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Multirate flowing fluid electric conductivity logging method

Chin-Fu Tsang and Christine Doughty

Earth Sciences Division, Ernest Orlando Lawrence Berkeley National Laboratory, University of California, Berkeley, California, USA

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[1] The flowing fluid electric conductivity logging method involves the replacement of well bore water by deionized or constant-salinity water, followed by constant pumping with rate Q, during which a series of fluid electric conductivity logs are taken. The logs can be analyzed to identify depth locations of inflow and evaluate the transmissivity and electric conductivity (salinity) of the fluid at each inflow point. The present paper proposes the use of the method with two or more pumping rates. In particular, it is recommended that the method be applied three times with pumping rates Q, $Q/2$, and $2Q$. Then a combined analysis of the multirate data allows an efficient means of determining transmissivity and salinity values of all inflow points along a well with a confidence measure, as well as their ambient or "far-field" pressure heads. The method is illustrated by a practical example. *INDEX TERMS:* 5104 Physical Properties of Rocks: Fracture and flow; 5114 Physical Properties of Rocks: Permeability and porosity; 0915 Exploration Geophysics: Downhole methods; 1894 Hydrology: Instruments and techniques; *KEYWORDS:* fluid logging, heterogeneous porous media, fracture flow, hydrologic characterization

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1. Introduction

[2] In the study of flow and transport in the subsurface, knowledge of flow zones and their hydraulic properties is essential. Often such knowledge is obtained through testing in boreholes penetrating into the ground for tens to thousands of meters. The objective of the tests is to determine the flow transmissivity T as a function of depth. Since the subsurface is typically heterogeneous, the transmissivity is expected to vary with depth, and the variability will be a function of spatial resolution along the borehole: the finer the resolution, the stronger the variability. For the particular case of fractured rock, flow will be localized to a number of discrete depth levels, corresponding to positions where the borehole intercepts hydraulically conductive fractures. In this paper, these locations along the borehole are designated as feed points, or feed zones if flow occurs through a thick permeable layer penetrated by the borehole.

[3] In addition to having individual T values, a feed point or zone is also characterized by its ambient "far-field" pressure head h and its salinity C. Here we define the ambient pressure head h of a flow zone as the steady (or pseudo-static) pressure head when the flow zone is isolated for a significant time period. The salinity C of the fluid flowing from the conductive rock zones into the borehole, in the context of this paper, is not considered to be directly measured. Instead, it is inferred from the fluid electric conductivity (FEC), which can be simply related to salinity or equivalent NaCl concentration C in g/L by [*Shedlovsky and Shedlovsky*, 1971]

$$\mathrm{FEC} = 1870\, C - 40\, C^2, \tag{1}$$

where FEC is measured at 20°C. For FEC measured at another temperature T in °C, *Schlumberger Ltd.* [1984] provides a conversion:

$$\mathrm{FEC}(20^\circ) = \frac{\mathrm{FEC(T)}}{1 + S(\mathrm{T} - 20^\circ)}, \tag{2}$$

where S is a parameter with value $0.024°\mathrm{C}^{-1}$. Often salinity increases with depth; however, it may also vary more erratically, depending on the flow paths that lead to a particular feed point. It has been noted in the field that two neighboring inflow points can have salinities that differ by as much as a factor of 5–10 [*Tsang et al.*, 1990].

[4] The ambient hydraulic heads of multiple feed points or zones in a borehole far from recharge or discharge areas would not vary with depth if the medium were homogeneous and well connected to a common land-surface level. However, the subsurface is normally heterogeneous and, in the case of a fractured medium, it is often hydraulically compartmentalized into discrete regions, each having a slightly different hydraulic head. These head differences at feed points along a well cause what is known as well bore internal flow; i.e., when the well is shut-in with no pumping out of or into the well, water flows into the well from points with higher pressure heads and exits at points with lower pressure heads.

[5] Making the measurements of T_i, C_i, and h_i for each feed point i along the well bore is a time consuming exercise. One typical method is to install a double packer across a feed point and then conduct a pumping test in the packed-off interval by measuring the pressure drawdown for the particular pumping rate applied. An analysis of such data will yield T_i. Similarly, C_i can be obtained by measuring the FEC value or C_i in the interval, after sufficient pumping is done to ensure that the formation fluid has fully

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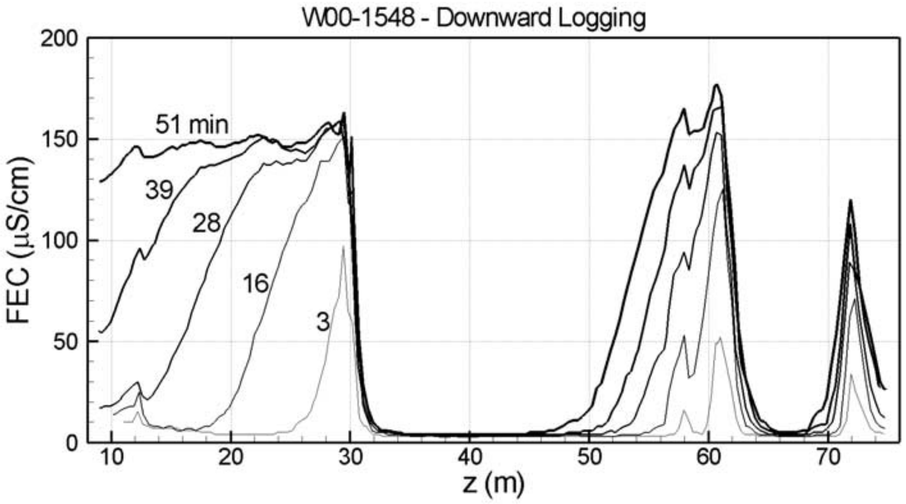

Figure 1a. FEC logs from the Raymond field site in California [*Cohen*, 1995]. The labels on the curves identify elapsed time in minutes from the start of logging.

replaced the initial fluid in the tubing and the packer interval. The ambient pressure head h_i for the inflow point can also be obtained by monitoring the pressure in the packer interval with no pumping for an extended time until the pressure equilibrates with the ambient, far-field pressure in the feed zone or conductive fracture. These measurements have to be conducted one feed point at a time. For a 500-m well in fractured rock, for example, there could be more than 20 inflow points, and it is quite laborious and time consuming to perform these tests one by one for each point.

