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Feasibility of Long-Term Passive Monitoring of Deep Hydrogeology with Flowing Fluid Electric Conductivity Logging Method

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ABSTRACT

The flowing fluid electrical conductivity (FFEC) logging method has been used in deep boreholes to obtain estimates for the transmissivity, salinity of formation water, hydraulic head, and formation water flow rate of hydraulically conducting layers. In this chapter we propose a modified FFEC logging procedure, involving a setup of a string of EC/T probes in the borehole, to passively monitor long-term temporal changes in local flow rates in a brine formation composed of multiple layers with different transmissivities over a period of months or years. The local flows in the layers can vary over time, for instance, as a result of seasonal or climatic changes. In the case of supercritical CO_2 storage in the deep subsurface, the local flow pattern of the storage formation will be disturbed; furthermore, it may change with time as the low-density and low-viscosity CO_2 enters more and more into the transmissive layers and interacts with in situ water and rock. The present chapter explores the possibility of using the FFEC method for such long-term monitoring in an observation well. The feasibility is demonstrated with field data from the Outokumpu test site in Finland.

4.1. INTRODUCTION

Knowledge of hydraulic structures and locations of hydraulically conductive zones in deep subsurface formation is important for understanding flow and transport behavior of regional groundwater and solutes. Such hydraulic information is usually obtained through established geophysical and hydrological methods applied to deep boreholes, such as straddle-packer tests [*Walton*, 1970], gamma and neutron logging [*Keys*, 1986; *Mendoza et al.*, 2010], borehole image logging [*Zemanek et al.*, 1970; *Paillet*, 1991], cross-well geophysical imaging [*Jardani et al.*, 2013], high-resolution flow logging [*Molz et al.*, 1989], and flowing fluid electrical conductivity (FFEC) logging [*Tsang et al.*, 1990; *Doughty and Tsang*, 2005; *Doughty et al.*, 2005; *Doughty et al.*, 2013]. Among all these methods, the FFEC logging has been suggested as an efficient method that can identify the locations of inflow zones and evaluate their hydraulic conductivity and fluid salinity as a function of depth along the borehole, using a standard conventional EC/T probe (electric conductivity and temperature probe; e.g., *Robertson Geologging*, 2014; *Mount Sopris*, 2014].

Measurements of local flow in a subsurface formation penetrated by a well have also been made with different methods, such as point dilution of radioisotopes [*Drost et al.*, 1968], tracer dilution analysis [*Brainerd and Robbins*, 2004], cross-well time-lapse tomography [*Jardani et al.*, 2013], and the FFEC logging method [*Doughty and Tsang*, 2005; *Doughty et al.*, 2013]. The understanding of slow water flows through transmissive layers or fracture zones and their change with time is important in the study of injection/pumping of fluids (such as petroleum products, supercritical CO_2 storage, etc). In cases where the flow in a transmissive layer at a monitoring well varies

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Dynamics of Fluids and Transport in Complex Fractured-Porous Systems, Geophysical Monograph 210, First Edition.
Edited by Boris Faybishenko, Sally M. Benson, and John E. Gale.

with time over a long time period, the changes in "regional" flow rate cannot be easily measured in a monitoring mode by methods such as that proposed by *Drost et al.* [1968], which requires an active testing procedure each time the measurement is made.

Not many simple methods are available for passive long-term monitoring of hydrologic processes of the subsurface. Pressure sensors are often used to monitor well pressures, but the pressure values are averaged over the whole depth of the well. For many applications, there is a need for information on flows and pressures as a function of depth in the monitoring well. Fiber optics–based high–spatial resolution temperature measurements have been found very useful in monitoring detailed depth-dependent temperature changes [*Freifeld et al.*, 2008]. The optical fiber can be emplaced all along the well casing and used for long-term monitoring. Although changes in temperature can indicate certain flow processes, they are less useful in yielding flow details because of the high thermal diffusivity.

