting FFEC profiles, and Figure 4 shows water level versus time for each test. For the three deep-zone tests, logging was conducted using pumping rates of 5 L/min, 10 L/min, and 15 L/min. Figure 5 shows the resulting FFEC profiles, and Figure 6 shows water level versus time for each test.

[23] Visual examination of the FFEC profiles (Figure 3 and Figure 5) indicates that not all the profiles can be used for analysis. In some cases it appears that the tool that measures fluid electric conductivity did not function at all (e.g., Figure 3, \( Q = 19.1 \) L/min, 5-h profile). In other cases, the results look qualitatively correct, but the profiles appear shifted with depth or otherwise distorted (e.g., Figure 5, \( Q = 5 \) L/min, 4- and 5-h profiles), suggesting that the tool did not move freely through the wellbore. Subsequent analysis suggested that the problems were caused by slime (muddy water used in drilling) adhering to the sensor. A total of seven FFEC profiles obtained during the six tests

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**Figure 3.** Original flowing fluid electric conductivity (FFEC) data for shallow zone.
primarily continued to decrease with time after \( Q_{I} \) equaled the total flow out \( Q_{tot} \) values assumed for the tests, with the water level in the wellbore dropped sharply during the high pumping-rate period, then declined at a nearly linear rate in response to the constant pumping rate (Figure 4). For the deep-zone tests, water level also dropped sharply during the first few minutes of the test, followed by a more gradual decline (Figure 6). The gradual decline of the deep-zone tests was less linear than for the shallow-zone tests, showing a decreasing rate of water level change. The times at which FFEC logs were collected are also shown in Figure 4 and Figure 6.

Figure 4. Water level data obtained during FFEC logging of shallow zone (dashed curve) and linear fit of the portion of the curve obtained while usable FFEC logs were collected (solid line). The early time sharp drop in water level is associated with a short-term increase in pumping rate. Times at which FFEC logging occurred are shown as boxes. The black-outlined box identifies the profile used as the initial condition for the BORE II model. The open box indicates an FFEC profile that could not be used for analysis.

were not included in the analysis because the FFEC profiles were not internally consistent with the remainder of the profiles; they are identified as “unusable FFEC profile” in Figure 3 and Figure 5.

The FFEC profiles collected at the end of the recirculation periods (the earliest profiles in Figure 3 and Figure 5) exhibited only small peaks, consistent with the low effluent FEC, indicating that little internal wellbore flow occurred during recirculation. This in turn suggests that there is little difference among the inherent hydraulic head values of the permeable features, and according to equation (2), that variations in inflow strength \( q_{I} \) primarily reflect variations in transmissivity \( T_{f} \).

Water level data (Figure 4 and Figure 6) were collected during the FFEC logging periods. For the shallow-zone tests, pumping rate increased by an unknown amount for a short period of time early in the tests, then returned to its specified value. The water level in the wellbore dropped sharply during the high pumping-rate period, then declined at a nearly linear rate in response to the constant pumping rate (Figure 4). For the deep-zone tests, water level also dropped sharply during the first few minutes of the test, followed by a more gradual decline (Figure 6). The gradual decline of the deep-zone tests was less linear than for the shallow-zone tests, showing a decreasing rate of water level change. The times at which FFEC logs were collected are also shown in Figure 4 and Figure 6.

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Moreover, because the water level declined throughout the logging period, we could not assume that the pumping rate during logging \( q \) equaled the total flow out of the formation, denoted \( Q_{form} \). Therefore we assumed that pumping rate \( q \) is the sum of two terms \( q = Q_{wb} + Q_{form} \), where \( Q_{wb} \) is water removed from the wellbore as the water level in the well declined. \( Q_{wb} \) can be estimated by multiplying the rate at which water level declined by the cross-sectional area of the wellbore at the depth of the water level. A linear decline in water level corresponds to a constant value of \( Q_{wb} \) and coupled with a constant value of \( q \) implies that \( Q_{form} \) is also constant, which greatly simplifies the BORE II analysis. For the shallow-zone tests, \( Q_{wb} \) was reasonably constant, suggesting that for time periods when \( q \) was constant, treating \( Q_{form} \) as a constant would be a reasonable assumption. Therefore the BORE II analysis did not attempt to match logs collected during the initial period of high pumping rate; instead, the first FFEC profile collected after \( Q \) became constant was used as the model initial condition. The FFEC logs that were not analyzed because \( Q_{form} \) could not be assumed constant are identified in Figure 5. Table 1 summarizes the \( Q, Q_{wb} \), and \( Q_{form} \) values assumed for the tests, with \( Q_{wb} \) determined from the slope of the linear fits to water level versus time data shown in Figure 4 and Figure 6.

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The presence of drilling mud in the wellbore may affect fluid logging two ways: through its salinity and its density. Possible salinity effects are described in section 4 below. Density effects were neglected in the analysis, because although the drilling mud itself is presumably significantly denser than formation fluid, most of the mud
should be flushed out of the wellbore during the initial recirculation period.

[29] In Well HDB-11, the borehole temperature varies from 11°C to 27°C over the depth range of FFEC logging. Prior to analyzing the FFEC logs with BORE II, the FEC values obtained in the field were temperature-corrected using the relationship [Schlumberger, Ltd., 1984]

\[ \text{FEC}(T) = \text{FEC}(20°C) / [1 + S(T - 20°C)] \]

with \( S = 0.024°C^{-1} \). This correction is required because BORE II assumes a constant temperature of 20°C.