[6] The flowing FEC logging method [*Tsang et al.*, 1990] was proposed as a method that can measure T_i effectively, and has been shown to take much less time than the packer test method (though the latter method can yield other information such as the flow geometry of the conductive zone and the distances to boundaries). The flowing FEC logging method also measures C_i of the flow zones. It has been applied regularly by *Kelly et al.* [1991], *Guyonnet et al.* [1993], and by *Marschall and Vomvoris* [1995] in deep wells down to 1500 m or more, and in inclined boreholes drilled in the underground Grimsel Test Laboratory. It has also been applied extensively by *Pedler et al.* [1992], *Evans et al.* [1992], and *Bauer and LoCoco* [1996] in shallower wells down to about 100 m. Additions to the analysis methods were made by *Evans* [1995]. More recently, *Doughty and Tsang* [2002] further improved the analysis method, on the one hand to allow analysis of natural regional flow, and, on the other, to provide distinctive signatures to help with log analysis.

[7] This paper builds on the earlier studies and introduces the concept of combined analysis of logs with two or more pumping rates. It is shown that such multirate logging will provide results not only for T_i and C_i, and but also for h_i. To be able to obtain these parameters for all feed points or zones along a well bore with two or three sets of measurements represents a powerful and potentially very useful tool in the study of flow and transport in heterogeneous media.

[8] The following section summarizes the basic flowing FEC logging method. Then the concept and analysis of the multiple-rate fluid logging method are presented. On the basis of actual field data, a set of synthetic logs with multiple rates is generated and analyzed with the new technique to demonstrate the new approach. Finally, some practical considerations for conducting such a field test are discussed. The paper concludes with some general remarks.

2. Flowing Fluid Electric Conductivity Logging Method

[9] The basic discussion of the method is given by *Tsang et al.* [1990]. In this method, the well bore water is first replaced by deionized water or, alternatively, by water of a constant salinity distinctly different from that of the formation water. This is done by passing the deionized water down a tube to the bottom of the borehole at a given rate, while simultaneously pumping from the top of the well at the same rate. Next, the well is shut in and the tube is removed. Then the well is pumped from the top at a constant low flow rate Q (e.g., a few liters per minute), while an electric conductivity probe is lowered into the borehole to scan the fluid electric conductivity (FEC) as a function of depth. With the constant pumping condition, a series of five or six FEC logs are typically obtained over a few-hour to one- or two-day period. At depth locations z_i where water enters the borehole (the feed points), the logs display peaks. Thus these peak locations give the depths of the inflow points or zones (with typical resolution of about 10 cm). These peaks grow with time and are skewed in the direction of water flow. The area under a peak is proportional to q_iC_i (where q_i is inflow rate at a particular feed point) and the skewness of the peak depends on Σq_i over the inflow points below (or upstream of) the point in question. Thus by analyzing these logs, it is possible to obtain the flow rate and salinity of groundwater inflow from each individual feed point.

[10] Figures 1a and 1b show two typical FEC logs. Figure 1a is from measurements in an 80-m well labeled "W00" at the Raymond field site in California, where a comprehensive study of field test methods to characterize

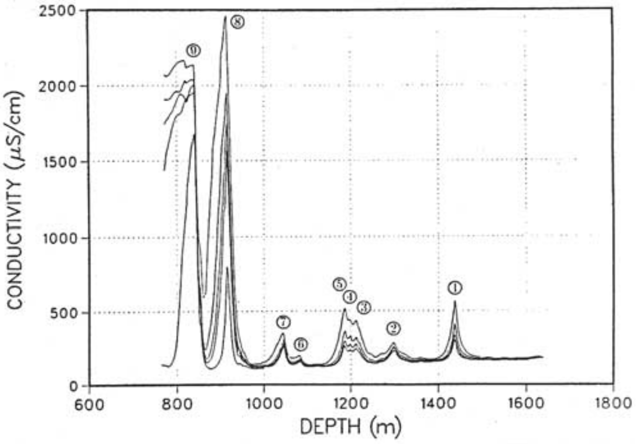

Figure 1b. FEC for the logged 770 to 1610 m section of the 1690 m Leuggern borehole in northern Switzerland [*Tsang et al.*, 1990]. The circled numbers identify feed points.

fracture hydrology was conducted [*Cohen*, 1993, 1995; *Karasaki et al.*, 2000]. The logs were taken over a period of about one hour after the well water was replaced by deionized water and pumping was initiated. The pumping rate from the well was 9 L/min. Five inflow points were identified over the 80-m depth. Figure 1b shows the FEC logs in a deeper well in northern Switzerland [*Tsang et al.*, 1990]. Five logs were taken along a depth interval from 700 to 1650 m over a two-day period. Nine inflow points were identified.

[11] The numerical model BORE [*Hale and Tsang*, 1988; *Tsang et al.*, 1990] and the recently enhanced version BORE II [*Doughty and Tsang*, 2000] calculate FEC profiles, given a set of inflow locations z_i, feed point flow rates q_i, and salinities C_i. The BORE II code solves the one-dimensional advection-diffusion equation for flow and transport along the well using the finite difference method, assuming (1) feed points act as mass sources or sinks, (2) fluid flow is steady, and (3) complete mixing occurs across the well bore cross-sectional area. BORE II is typically employed in a trial-and-error inverse process to obtain feed point parameters by comparing calculated FEC profiles to observed FEC logs.