In this chapter, we propose that the FFEC method may be able to provide, in a continuous and passive way, the monitoring of water flow through the individual fractures/layers in a deep formation over a long time period. We investigate, through modeling, the possibility of monitoring flow rates in the individual layers of the storage formation at a monitoring well. In the next section, motivation in the context of CO_2 geological storage is presented. Then the FFEC logging method is described, followed by an investigation of its use for long-term flow monitoring. A partial demonstration of this approach is then presented through a preliminary analysis of a set of three-year FFEC field data from the Outokumpu test site in Finland.

4.2. MOTIVATION AND PROBLEM DEFINITION

In one of the main concepts of geosequestration of CO_2, supercritical CO_2 ($ScCO_2$) is injected deep underground into a hydraulically conductive brine formation at a depth of around 1000 m. At such depth, the $ScCO_2$ has a compressibility an order of magnitude larger than that of in-situ brine, a low density (0.47 g/cm^3), and a viscosity that is about 10% that of water [*Colina et al.*, 2003; *Beckman*, 2004]. The brine formation, into which $ScCO_2$ is injected and stored, is typically heterogeneous and often displays a layered structure.

An example is the geologic carbon storage project at Heletz test site in Israel, where it happens that the natural groundwater flow in the storage formation of interest is very small. The storage formation is composed of three conductive layers with different values of hydraulic conductivities. As $ScCO_2$ is injected into the aquifer, it pushes the ambient water away from the injection well. An appropriately positioned monitoring well can be used to measure these induced "natural" or "regional" flow velocities in the three layers and serve as a means to monitor the development of flow into the transmissive layers due to $ScCO_2$ injection.

With three transmissive layers of different hydraulic conductivities, the flow rates in the three layers will be different. The partitioning of the injected $ScCO_2$ among the three layers would be useful information in modeling the behavior of the CO_2 storage system. Recent studies [*Rasmusson et al.*, 2014] have shown that, because of buoyancy effects operating in the injection well coupled with the transmissive layers of the storage formation, flows into the layers do not follow the simple ratios of hydraulic transmissivities of these layers but are also a function of the relative depths and actual transmissivity values of these layers.

Furthermore, if $ScCO_2$ enters one layer more than the other two, the effective hydraulic conductivity of this layer may become larger because $ScCO_2$ has a larger compressibility, a lower density than water, and a much lower viscosity. This means that the flow of $ScCO_2$ and formation water in this layer may change with time, with corresponding changes in $ScCO_2$ flow into the other two layers, assuming a constant total injection rate. Such temporal changes in flow rates in the three layers may be very useful information for understanding and modeling of $ScCO_2$ injection and storage. Other processes, such as $ScCO_2$ dissolution into brine, mineral trapping of $ScCO_2$, and leakage from the storage formation, may also cause flow changes in the storage brine formation over the time period of injection storage, which can be 30–50 years. Thus, long-term monitoring of flow rate changes in the conductive layers of the storage formation would yield very useful information to characterize the development and movement of the $ScCO_2$ being stored and also to detect potential leakage.

Seasonal or longer-term changes in groundwater recharge and discharge may also change flow rates in subsurface hydraulic conductive formations. Additionally, varying formation water flow rate is also expected during long-term pumping/injection of groundwater, which is a very common scenario for the purpose of drinking and irrigation water as well as the treatment of contaminated water. If the pumping and injection rates are not held constant, the flow rates in those transmissive layers can be varying in the surrounding area.

4.2.1. Approach of FFEC Method

This section gives a brief summary of data collection and analysis methods using the FFEC logging, followed by a proposed modification to adapt it for long-term monitoring. Further details of the data collection method may be found in *Tsang et al.* [1990] and *Doughty et al.* [2005], and details of the analysis method may be found in *Doughty and Tsang* [2005].

In the FFEC logging method, the water in a wellbore is first replaced by water of a constant salinity significantly different from that of the formation water. This may be accomplished, for example, by injecting deionized water or drinking water through a tube to the bottom of the wellbore at a constant rate, while simultaneously pumping from the top of the well at the same rate (wellbore water replacement phase). In the normal FFEC logging method, the well is then pumped at a low constant rate and the FFEC profiles are measured for a series of times by moving an electrical conductivity probe down and up the wellbore. The profiles will exhibit peaks at depth levels where formation water enters the borehole. At successive times, the peaks will increase in size corresponding to the increase in inflow rate times the salinity concentration. The peaks will also tilt up or down the borehole depending on the flow velocity being up or down the borehole, respectively. Thus, these profiles can be analyzed to obtain the inflow into the well and its salinity at different depths [*Doughty and Tsang*, 2005].