[30] Typically during FFEC logging, electric conductivity in mS/m or \( \mu \)S/cm is converted to salinity in g/L, using a quadratic relationship developed by Hale and Tsang [1988]. However, for the present study, FEC values were above the range of applicability of the relation. Therefore no unit conversion was made and salinities \( C_i \) are presented in electric conductivity units mS/m.

4. Analysis of Shallow FFEC Logs

[31] The numerical model BORE II [Doughty and Tsang, 2000] was used to analyze the three sets of shallow-zone FFEC logs for three pumping rates \( Q = 2 \text{ L/min}, 10 \text{ L/min}, \) and \( 19.1 \text{ L/min} \), to obtain a set of inflow locations \( z_i \), feed point strengths \( q_i \), and salinities \( C_i \). First, the \( z_i \) values were obtained by visually examining early time FFEC logs obtained in the field, before individual peaks begin to interfere with each other. Generally, the \( z_i \) were easy to

Figure 5. Original FFEC data for deep zone.
determine with good accuracy. Given the inflow locations \( z_i \), the matching process was then conducted by using BORE II to model FFEC profiles with feed point strengths \( q_i \) and salinities \( C_i \) chosen by trial and error, in order to produce the best match to the FFEC logs obtained in the field. The \( C_i \) values for different depths \( z_i \) could vary among one another, but each \( C_i \) was maintained the same for all three data sets with different pumping rates. The feed point strengths \( q_i \) were allowed to be different for different \( z_i \) and for the different pumping rates.

The matching made use of the following facts: The area under an isolated FEC peak is proportional to the product \( q_i C_i \), the speed of a peak moving up the wellbore depends only on the sum of \( q_i \) values for the current and deeper peaks, and the steady state height of the deepest peak depends only on \( C_i \). The initial trial considered the \( C_i \) to be the same for all inflow points (corresponding to 1000 mS/m), but this restriction was relaxed as needed to improve the match. At the early stages of the fitting process, each test was treated individually. Later, the \( q_i \) values for all three tests were varied concurrently, using equations (1) and (2) to constrain possible values of \( q_i \), and \( q_i \) so that the three pairs of tests produced consistent results for \( T_i / T_{tot} \) and \( \Delta S \).

Figure 7 shows the best model fit to the subset of FFEC profiles that are amenable to analysis. The first profile shown for each test was used as the model initial condition, and as shown in Figure 4, this was the first profile collected after \( Q \) became constant. The deepest peak, barely visible at 438 m depth, was not analyzed, as it does not evolve like a peak caused by a normal inflow point. This peak may be caused by the drilling sludge at the bottom of the wellbore. The next three distinct peaks (depths of 350, 280, and 220 m) show classic growing and skewing behavior. Within a given test (e.g., Figure 7a), upward flow within the borehole ("upflow") increases as one moves up the borehole, so peak skewing increases, with the upgradient (deeper) limb of the peak becoming steeper and the downgradient (shallower) limb of the peak becoming flatter. Comparing tests with successively greater pumping rates (e.g., Figures 7a–7c, peak at 280 m) shows the same pattern: As pumping rate increases, upflow increases and peak skewing increases. The model matches for all these peaks are very good, and the distinctive dependence of peak features on upflow means that the corresponding estimates for feed point strengths are well constrained.

Another unknown parameter that was determined by trial and error along with the \( q_i \) and \( C_i \) values is the solute dispersion coefficient in the borehole. Because the FEC probe moves up and down the well, and the well is being pumped, this dispersion coefficient is generally several orders of magnitude bigger than the molecular diffusion coefficient. We obtained a value of 0.004 m²/s for the dispersion coefficient. Despite the common conceptual model that dispersion coefficient should increase with fluid

<table>
<thead>
<tr>
<th>( Q ) (L/min)</th>
<th>( Q_{wb} ) (L/min)</th>
<th>( Q_{form} ) (L/min)</th>
<th>( \Sigma q_i ) (L/min)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shallow tests</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.69</td>
<td>1.31</td>
<td>1.31</td>
<td>( \Sigma q_i ) unreliable because ( q ) of shallowest peak cannot be determined accurately</td>
</tr>
<tr>
<td>10</td>
<td>5.82</td>
<td>4.18</td>
<td>4.18</td>
<td></td>
</tr>
<tr>
<td>19.1</td>
<td>12.76</td>
<td>6.34</td>
<td>6.34</td>
<td></td>
</tr>
<tr>
<td>Deep tests</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1.66</td>
<td>3.34</td>
<td>2.04</td>
<td>( \Sigma q_i ) much less than ( Q_{form} )</td>
</tr>
<tr>
<td>10</td>
<td>3.16</td>
<td>6.84</td>
<td>3.90</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>7.15</td>
<td>7.85</td>
<td>5.12</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\)In each case, \( Q_{form} = Q - Q_{wb} \) with \( Q_{wb} \) determined from the slope of the linear fits to water level versus time data shown in Figures 4 and 6.
velocity, we found no need to use a velocity-dependent dispersion coefficient, either for different depth ranges within a single test or for tests with different pumping rates.