3. Multirate Logging Method

[12] To date, the flowing FEC logging method has been applied to the analysis of a set of logs with one constant pumping rate Q from the well. The values of z_i, q_i and C_i are obtained through the use of the BORE or BORE II code. Then the transmissivity of each inflow point, T_i, can be calculated from q_i and the pressure-head drawdown in the well bore Δh_{wb}.

[13] We show below that by simultaneously analyzing one or more additional sets of flowing FEC logs with different Q values, not only T_i and C_i can be determined with better confidence, but the ambient pressure heads of each inflow point h_i can also be obtained. In principle, two sets of logs with two different Q values are enough. However, three sets at three different Q values are recommended to provide additional internal checking of the results.

[14] Let us consider a well bore containing N inflow points. The strength of the ith feed point is q_i and $\Sigma q_i = Q$. By convention, inflow points have positive q_i and outflow points have negative q_i. Upflow from below the studied interval can be absent (e.g., the lower end of the interval is at the well bottom or at an inflated packer), or represented by an additional feed point at the lower end. For each feed point, q_i and concentration C_i are assumed to be constant in time, i.e., they are under steady state (or pseudo-steady state) condition. Let us further assume that the flow toward the well is describable by Darcy's Law and that the flow geometry is radial. The general approach still holds even if the flow geometry is not radial, but the flow geometries must be the same for all flow zones. Under these assumptions, the strength of a feed point q_i is related to its hydraulic transmissivity T_i^*, the ambient "far-field" pressure head h_i at a distance r_i away from the well bore, and the pressure head h_{wb} at the well bore radius r, through the Darcy law as follows:

$$q_i = \frac{2\pi T_i^*(h_i - h_{wb})}{\ln(r_i/r)} = T_i(h_i - h_{wb}), \tag{3}$$

where T_i represents an effective hydraulic transmissivity, into which the constant factors involving radial distances have been lumped. Equation (3) describes the case of a horizontal flow zone tapped by a vertical well. If no density-driven flow is present, the equation also applies to the more general case of nonhorizontal flow zones tapped by a nonvertical well, in which case the distances r and r_i are interpreted as distances measured in the plane of the flow zone. The hydraulic transmissivity within the well bore itself is normally much greater than that of any inflow zone, so that h_{wb} is constant over the well bore interval being studied. Since $\Sigma q_i = Q$, we can write

$$Q = \sum T_i(h_i - h_{wb}). \tag{4}$$

[15] If we now alter the pumping rate from Q to Q', T_i and h_i remain unchanged but h_{wb} becomes h'_{wb}, and

$$q'_i = T_i\left(h_i - h'_{wb}\right) \tag{5}$$

$$Q' = \sum T_i\left(h_i - h'_{wb}\right). \tag{6}$$

Taking the difference between equations (3) and (5) and between equations (4) and (6) give, respectively,

$$\Delta q_i = T_i\left(h_{wb} - h'_{wb}\right). \tag{7}$$

$$\Delta Q = T_{tot}\left(h_{wb} - h'_{wb}\right) \tag{8}$$

where $\Delta q_i = q'_i - q_i$, $\Delta Q = Q' - Q$, and $T_{tot} = \Sigma T_i$.

[16] Equations (7) and (8) can be combined to yield

$$\frac{T_i}{T_{tot}} = \frac{\Delta q_i}{\Delta Q} \tag{9}$$

which is the fundamental relationship between the change in feed-point strength Δq_i and the change in pumping rate

ΔQ. Note that Δq_i is directly proportional to T_i, and thus the feed points with larger hydraulic transmissivity show greater changes in strength when Q is modified. In particular, if the jth feed point has a much larger hydraulic transmissivity than all the others ($T_j \approx T_{tot}$), then $\Delta q_j \approx \Delta Q$ and all the other feed-point strengths will not change much. This situation might arise if the well intercepts an extensive feed zone that has not been excluded from the logging section by packers.

[17] Equation (7) can be used to relate T_i to a particular T_j at feed point j

$$\frac{T_i}{T_j} = \frac{\Delta q_i}{\Delta q_j}. \tag{10}$$

Furthermore, when we divide equation (3) by equation (7) we obtain

$$\frac{q_i}{\Delta q_i} = \frac{h_i - h_{wb}}{h_{wb} - h'_{wb}} \tag{11}$$

so that

$$\frac{h_i - h_{wb}}{h_j - h_{wb}} = \frac{q_i/\Delta q_i}{q_j/\Delta q_j} \tag{12}$$

This means that if we know the T_j and h_j for a particular feed point (e.g., by means of a normal pressure test using a double-packer to isolate it), we can use the analysis results q_i and Δq_i of two-rate flowing FEC logs, to obtain T_i and h_i for all the other feed points by means of equations (10) and (12) without having to make double-packer pressure tests for the feed points one by one. Note that equations (10) and (12) consider only two feed points at a time, and are not dependent on inaccuracies in measurements of the other inflow points and in the total quantities Q and T_{tot}.

[18] There are several special cases of equation (9) that are of interest. If all the T_i values are the same, then $T_i = T_{tot}/N$, and equation (9) simplifies to

$$\Delta q_i = \frac{\Delta Q}{N}, \tag{13}$$

where N is the number of feed points. In this case, when Q is modified, all feed-point strengths change by the same amount.

[19] On the other hand, if the h_i values are all the same, then combining equations (3) and (4) yields

$$\frac{q_i}{Q} = \frac{T_i}{T_{tot}}. \tag{14}$$

Then, substituting for T_i/T_{tot} using equation (9) gives

$$\frac{q_i}{Q} = \frac{\Delta q_i}{\Delta Q}. \tag{15}$$

Note that when all the h_i values are the same, feed points must be either all inflow points or all outflow points. In this case, when Q is modified, the relative change of each feed point $\Delta q_i/q_i$ is the same and is equal to the relative change of Q, i.e.,

$$\frac{\Delta q_i}{q_i} = \frac{\Delta Q}{Q}. \tag{16}$$

Conversely, increasing or decreasing Q by a factor of two and finding q_i not changed by the same factor of two is a clear indication that the h_i values are not the same.