For our present purpose of monitoring the temporal changes in formation water flow rates at a monitoring well, a modified FFEC logging procedure is proposed. Instead of the moving electric conductivity probe, a series of electrical conductivity and temperature probes at one- or two-meter intervals are attached onto an injection tubing and installed in the monitoring well. The series of probes should cover a depth range containing the transmissive layers of interest. They can then be used for continuous monitoring of fluid electrical conductivity (FEC) values with time due to formation water flow passing through the well, as a function of depth. Data from these probes are collected via a data scanner and sent to a surface data logger through a cable. This is illustrated by Figure 4.1. Suppose we would like to monitor the flow

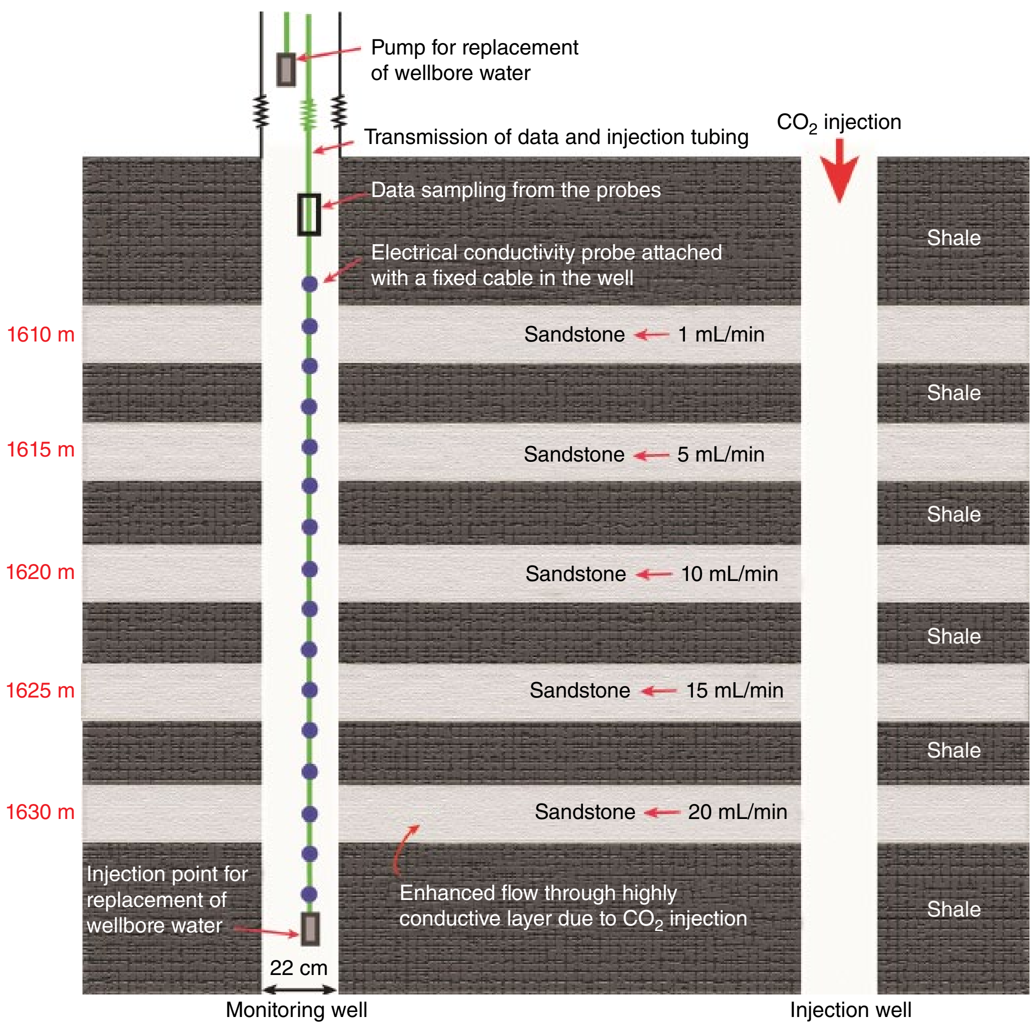

Figure 4.1 An example of FFEC logging arrangement for replacement of wellbore water (with pumping point at the top of the well and injection point at the bottom) and for monitoring temporal formation water flow rates during CO_2 injection at a monitoring well located 50 m away from the injection well.

rates in the transmissive layers after one month, six months, one year, or three years, which we may call the monitoring time, t_m, followed by a monitoring period typically of a few days. At the starting time t_m, water with salinity significantly different from that of the formation water is injected to the bottom of the wellbore, while the well is pumped at the same rate at the top (wellbore water replacement). This is stopped when the probes in the depth interval of interest record a constant FEC value similar to that of the injected water. Then the data from the probes at successive times, $t_m + \Delta t$, $t_m + 2\Delta t$, $t_m + 3\Delta t$, …… (where Δt can be 1, 2, 10, 20 hours) can be downloaded, extracted, and analyzed as described below. Note that the proposed method allows the monitoring of temporal change in FEC of the wellbore water as a function of depth continuously over a long period of time in a passive mode, without the need for any further instrument emplacement or adjustment after the initial setup.