[13] The largest, shallowest peak at 164 m shows very little upflow (Figure 7), in fact, significantly less than the upflow shown by the smaller, deeper peaks. The upgradient limb of this peak is steep, consistent with the upflow inferred by matching the deeper peaks. However, the downgradient limb of this peak is not as flat as would be expected for continued upflow. This suggests that there is either an outflow just above the large, shallow peak, or an inflow of low-salinity water there. One possibility is that low-salinity shallow groundwater got into fractures at this level during the recirculation operation and is moving back into the wellbore during logging. This situation is too complicated to model with any accuracy, so the large shallow peak was not included in the quantitative analysis, but we inferred from this behavior that its transmissivity is large and its inherent hydraulic head is low.

[36] An interesting observation from the FFEC logs that has not been seen in previous studies involving granitic rock [Doughty et al., 2005] is that the FEC value grew uniformly in time where no discrete peaks were present (e.g., around 375 m depth in Figure 7). One possibility is that water was flowing slowly into the wellbore through unfractured portions of mudstone rock matrix. The hydraulic conductivity

---

**Figure 7.** Processed FFEC data and model fit for shallow-zone tests. Note the different vertical scales for different depth ranges.
of intact mudstone at the Horonobe URL site has been estimated to be 100–10,000 times lower than the hydraulic conductivity of fractures and fracture zones [Shigeta et al., 2003]. To simulate this formation flow, we introduced numerous tiny feed points distributed uniformly along the wellbore, all with the same $q_i$ and $C_i$ values. The $q_i$ values were then varied in concert to match the portion of FFEC profiles where no discrete peaks exist. Another possibility is that the wellbore walls were coated with drilling mud, which contains salt that diffused into the wellbore fluid, causing a small FEC increase all along the borehole interval without the inflow of any formation fluid. To simulate this effect, we maintained the same $q_iC_i$ product for the tiny points but increased $C_i$ and decreased $q_i$ by several orders of magnitude so that $q_i$ would be small enough to have a negligible effect on flow up the wellbore. Both these approaches resulted in a slightly improved match to the shallow FFEC profiles, but the derived parameters $q_i$ and $C_i$ for the FEC peaks were not significantly changed. In conclusion, for this particular data set, the discrete FEC peaks are large enough so that any matrix flow or diffusion effect can be neglected.

[37] The direct-fit results for the shallow-zone tests are shown in Figure 8. Note that the $C_i$ values are presented with FEC units of mS/m and that the values of $z_i$ and $C_i$ are the same for the three tests; only the $q_i$ values differ between the three tests. Comparison of the $C_i$ values with salinity and electric resistivity values found in other HDB Wells in the area [Yamamoto et al., 2002a, 2002b; Hama et al., 2007] shows that the values of $C_i$ obtained by FFEC logging are consistent with those obtained by independent measurements.

[38] The mass integral method provides a way to look at the overall behavior of all the fractures intersecting the wellbore at one time, and can provide useful information for helping the FFEC log fitting process. In the mass integral method, each $C(z)$ profile is integrated over the depth interval of interest to obtain the area $A(t)$ under the $C(z)$ profile at time $t$. Then, $A(t)$ is multiplied by the mean wellbore cross-sectional area to determine ion mass in place at time $t$, which is denoted the mass integral $M(t)$ (for the present study, with $C$ represented in FEC units mS/m rather than a salinity unit g/L, $M(t)$ is not a true mass, but the principle remains the same). If peaks reach the upper limit of the integration, a correction factor is introduced to account for mass being lost from the system, enabling subsections of the logged interval to be examined. Figure 9 shows a schematic diagram of three $M(t)$ integrals for the depth interval between 500 and 750 m.

[39] A plot of $M(t)$ versus $t$ will be linear if mass is being added to the wellbore fluid at a constant rate, which will occur if $q_i$ and $C_i$ do not vary in time for any feed points, and additionally if all feed points are inflow points. Thus deviations of $M(t)$ from linearity provide information on the validity of model assumptions. If $M(t)$ is concave up, it

---

**Figure 8.** Direct-fit results for shallow-zone tests: (a) feed point strength $q_i$ and (b) salinity (expressed as FEC in mS/m).

**Figure 9.** Schematic of the mass integral method for the depth interval 500–750 m.
increases in time (a transient response
was decreasing in time and
> 0 at which
values were introduced as needed to
increases in time (low-salinity
was increasing. Additionally, there is the possibility
decreases in time
and
T
M
M
is significantly less than
movement so that during pumping inflow begins with low
shallow groundwater moved into fractures during recircu-
lation and/or that
points are present.

Figure 10 very well; the model symbol would overlap at
multirate results for the shallow-zone logs. Coupled with the good matches to the FFEC profiles
themselves (Figure 7), and the fact that the feed point salinities are all within the range shown for other HDB
wells in the area [Yamamoto et al., 2002a, 2002b; Hama et
al., 2007], this consistency provides a measure of confi-
dence in the correctness of the FFEC-analysis results.