[20] Finally, if all the T_i values are the same and all the h_i values are the same, then according to equation (3), all the q_i values must be the same. Thus $q_i = Q/N$, and equations (13) and (16) become equivalent.

[21] The above development provides a practical way to analyze flowing FEC logs when two sets of logs, obtained with Q and $Q + \Delta Q$, are available. Let us assume that we apply the BORE II code to each set and obtain the q_i values and C_i values. Then equation (9) can be used to obtain T_i/T_{tot}. Further, we can rewrite equation (4) as

$$Q = \Sigma T_i(h_i - h_{wb}) = T_{tot}\left(h_{avg} - h_{wb}\right), \tag{17}$$

where h_{avg}, defined as

$$h_{avg} = \Sigma(T_i h_i)/T_{tot}, \tag{18}$$

is the hydraulic-transmissivity weighted average of the ambient pressure heads. Note that h_{avg} can be measured by a pressure probe in the well bore when it is shut-in, because with $Q = 0$, equation (17) gives $h_{wb} = h_{avg}$.

[22] Taking the ratio of equation (3) and equation (17), then rearranging, yields

$$\frac{\left(h_i - h_{avg}\right)}{\left(h_{avg} - h_{wb}\right)} = \frac{q_i/Q}{T_i/T_{tot}} - 1. \tag{19}$$

Using equation (9) to eliminate T_i/T_{tot} yields a convenient measure of feed point ambient pressure head

$$\frac{\left(h_i - h_{avg}\right)}{\left(h_{avg} - h_{wb}\right)} = \frac{q_i/Q}{\Delta q_i/\Delta Q} - 1. \tag{20}$$

The group on the left-hand side provides a dimensionless measure of the departure of feed point ambient pressure head from h_{avg}. Note that all the terms on the right-hand side can be obtained from a BORE II analysis and the denominator in the left-hand side of equation (20) is nothing other than the pressure head draw-down in the well when it is pumped at rate Q, and this can be measured directly.

[23] Note also that the right-hand side of equation (20) is a linear function of only one variable, $q_i/\Delta q_i$, the other terms being constants for a given set of flowing FEC logs. Thus a plot of $q_i/\Delta q_i$ versus depth is also a measure of the ambient pressure head variation among the flow zones along the well, so that those flow zones with similar $q_i/\Delta q_i$ have similar ambient pressure head, possibly indicating that they are well connected to one another.

[24] In summary, equations (9) and (20) provide the fundamental formulas that enable the use of quantities provided by a combined BORE II analysis of multirate

Table 1. Parameters of Example Application

z_i,[a] m	q_i,[a] L/min	C_i,[a] g/L	T_i/T_{tot} (Constant h_i)[b]	$(h_i - h_{avg})/(h_{avg} - h_{wb})$[c]	T_i/T_{tot} (Variable h_i)[d]	T_i,[e] m^2/s
12	0.72	0.15	0.08	−0.76	0.34	6.8×10^{-6}
26.1	4.00	0.07	0.43	0.99	0.22	4.4×10^{-6}
29.2	2.41	0.16	0.26	0.99	0.14	2.8×10^{-6}
44[f]	−0.30[f]	0.15[f]	–	−1.51	0.06	1.2×10^{-6}
58.1	0.66	0.12	0.07	−0.01	0.07	1.4×10^{-6}
61	1.40	0.12	0.15	−0.01	0.16	3.2×10^{-6}
72	0.10	0.52	0.01	0.49	0.01	2.0×10^{-7}

[a] Fit to field data using BORE II.

[b] Assume constant $h_i = h_{avg}$ (see equation (14)).

[c] Variable h_i (set externally).

[d] Assume column 5 (see equation (19)) .

[e] Use T_{tot} from open-hole well test.

[f] Not part of the original match to field data; added for the synthetic data set.

logging data to calculate T_i/T_{tot} and $(h_i - h_{avg})/(h_{avg} - h_{wb})$, where h_{wb} is the well bore pressure head measured for pumping rate Q. To conduct the analysis, two sets of flowing FEC logs at two pumping rates (at Q and $2Q$, for example) are all that is needed. However, if we have three sets of logs for three pumping rates, Q_1, Q_2, and Q_3, then we can obtain three sets of results by analyzing three combinations of data (Q_1, Q_2), (Q_2, Q_3), and (Q_3 and Q_1). This provides internal checking, reduces the impact of measurement errors, and gives a confidence measure in the analysis results.

[25] For the particular case that T_j and h_j at one particular feed point j are known, through a packer test either just before or after multirate flowing FEC logging, equations (10) and (12) can be used to obtain T_i and h_i of all the other feed points along the borehole.

[26] In principle, if multiple sets of logs from three or more tests with different pumping rates are measured, an inversion process can be conducted to obtain the results by optimization and provide the corresponding confidence levels. However, in practice it is unlikely that more than three sets of logs will be taken, to minimize costs and testing time. Then the simple approach described above to provide internal checking and indicate confidence level should be adequate. Note also that the multiple rate method described in this paper can also be applied to other open-hole flowmeter methods, such as spinner and heat pulse flowmeters.

4. Example of Application

4.1. Generation of a Synthetic Case

[27] A synthetic case is generated based on the data from the Raymond field site shown in Figure 1a. The five FEC logs were analyzed with the BORE II code, using a model for the 80 m deep well with 180 cells, resulting in about 0.4 m spatial resolution. The results of the analysis identify six inflow locations, with q_i and C_i determined for each feed point. These z_i, q_i, and C_i values are shown in the first three columns of Table 1 and Figures 2a and 2b. To obtain T_i/T_{tot} from q_i requires an assumption for h_i. Commonly it is assumed that all the h_i values are the same and equal to h_{avg}. Then T_i/T_{tot} values are directly proportional to q_i/Q (equation (14)). These T_i/T_{tot} quantities are shown in the fourth column of Table 1 and also as solid bars in Figure 2c. However, there are cases for which all the h_i values may not be the same, then T_i/T_{tot} will be different from those shown in the fourth column of Table 1.