To explore the feasibility of FFEC logging for monitoring natural flows in different transmissive layers and their changes, calculations of FFEC profiles as a function of depth are first made (forward calculation) by assuming that, in each layer intercepted by the well, there is inflow into the well from one side, with simultaneous outflow of an equal rate at the opposite side, thus representing the process of "regional" flow crossing the well (similar to *Doughty et al.*, 2013). The formation water entering through the wellbore will mix with borehole water before exiting the wellbore, at a mixing strength controlled by a dispersion parameter D_w of water salinity along the wellbore. By keeping the salinity differences relatively small but still significant, the density-driven mixing of wellbore water can be assumed to be negligible. The FFEC logs will then display peaks at the depth locations where the formation water enters and exits the wellbore at different rates as shown in Figure 4.2. In this figure, we consider five depth locations with formation water flow crossing the well, and the resulting five peaks of salinity in mg/L are found to grow with time. The salinity value is related to the measured electric conductivity in μS/cm by an equation also dependent on the local water temperature [*Tsang et al.*, 1990]:

$$FEC = 1870C - 40C^2 \tag{4.1}$$

where C is salinity of formation fluid (in g/L) and FEC is fluid electric conductivity (in μS/cm) corrected for temperature dependence to be that at 20°C by using the following equation [Tsang et al., 1990]:

$$FEC(20°\text{C}) = \frac{FEC(T°\text{C})}{1 + S(T°\text{C} - 20°\text{C})} \tag{4.2}$$

where $S = 0.024°\ \text{C}^{-1}$.

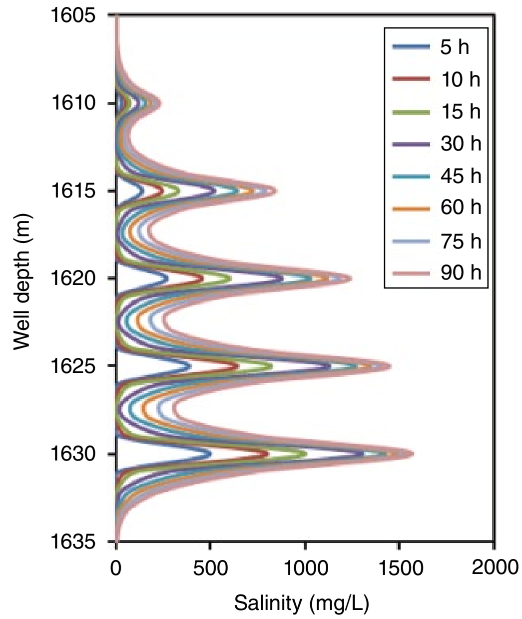

Figure 4.2 The FFEC profiles in the well as a function of depth at different times from 5 h to 90 h after replacement of wellbore water at beginning of the monitoring time t_m. Flow rates in individual layers from top to bottom are V_1: 1 mL/min, V_2: 5 mL/min, V_3: 10 mL/min, V_4: 15 mL/min, and V_5: 20 mL/min.