5. Analysis of Deep FFEC Logs

Because the water level declines for the deep-zone tests (Figure 6) are not linear, the mass integral analysis was
done for the deep-zone tests prior to direct fitting, to provide
guidance on which profiles may be most amenable to
analysis. Results are shown in Figure 12. All
profiles are concave up at early times, suggesting that consistent
with the water level data, \( Q_{w,d} \) was decreasing in time and
\( Q_{fb} \) was increasing. Additionally, there is the possibility
that early time \( C_i(t) \) was affected by low-salinity shallow
groundwater that moved into the fractures during recircula-
tion. Thus the late-time profiles, obtained when
\( M(t) \) is more linear, were emphasized in the fitting process. The FFEC
profiles used for the model initial condition for each test are
identified in Figure 12. Initial conditions were chosen so
that the model period corresponds to the time period when
\( M(t) \) and water level decline (Figure 8) are linear.

Matching the FFEC profiles for the deep-zone logs
followed the same procedure as for the shallow-zone logs
(described in the first paragraph of section 4). The initial
trial assumed that all feed points had the same salinity
(corresponding to 3000 mS/m). During the matching pro-
cess, variable \( C_i \) values were introduced as needed to
improve the match. For the dispersion coefficient, a value
of 0.005 m/s was obtained, nearly the same as for the
shallow zone.

The FFEC profiles used for the analysis and the best
model fit are shown in Figure 13. The match is excellent for
the peaks below 620 m. The match for the large peaks at
603 m and 611 m is not quite as good, and this error
propagates upward, making the matches for peaks above
600 m somewhat worse as well. Results for depths above
540 m are less certain because of the wellbore diameter
change. Direct-fitting results of the individual tests are
shown in Figure 14. Mass integral results for the best model
(not shown) match the observed \( M(t) \) data shown in
Figure 12 very well; the model symbol would overlap at
least half of observed symbol for all points. Multirate results
are shown in Figure 15 and Table 3. A total of 18 deep feed
points are identified.

It is interesting to note from Table 1 that the sum of
the feed point strengths \( \sum q_i \) is significantly less than \( Q_{fb} \). This could be partly attributable to the diameter change, but
calculations indicated that the magnitude of the diameter change is not nearly big enough to account for the whole discrepancy. A bigger issue is the uncertainty in \( Q_{\text{form}} \) itself. In a sensitivity study, we found that if the \( q_i \) values were increased enough so that \( \Sigma q_i = Q_{\text{form}} \), the resulting FFEC profiles showed far too much upflow. Therefore we hypothesize \( Q_{\text{form}} \) cannot be determined as \( Q/C_0 \) in \( Q_{\text{wb}} \), and that fluid is entering the wellbore above the logged interval, a phenomenon that has been noted at other sites [e.g., Karasaki et al., 2000].

6. Comparison With Packer Test Results

[46] During the surface-based investigations (phase 1) of the Horonobe URL project, conducted between years 2000 and 2005, a total of 11 deep boreholes (HDB-1 through HDB-11) were drilled for an underground investigation of the geological environment in and around the main URL area at Horonobe. Well HDB-11, the deepest borehole (1020 m) in the URL area, was drilled during 2005 and 2006. A sequential approach to hydraulic testing was used at Well HDB-11, in which packer inflation, shut-in, pressure recovery, pulse test, slug test, long-term pumping test, and packer deflation were sequentially conducted in each of 10 packed-off intervals. The transient pressure responses to the multiple testing events in each interval were measured. In order to calculate hydraulic parameters such as transmissivity, hydraulic conductivity, storativity, and specific storage for each interval, standard analysis methods assuming radial flow geometry, such as those of Cooper et al. [1967], Agarwal [1980], Hvorslev [1951], and Jacob [1947], were applied to the pressure-transient data. Then the best fit parameters were selected as the representative values. Table 4 summarizes the depths, estimated transmissivities, and static hydraulic heads of the packed-off intervals, and the analysis methods used for the successful tests.

[47] Packer test results were made available to us after the conclusion of our FFEC analyses. They provide transmissivity and inherent hydraulic head values for seven 10–80 m intervals along the borehole where FFEC logging was done (Figure 16). In order to compare FFEC analysis results for the normalized transmissivity of fracture \( i \), \( T_i/T_{\text{tot}} \), to packer test results for transmissivity of interval \( L \), \( T_{L-pt} \), individual values of \( T_i/T_{\text{tot}} \) were summed over the depth intervals of the packer tests to obtain \( T_{L-fec} \). Recall that transmissivity \( T \) (m²/s) is an extrinsic property (it is proportional to the product of intrinsic permeability and a