[28] Now, to study this effect, we assume for our synthetic data set that the pressure heads h are different from each other as specified in the fifth column of Table 1 and shown in Figure 2d (we have no information from the field on the actual pressure heads of the different feed points). Here we have imposed pressure head h_i greater than h_{avg} for the feed points at z = 26.1, 29.2, and 72 m, slightly smaller than h_{avg} for the feed points at z = 58.1 and 61 m, and significantly smaller than h_{avg} for the feed point at z = 12 m. Further, we added a feed point at z = 44 m, with a sufficiently small h_i, so that the initial pumping rate Q would not cause a low enough pressure head in the well h_{wb} to induce inflow into the well (i.e., $h_i < h_{wb}$), with the result that no peak is seen at this point in the original FEC log. For the initial pumping rate Q, we arbitrarily assign $q_i = -0.3$ L/min (water flow out of the well) for the new feed point. Given variable h_i values, T_i/T_{tot} values can be calculated using equation (19); the results are shown in the sixth column in Table 1 and as open bars in Figure 2c. Finally, Theis curve analysis of the pressure-transient obtained from an open-hole pump test of Well W00 at the Raymond field site yields a transmissivity of 2.10^{-5} m²/s [*Cohen*, 1993], which we take as T_{tot}, producing the T_i values shown in the seventh column of Table 1.

[29] Note that Figure 2c shows the errors introduced in T_i/T_{tot} when calculated assuming constant pressure heads h_i for all feed points, if in fact the real h_i are as shown in Figure 2d.

[30] The multirate flowing FEC logging method provides a means to determine the ambient pressure heads of the feed points and their transmissivities as discussed in the last section. To test the method, a synthetic data set is constructed based on parameters, C_i, T_i/T_{tot}, and $(h_i - h_{avg})/(h_{avg} - h_{wb})$, (where h_{wb} corresponds to Q used in the field data). The parameters are shown in Table 1, columns 3, 5, and 6. Three synthetic FEC logs were generated by forward calculations using the BORE II code for Q, $2Q$ and $Q/2$. They are shown in Figure 3. Random errors have been introduced into the synthetic data so that they better reflect the noisy character of real field data. These are the logs to be analyzed by the multirate log analysis method as discussed below.

4.2. Multirate Log Analysis and Results

[31] Using the standard fluid conductivity logging methods, the three logs in Figure 3 were analyzed using the BORE II code, with the constraint that the set of C_i values for the three logs must be the same. The q_i values for the three pumping ratios $Q/2$, Q and $2Q$ are then obtained

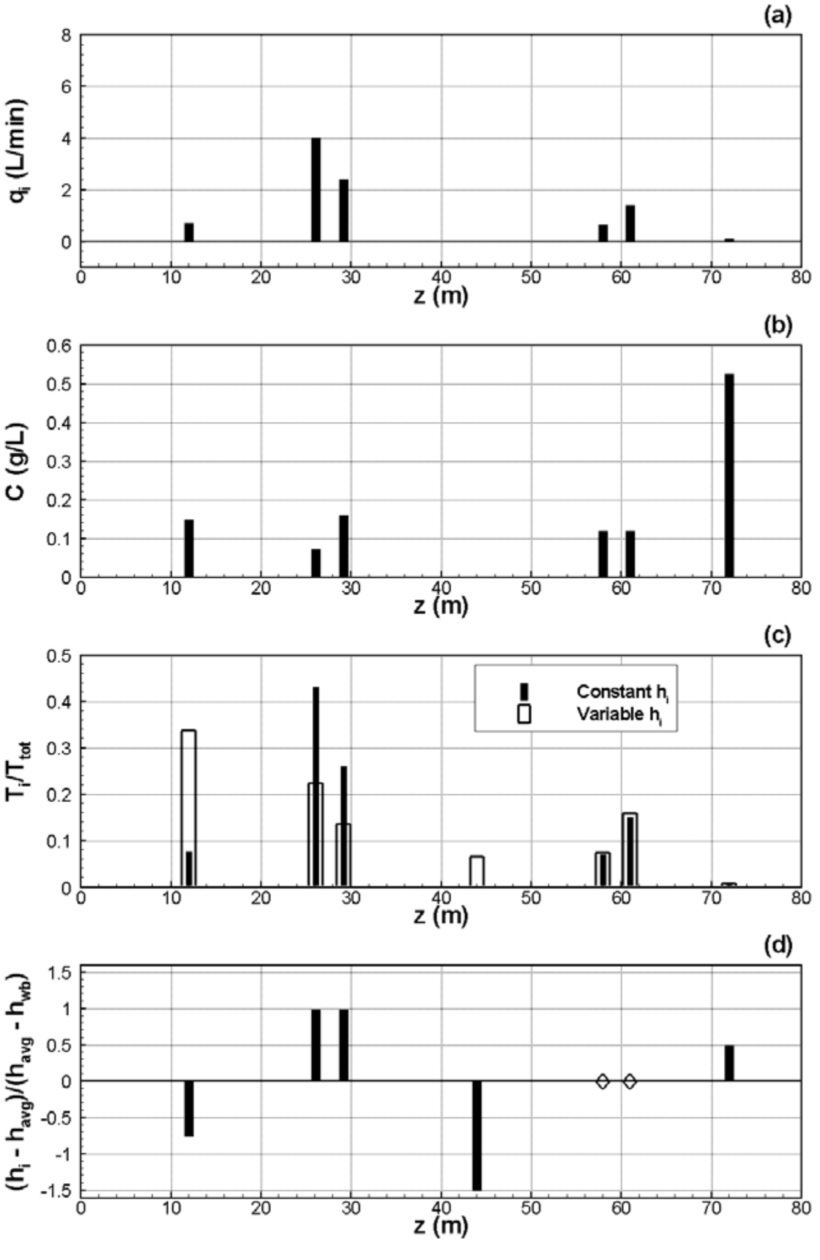

Figure 2. Parameters of example application: (a and b) the q_i and C_i values, respectively, obtained using BORE II to fit Raymond field data; (c) T_i/T_{tot}, values obtained from Figure 2a for two alternative assumptions about ambient pressure heads h_i, constant or variable; (d) the variable h_i values assumed for the synthetic case (bars and diamond symbols).

and are shown in Figure 4a. If the h_i had been the same for all feed points, the q_i values should be proportional to Q. The fact that they are not indicates that the h_i values are not the same.