### Table 2. Multirate Analysis Results for Shallow-Zone Tests

<table>
<thead>
<tr>
<th>Peak Number</th>
<th>Depth (m)</th>
<th>( C_i ) (mS/m)</th>
<th>( T_i/T_{\text{tot}} )</th>
<th>( I_D ) (L/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>417</td>
<td>1000</td>
<td>0.013</td>
<td>−0.34</td>
</tr>
<tr>
<td>2</td>
<td>402</td>
<td>1000</td>
<td>0.019</td>
<td>−0.38</td>
</tr>
<tr>
<td>3</td>
<td>385</td>
<td>1000</td>
<td>0.065</td>
<td>−0.77</td>
</tr>
<tr>
<td>4</td>
<td>370</td>
<td>1000</td>
<td>0.007</td>
<td>−0.82</td>
</tr>
<tr>
<td>5</td>
<td>360</td>
<td>1000</td>
<td>0.014</td>
<td>−0.22</td>
</tr>
<tr>
<td>6</td>
<td>351</td>
<td>750</td>
<td>0.050</td>
<td>0.27</td>
</tr>
<tr>
<td>7</td>
<td>348</td>
<td>750</td>
<td>0.048</td>
<td>0.13</td>
</tr>
<tr>
<td>8</td>
<td>338</td>
<td>1000</td>
<td>0.013</td>
<td>0.29</td>
</tr>
<tr>
<td>9</td>
<td>332</td>
<td>1000</td>
<td>0.011</td>
<td>0.39</td>
</tr>
<tr>
<td>10</td>
<td>325</td>
<td>1000</td>
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<td>−0.40</td>
</tr>
<tr>
<td>11</td>
<td>316</td>
<td>1000</td>
<td>0.009</td>
<td>−0.19</td>
</tr>
<tr>
<td>12</td>
<td>312</td>
<td>1000</td>
<td>0.013</td>
<td>−0.55</td>
</tr>
<tr>
<td>13</td>
<td>299</td>
<td>1000</td>
<td>0.008</td>
<td>0.81</td>
</tr>
<tr>
<td>14</td>
<td>292</td>
<td>2000</td>
<td>0.007</td>
<td>1.63</td>
</tr>
<tr>
<td>15</td>
<td>287</td>
<td>2000</td>
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<td>0.83</td>
</tr>
<tr>
<td>16</td>
<td>282</td>
<td>2000</td>
<td>0.006</td>
<td>0.06</td>
</tr>
<tr>
<td>17</td>
<td>278</td>
<td>2000</td>
<td>0.036</td>
<td>0.36</td>
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<tr>
<td>18</td>
<td>262</td>
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<td>0.086</td>
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<tr>
<td>19</td>
<td>259</td>
<td>450</td>
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<tr>
<td>20</td>
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<td>0.041</td>
<td>−0.24</td>
</tr>
<tr>
<td>21</td>
<td>226</td>
<td>1000</td>
<td>0.221</td>
<td>−0.38</td>
</tr>
<tr>
<td>22</td>
<td>220</td>
<td>1000</td>
<td>0.044</td>
<td>0.22</td>
</tr>
<tr>
<td>23</td>
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<td>1000</td>
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<td>−0.08</td>
</tr>
<tr>
<td>24</td>
<td>211</td>
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<td>0.029</td>
<td>0.28</td>
</tr>
<tr>
<td>25</td>
<td>201</td>
<td>1000</td>
<td>0.061</td>
<td>0.67</td>
</tr>
<tr>
<td>26</td>
<td>190</td>
<td>1000</td>
<td>0.044</td>
<td>−0.28</td>
</tr>
</tbody>
</table>
The average inherent hydraulic head of interval $L$ is denoted $P_L$. The value measured by the packer tests is denoted $P_{L-pt}$. The value determined by FFEC logging is denoted $P_{L-fec}$, and is obtained by averaging over inherent head values of individual fractures $P_i$

$$P_{L-fec} = \sum_{i \leq L} P_i T_i / T_{L-fec}. \quad (5)$$

However, because the multirate FFEC logging method does not determine the $P_i$ values directly, but rather the $\Delta P_i$ group given by equation (2), equation (5) does not provide a simple means for determining $P_{L-fec}$. The actual procedure used was to first rearrange equation (2) to provide an expression for $P_i$ in terms of the outputs of a multirate FFEC analysis, $P_{avg}$, and $I$:

$$P_i = P_{avg} + \frac{Q_i}{T} \left( \frac{\sum_{i \leq L} q_i}{T_{L-fec}/T_{tot}} - 1 \right). \quad (6)$$

Then, assuming that inflow strength and transmissivity are additive (i.e., that the fractures respond independently), a comparable expression was written for $P_{L-fec}$:

$$P_{L-fec} = P_{avg} + \frac{Q_i}{T} \left( \frac{\sum_{i \leq L} q_i}{T_{L-fec}/T_{tot}} - 1 \right). \quad (7)$$

Recall that $I$ is defined in equation (3) as the ratio of pumping rate $Q$ to steady state drawdown $\Delta P$ for an open-borehole well test. For the present analysis, no independent well test was done, so the value of $I$ had to be determined from water level data collected during FFEC logging (Figure 4 and Figure 6), for which neither $Q$ nor $\Delta P$ can be determined unequivocally. For each zone, reasonably consistent values of $I$ were obtained for the three tests, by extrapolating the late-time water level data to estimate $\Delta P$ and, for the deep zone, using the sum of the model values of $q_i$ in place of $Q$. There is a significant degree of subjectivity in determining $I$, so there is a correspondingly large uncertainty in the resulting values of $P_{L-fec}$.

Equation (7) indicates that the value of $I$ controls the spread among $P_{L-fec}$ values for different $L$ intervals and that $P_{avg}$ simply provides a constant shift to the different $P_{L-fec}$ values. $P_{avg}$ was inferred to be the value which sets

$$\sum_L P_{L-fec} = \sum_L P_{L-pt}$$

within each zone. The resulting values of $P_{avg}$ for the shallow and deep zones are shown in Table 5.