[32] With the three sets of q_i values for the three different pumping rates, we can take two sets at a time and use equation (9) to calculate three sets of T_i/T_{tot} values. The results are as shown in Figure 4c. The degree of agreement among the three sets of results gives a confidence measure of how well the transmissivity at the different feed points are determined.

[33] Then, equation (20) can be used to calculate the ambient pressure heads associated with the feed points. Using results for pumping rates Q and $Q/2$, and then for Q and $2Q$, $(h_i - h_{avg})/(h_{avg} - h_{wb})$ values are calculated and shown in Figure 4d, where h_{wb} corresponds to the well bore pressure for pumping rate Q. Again the degree of their agreement with each other indicates a confidence level of these results. A comparison of Figure 4d and the input Figure 2d shows the input parameters are well reproduced and the "degree of agreement" shown in Figure 4d is a good measure of the degree to which Figure 2d is reproduced.

[34] Now, since the h_i values are different, one would expect internal flow within the well bore when the well is shut-in (Q = 0). Flow will enter the well from feed points with high h_i and exit through feed points with low h_i. If an FEC log is taken after the well bore is replaced with deionized water, but before pumping starts, the logs will register the internal flow conditions.

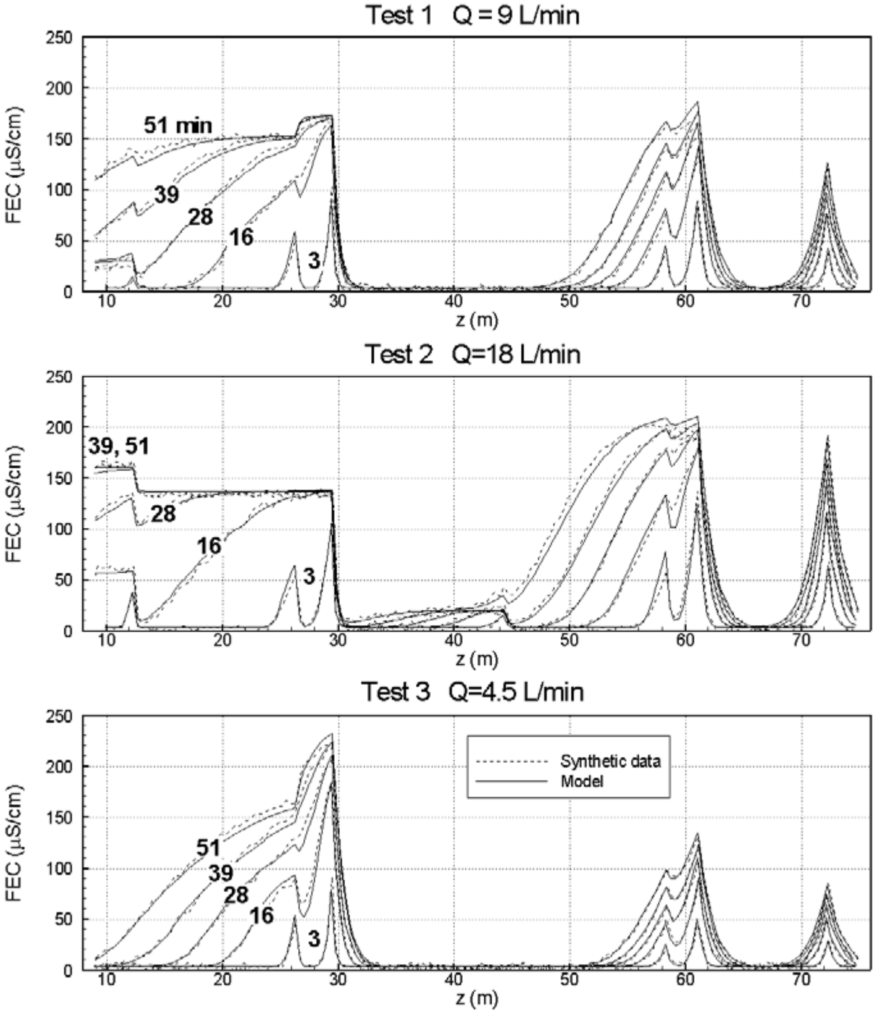

Figure 3. Synthetic FEC data for three pumping rates (synthetic data) and corresponding BORE II match (model). The Q in test 1 corresponds to what was used at the Raymond field site. Curve labels show elapsed time in minutes since pumping began.

[35] With the results from Figures 4b–4d, FEC logs are calculated assuming $Q = 0$ for a series of times after the well bore fluid replacement. The results are shown in Figure 5, in which peaks are seen at feed points where $h_i > h_{avg}$, as one would expect, and these grow with time. In Figure 5 the dashed lines labeled “Synthetic data” are obtained by forward BORE II calculations using parameters in Table 1 (columns 1–3 and 6) and the solid lines labeled “Model” are calculated using parameter values obtained from the multirate flowing FEC log analysis (Figure 4). The possibility of obtaining results with $Q = 0$ as shown in Figure 5 depends on actual field conditions. It is conceivable that unsteady flows in the well during borehole water replacement and movement of measurement probe would introduce significant uncertainties to this type of data. Thus much care needs to be exercised prior to and during the $Q = 0$ logging runs.