[50] Figure 16 compares the transmissivities $T_L$ and hydraulic heads $P_L$ obtained from the packer tests with the results of the multirate analysis. Note that the deep logged interval extends to 775 m in depth, but no peaks develop below 700 m. This is consistent with the very low $T_{L-pt}$ value obtained for the 700–730 m depth interval, which is inferred to represent the unfractured rock matrix. For the shallow zone, the two $T_{L-pt}$ values are nearly the same, whereas the $T_{L-fec}$ values differ by about a factor of 2.
a reasonable agreement for fracture transmissivities, which can vary by orders of magnitude. For the deep zone, there are two $T_{L\text{-pt}}$ values shown for the depth interval 600–640 m. The larger one (from a slug test) is considered less reliable than the smaller one (from a long-term pumping test). The $T_{L\text{-fec}}$ and $T_{L\text{-pt}}$ values agree very well for the three intervals between 600 and 700 m depth. For the interval just above 600 m depth, $T_{L\text{-pt}}$ is again about a factor of 2 larger than $T_{L\text{-fec}}$. In this case, $T_{L\text{-fec}}$ may be the more accurate value, as it reflects flow through the permeable features at 565–585 m depth only. In contrast, $T_{L\text{-pt}}$ may reflect flow through the features at 565–585 m depth as well as flow from the higher-transmissivity interval at 600–640 m depth [Doughty et al., 2005].

Values of $P_{L\text{-fec}}$ are considered less reliable than $T_{L\text{-fec}}$ for two reasons. First, among the fundamental results of the matching process, $I\Delta P_i$ is less reliable than $T_i/T_{tot}$ because, by nature of its more complicated functional form (compare equations (1) and (2)), $I\Delta P_i$ is more sensitive to small errors in $q_i$ values than is $T_i/T_{tot}$. Second, the value of $I$ used to convert $I\Delta P_i$ to $P_i$ is highly uncertain, making $P_{L\text{-fec}}$ highly uncertain as well. With these caveats, the comparison of $P_{L\text{-pt}}$ and $P_{L\text{-fec}}$ shown in Figure 16 is considered reasonable. For the shallow zone, $P_{L\text{-pt}}$ values show more variability, whereas for the deep zone, $P_{L\text{-fec}}$ values show more variability, but the range of all the variations is relatively small, consistent with our findings from recirculation and logging initial conditions that internal wellbore flow is a minor effect.

7. Discussion

In the present paper, we addressed a number of nonideal conditions that may be encountered in FFEC logging. In a system with a rapid hydrologic response, the
water level in the borehole $P_{wb}$ would drop quickly in response to the onset of pumping, and remain at a steady value thereafter. Thus after a short transient period, $Q_{wb}$ would be zero and $Q_{form}$ would equal the pumping rate $Q$, a constant, and the steady-flow assumption of BORE II would be met. We would then be well justified to use the difference between the unpumped water level $P_{avg}$ and the pumped water level $P_{wb}$ as part of the multirate analysis. The nonsteady water level observed during logging in the present set of measurements (Figure 4 and Figure 6) indicates that the hydrologic response of the system to the initiation of pumping was quite slow, and in fact water level changed throughout the logging period. This complicated several facets of the FFEC analysis. At a fundamental level, the assumption of steady state flow from the formation to the wellbore, $Q_{form}$, which BORE II relies on, may not be valid. Thus there was a need to determine which portions of the logging period were most amenable to analysis. For this, we used water level data and mass integral analysis to ascertain when $Q_{form}$ was most constant: For a constant

![Figure 14](image)

**Figure 14.** Direct-fit results for deep-zone tests: (a) feed point strength $q_i$ and (b) salinity (expressed as FEC in mS/m).

![Figure 15](image)

**Figure 15.** Multirate results for deep-zone tests: (a) $T_i/T_{tot}$ and (b) $I\Delta P_i$. 

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pumping rate $Q$, a linearly declining water level implies a constant $Q_{wb}$, and hence a constant $Q_{form}$; a linearly declining $M(t)$ implies a constant $Q_{form}$ and also constant $C_i$ values. When $Q_{form}$ was uncertain, the constraint on the $q_i$ requiring $S_q = Q_{form}$ had to be relaxed.

Generally, with a slowly responding system, it is difficult to determine $P_{wb}$, and even difficult to ascertain whether the hydraulic head measured before pumping begins is truly representative of $P_{avg}$. An open-hole well test to determine $T_{tot}$, natural-state hydraulic head $P_{avg}$, and drawdown $P_{avg} - P_{wb}$ would remove some uncertainty. Such results would also be useful for comparing with FFEC results and to packer test results. Paillet [2004] has investigated difficulties associated with flow logging in slowly responding systems, and made several suggestions for ameliorating them. However, for the schedule required for FFEC logging, in which recirculation should take place with no hydraulic head change, followed immediately by logging, which must begin as soon as pumping is initiated to resolve early growth of FEC peaks, it is not clear if these suggestions can be applied.

For Well HDB-11, the shallow-zone tests showed more linear water level declines than did the deep-zone tests, enabling $Q_{form}$ to be ascertained with greater certainty. For the shallow-zone tests, a good match was obtained for all the small peaks. Only the uppermost, largest peak was not analyzable. It is fortunate that the peak that could not be analyzed is the shallowest peak, because as such it has no effect on any deeper peaks. Generally, any peaks occurring above a nonanalyzable peak would also be nonanalyzable.

For the deep-zone tests, a reasonably good match was obtained for all the peaks, but the nonlinearity of the water level decline indicated that $Q_{form}$ was not constant.

<table>
<thead>
<tr>
<th>Peak Number</th>
<th>Depth (m)</th>
<th>$C_i$ (mS/m)</th>
<th>$T_i/T_{tot}$</th>
<th>$\Delta P_i$ (L/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>674</td>
<td>3200</td>
<td>0.113</td>
<td>0.69</td>
</tr>
<tr>
<td>2</td>
<td>656</td>
<td>3000</td>
<td>0.065</td>
<td>-1.43</td>
</tr>
<tr>
<td>3</td>
<td>648</td>
<td>3000</td>
<td>0.029</td>
<td>-0.40</td>
</tr>
<tr>
<td>4</td>
<td>633</td>
<td>3000</td>
<td>0.029</td>
<td>-0.50</td>
</tr>
<tr>
<td>5</td>
<td>629</td>
<td>3000</td>
<td>0.021</td>
<td>-0.36</td>
</tr>
<tr>
<td>6</td>
<td>618</td>
<td>5000</td>
<td>0.011</td>
<td>-0.72</td>
</tr>
<tr>
<td>7</td>
<td>611</td>
<td>5300</td>
<td>0.382</td>
<td>-0.29</td>
</tr>
<tr>
<td>8</td>
<td>603</td>
<td>5000</td>
<td>0.016</td>
<td>1.25</td>
</tr>
<tr>
<td>9</td>
<td>591</td>
<td>5000</td>
<td>0.019</td>
<td>1.61</td>
</tr>
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<td>10</td>
<td>575</td>
<td>5400</td>
<td>0.049</td>
<td>2.18</td>
</tr>
<tr>
<td>11</td>
<td>566</td>
<td>5000</td>
<td>0.010</td>
<td>2.88</td>
</tr>
<tr>
<td>12</td>
<td>544</td>
<td>5000</td>
<td>0.002</td>
<td>-0.32</td>
</tr>
<tr>
<td>13</td>
<td>530</td>
<td>5200</td>
<td>0.078</td>
<td>-0.26</td>
</tr>
<tr>
<td>14</td>
<td>522</td>
<td>5000</td>
<td>0.036</td>
<td>0.88</td>
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<tr>
<td>15</td>
<td>484</td>
<td>3000</td>
<td>0.100</td>
<td>-0.21</td>
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<tr>
<td>16</td>
<td>478</td>
<td>3000</td>
<td>0.016</td>
<td>-0.23</td>
</tr>
<tr>
<td>17</td>
<td>473</td>
<td>3000</td>
<td>0.016</td>
<td>-0.23</td>
</tr>
<tr>
<td>18</td>
<td>463</td>
<td>3000</td>
<td>0.009</td>
<td>-0.28</td>
</tr>
</tbody>
</table>

Table 4. Summary of Packer Test Results

<table>
<thead>
<tr>
<th>Packed-Off Intervals</th>
<th>Test Results (Representative Values)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper End (m bgs)</td>
<td>Lower End (m bgs)</td>
</tr>
<tr>
<td>---------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>55.5</td>
<td>75.5</td>
</tr>
<tr>
<td>115</td>
<td>153</td>
</tr>
<tr>
<td>171</td>
<td>237</td>
</tr>
<tr>
<td>311</td>
<td>380</td>
</tr>
<tr>
<td>564</td>
<td>584</td>
</tr>
<tr>
<td>606</td>
<td>644</td>
</tr>
<tr>
<td>606</td>
<td>644</td>
</tr>
<tr>
<td>646</td>
<td>666</td>
</tr>
<tr>
<td>670</td>
<td>690</td>
</tr>
<tr>
<td>704</td>
<td>724</td>
</tr>
<tr>
<td>923</td>
<td>1000</td>
</tr>
</tbody>
</table>

$^a$Meters below ground surface.

$^b$Meters above ground surface.

$^c$The upper packer test labeled 606–644 shows the results of a slug test, while the lower test labeled 606–644 shows results of a long-term pumping test. Therefore the lower results are more reliable.
Table 5. Parameters Used for Comparison Between Results of Multirate Flowing FFEC Logging Analysis and Packer Tests

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Shallow</th>
<th>Deep</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth (m)</td>
<td>150–450</td>
<td>450–775</td>
</tr>
<tr>
<td>$T_{sat}$ (m$^3$/s)</td>
<td>$4.3 \times 10^{-7}$</td>
<td>$2.2 \times 10^{-6}$</td>
</tr>
<tr>
<td>$J$ (m$^3$/s)</td>
<td>$2.5 \times 10^{-6}$</td>
<td>$5.5 \times 10^{-6}$</td>
</tr>
<tr>
<td>$P_{avg}$ (mVs)*</td>
<td>1.5</td>
<td>5.9</td>
</tr>
</tbody>
</table>

*aMeters above ground surface.

again precluding the constraint $\sum q_i = Q_{form}$ from being used. In fact, it was impossible to match the profiles unless $\sum q_i \ll Q_{form}$, suggesting that inflow to the well occurred above the depth interval that was logged.