5. Practical Considerations for Field Testing Based on Multirate Method

[36] To conduct actual field tests using the multirate flowing FEC logging method, a number of practical points need to be considered. First, we have assumed steady state (or pseudo-steady state) conditions for q_i and C_i, which means that sufficient time needs to be allowed between the start of pumping after borehole water replacement and the logging runs. Secondly, because of well flushing during borehole water replacement, the method is limited to wells with mechanically stable borehole conditions, such as wells in fractured granites or cased boreholes in unstable formations with perforation all along the section under study. Thirdly, multirate flowing FEC logging should always be preceded by a conventional open-hole hydraulic test (normally pumping) over the whole borehole. This helps to determine the Q to be used in the multirate flowing FEC logging runs, as well as providing values of T_{tot} and ($h_{avg} - h_{wb}$), from which specific values of transmissivities and ambient pressure heads of all the individual flow zones can be calculated from equations (9) and (20).

[37] Also, in actual field tests, there may be cases where a highly transmissive feature may occur in the middle of the well section under study. In such a case, the down-stream-flow zones (higher up in the well) will be fully masked by flow from this feature, and their transmissivities cannot be clearly determined. One may be able to remedy this situa-

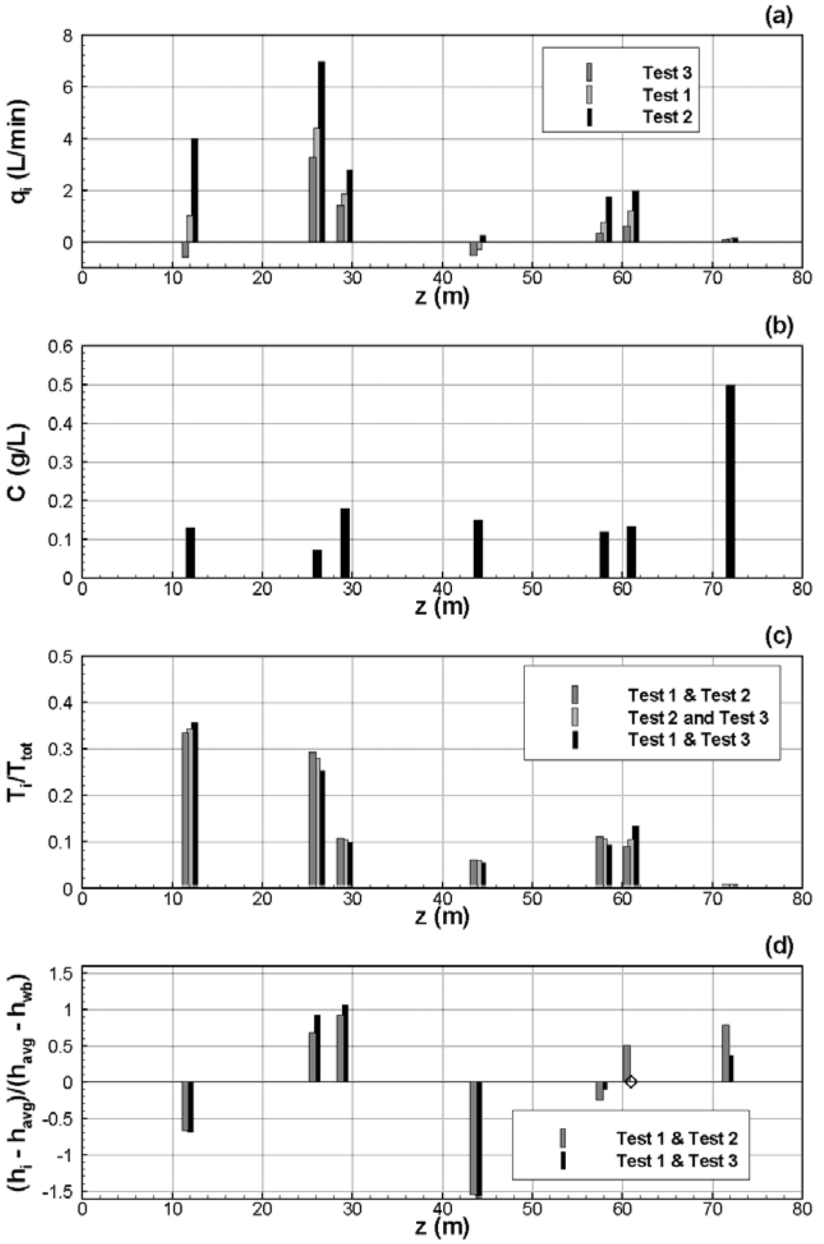

Figure 4. Results of BORE II multirate logging analysis: (a) feed point strengths for each of the three tests; (b) feed point salinities (constrained to be same for all three tests); (c) feed point T_i/T_{tot} values obtained by analyzing three pairs of tests; (d) feed point ambient pressure heads obtained by analyzing the two pairs of tests that include test 1 (i.e., h_{wb} corresponds to test 1). See color version of this figure at back of this issue.

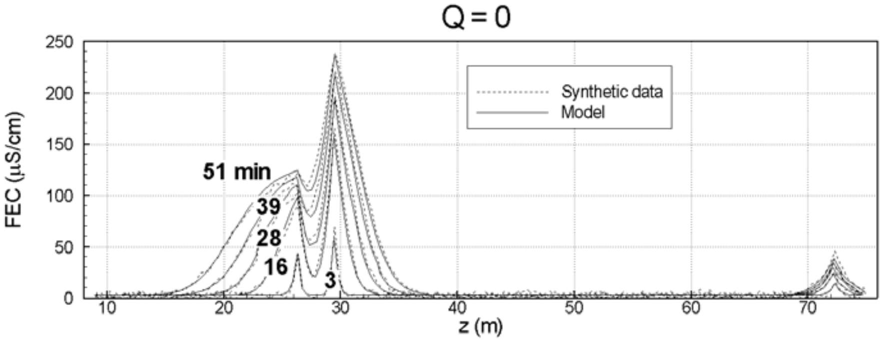

Figure 5. Synthetic FEC data for zero pumping rate (synthetic data) and corresponding BORE II match (model). Curve labels show elapsed time in minutes since the well was shut in.

tion by conducting a supplementary test with pumping at the bottom of the well to induce a downward flow, or to apply a packer to isolate this high flow feature. Similarly, if one of the flow features has an exceptionally large positive or negative ambient pressure head, that would also impact the FEC logs. Thus conducting multirate flowing FEC logging and analysis requires an understanding of the system, and special procedures may need to be applied for special situations. This should be the practice in field tests using any method.

6. Concluding Remarks

[38] The paper presents a powerful method that efficiently determines values of T_i/T_{tot}, C_i and $(h_i - h_{avg})/(h_{avg} - h_{wb})$ of hydraulically conductive features along a well bore. The method can be applied to a well with depths from about 10 to 2000 meters, and involves only three sets of logging runs over a very short time compared with the time required by many other methods.

[39] By conducting a conventional well test analysis over the whole length of the well, T_{tot} and h_{wb} can be obtained. Then, T_i, C_i and h_i can be individually determined. Alternatively, if, for a particular feed point j, T_j, C_j and h_j are measured by a double-packer pressure test and sampling, these quantities for all other feed points can also be determined. Note that the C_i values determined by the multirate flowing FEC logging method are inherent to the feed point characteristics and not affected by dilution, which is often associated with some other measurement methods. Also the determination of h_i is quite accurate, since it is scaled by $(h_{avg} - h_{wb})$, which in some cases may be only a few meters. Thus the accuracy of h_i determination could be a fraction of a meter.

[40] Results of C_i can be independently verified against measurements of water samples taken from the well at different depths. Results of h_i can also be independently verified using flowing FEC logging with $Q = 0$. Thus an FEC log can be taken at a time after borehole water replacement and before pumping starts for the regular flowing FEC log measurements. Such $Q = 0$ logs can be used to verify predicted results, as shown in Figure 5.

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C. Doughty and C.-F. Tsang, Earth Sciences Division, Ernest Orlando Lawrence Berkeley National Laboratory, University of California, Berkeley, Berkeley, CA 94720, USA. (cftsang@lbl.gov)

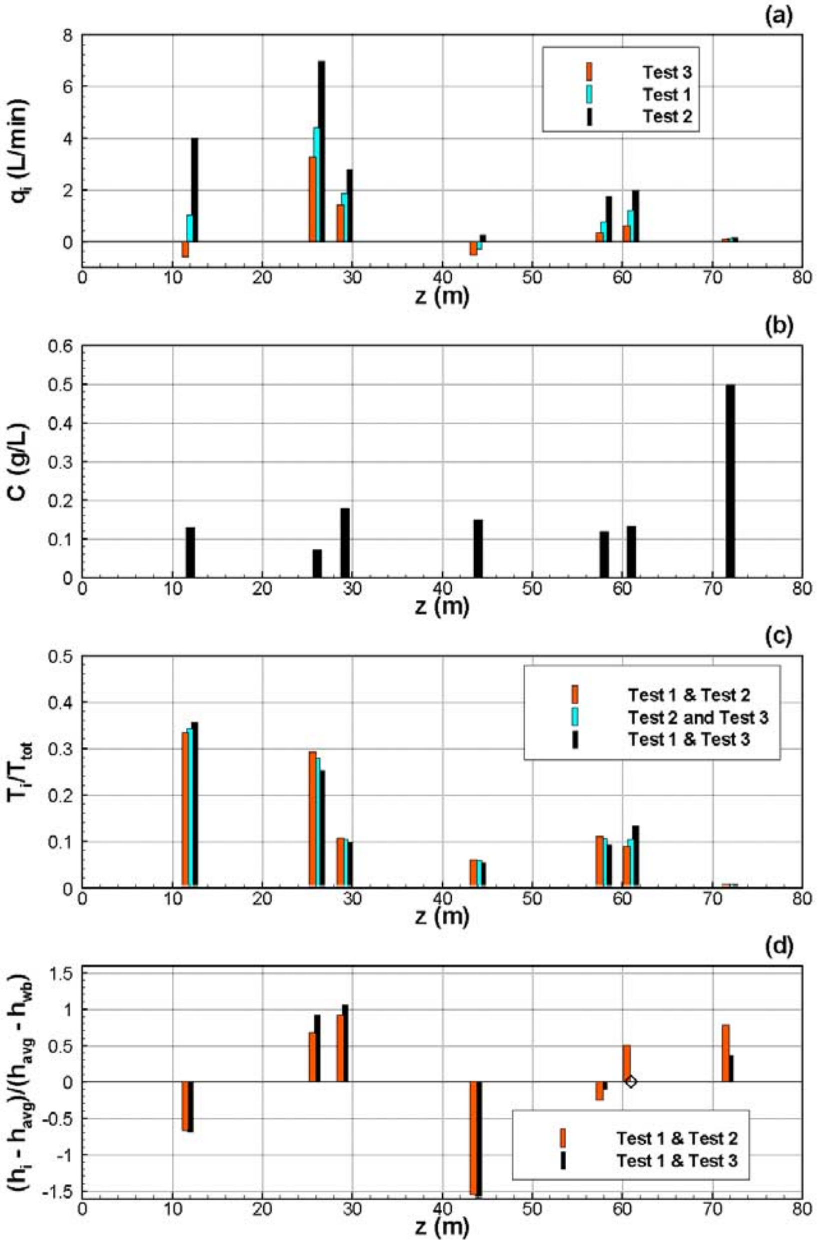

Figure 4. Results of BORE II multirate logging analysis: (a) feed point strengths for each of the three tests; (b) feed point salinities (constrained to be same for all three tests); (c) feed point T_i/T_{tot} values obtained by analyzing three pairs of tests; (d) feed point ambient pressure heads obtained by analyzing the two pairs of tests that include test 1 (i.e., h_{wb} corresponds to test 1).