[57] During the deep-zone matching procedure, it became apparent that the FFEC profiles could be equally well matched with alternative sets of salinity values. $C_i$ values of 5000, 10,000, 15,000, or 25,000 mS/m could be assigned to feed points at depths around 600 m, and with suitable $q_i$ choices all could produce reasonable matches to the observed FFEC profiles. This nonuniqueness points out the usefulness of independent information when applying the FFEC method. Figure 17 compares FEC obtained from groundwater squeezed from core samples obtained during the drilling of Well HDB-11 with the $C_i$ values inferred from FFEC logging. There is not expected to be a one-to-one correspondence between the two independently obtained data sets, as core samples mainly contain groundwater held in the rock matrix, as opposed to FFEC analysis results, which reflect groundwater moving through fractures.

Because matrix permeability is much smaller than fracture permeability, the spatial range that the electric conductivity values represent is quite different. However, because there is expected to be at least some communication between fracture and matrix fluids, core sample FEC values should be useful to constrain the order of magnitude of FFEC analysis values. Additionally, differences between core sample values and FFEC analysis values may indicate areas where fluid flow through fractures is significant.

[58] Figure 17 shows that core samples have a maximum FEC of 3500 mS/m. This certainly favors the FFEC analysis using $C_i = 5000$ mS/m for feed points at 600 m depth as opposed to the analyses using higher $C_i$ values. FFEC matching was attempted using $C_i \approx 3500$ mS/m, consistent with the HDB-11 core sample values, but the model produced far too low a peak at a depth of 600 m, regardless of the $q_i$ values chosen. Moreover, groundwater squeezed from core samples from Well HDB-1, located about 500 m NW of Well HDB-11, produced FEC values as high as 6000 mS/m for depths around 600 m [Hama et al., 2007], corroborating the plausibility of the FFEC-analysis results.

[59] For the shallow zone, Figure 17 shows an increase in FEC at a depth of about 280 m in both data sets, but the FEC values used in the FFEC analysis are consistently smaller than the core sample values. FFEC matching was attempted using larger $C_i$ values consistent with core sample results, but the correspondingly smaller $q_i$ values produced far too small an upflow in the wellbore. Again, core samples from Well HDB-1 provide support for the use of smaller $C_i$ values, showing FEC values around 1000 mS/m for depths of 300–400 m [Hama et al., 2007].

8. Concluding Remarks

[60] In spite of the various complications associated with the test data described in the analysis sections above, the 6 days of FFEC logging have yielded internally consistent information on location, salinity, and transmissivity and inherent hydraulic heads of 44 conducting fractures. Data collection included 3 days of FFEC logging for the shallow zone (Koetoi formation, 150 to 450 m depth; Table 2) and 3 days of FFEC logging for the deep zone (Wakkanai formation, 450 to 775 m depth; Table 3). Among the results, location is determined unequivocally and transmissivity is considered to be well determined. Salinity and hydraulic head values are somewhat less certain, but the small variability among hydraulic head values makes the latter uncertainty of minimal importance.

[61] A careful study was made to compare the detailed results on these 44 conducting fractures with transmissivity and hydraulic head data obtained from packer tests for seven intervals with length ranging from 10 to 80 m. Overall, it has been shown that the FFEC logging results are consistent with these independent data. The success of the FFEC analysis method under these nonideal conditions provides evidence of the robustness of the method. Further, FFEC results provide more detailed information than packer tests, as they yield hydraulic properties of individual fractures rather than averaged properties of the intervals between packers.

Figure 17. Comparison of FEC values inferred from FFEC logging and electric conductivity from groundwater squeezed from core samples from Well HDB-11.
A number of further analyses are possible, in order to improve confidence in the results. We could specify time-dependent feed point strengths $q_i(t)$, to account for a time-dependent $Q_{\text{form}}$, and time-dependent feed point salinities $C_i(t)$, to account for the presence of low-salinity shallow groundwater water in the fractures at the onset of pumping. We could also model the recirculation period and the rest period between the end of the recirculation period and the onset of pumping as was done for the Tono FFEC logging analysis [Doughty et al., 2005], in order to develop insight into internal flow and produce more accurate initial conditions for the logging period. For the deep-zone tests, we could try to account for the variable wellbore diameter. It may be possible to do this with fictitious outflow points as was done by Doughty et al. [2005] for a simple one-time change in borehole diameter. Another alternative would be to modify the BORE II code itself to enable variable borehole diameters to be considered.

Concerning potential improvements of field test procedures for future FFEC logging applications, we make the following recommendations. If possible, do recirculation at a lower rate to maintain wellbore hydraulic head closer to $P_{\text{avg}}$ and thus, to minimize flow of low-salinity groundwater water into fractures. Keep the pumping rate constant during logging, or at least measure rate changes if they are unavoidable. Continue logging until logs show evidence of the approach to steady state FFEC profiles (plateaus). Plateaus greatly reduce ambiguity in parameter choice for diffusion coefficient, $q_i$, $C_i$. Continue logging until water level in the wellbore is constant or linearly declining, to enable $Q_{\text{form}}$ to be determined unambiguously. If possible, emplace a packer in the well just above the pump to avoid the problem of a declining water level in the well during pumping (i.e., setting $Q_{\text{ob}} = 0$). If a profile of FEC is distorted by muddy water adhering to a sensor, withdraw and clean the sensor and repeat the log. Obtain and use (at least) one salinity measurement at a deeper borehole inflow point in FFEC log analysis. This can greatly reduce the nonuniqueness inherent in matching peaks that do not move strongly up the well.

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