The peaks shown in Figure 4.2 will grow with time symmetrically in the wellbore direction across the inflow/outflow point in the absence of pumping, with the peak height depending on D_w. At long times, the peak heights reach a constant value when they reach the salinity of the corresponding formation layers.

Now for the inverse problem, we can fit these FFEC logs to the one-dimensional advection-dispersion numerical model, so that the position of inflow points, the water flow rates, and the salinity of the formation water can be obtained. We accomplish this by using the BORE-II code developed by *Doughty and Tsang* [2005]. The BORE-II code estimates the inflow/outflow locations and flow rates by examining the early time FFEC profiles and by assigning the inflow salinity and flow rates in a trial and error procedure until an acceptable match is achieved.

4.3. RESULTS AND DISCUSSION

4.3.1. Water Flow Rates Constant with Time

Figure 4.2 shows that the FFEC profiles (salinity of wellbore water as a function of depth for several times after the start of monitoring time t_m) cover five hydraulically conductive layers (from top to bottom: L_1, L_2, L_3, L_4, and L_5) having a range of formation water flow rates (1, 5, 10, 15, and 20 mL/min) in these layers. The parameters are chosen similar to those of the Heletz test site where $ScCO_2$ injection of 3.5 tons/hour is being planned. We have conducted the study of FFEC method in a monitoring well 50 m away from the injection well by considering the probes to be at 1-m intervals for simplicity and by considering the five layers each having a single depth point for formation water flowing into and out of the well. Each inflow point was separated by 5 m from its neighbors in this simulation (Figure 4.2). The uppermost layer at 1610 m depth was the lowest conductive fracture with only 1 mL/min of induced flow rate at the monitoring well, while the lowermost layer at 1630 m depth was the highest conductive fracture with 20 mL/min flow rate. All inflows have the same salinity of 2 mg/L. A series of conductivity profiles are plotted at 5 h, 10 h, 15 h, 30 h, 45 h, 60 h, 75 h, and 90 h after t_m, as shown in Figure 4.2. It is noticed that the peaks in the profiles increase at a decreasing rate after 45 h due to the increased mixing of well water with influx from natural water flow. These results show a clear difference in the peaks of the FFEC profiles, demonstrating that the FFEC logging may actually be used to distinguish the different "regional" flow rates in different transmissive layers.

Next we calculate the total masses of salt under each peak corresponding to the individual layers as a function of time. After some exploratory study, we found that the total salt mass displays a consistent linear trend in a log-log scale of total mass of salt (M) with time (t) over the first part of time period for each conductive layer (see Figure 4.3a). This linear trend is given as

$$\log M = a + b \log t \tag{4.3}$$

where a and b are constant coefficients. The total salt that enters through formation water to the monitoring well (from the end of recirculation period with deionized water) increases as a power law with time, however, different coefficients a and b varies for the different flow rates (Figure 4.3a). The linearity with log of time is thus a signature that the formation water is passing across the well at a constant rate. This linearity is however expected to be invalid as the salinity in the wellbore at the inflow/outflow zone becomes saturated to be the salinity value of the formation water at the corresponding depth. Then the increase of mass in the borehole will be less and less until it becomes equal to the dispersion of salinity up and down the borehole.

4.3.2. Varying Water Flow Rates

To evaluate the effect of changes in formation water flow on the FFEC logging profile during the monitoring time period, a study is made by an increase or decrease of the flow rates through three different conductive zones, V_1, V_3, and V_5, at a prescribed time of 45 h (after t_m) of constant local water flow. As expected, it is found that a decrease in local flow (from 1 to 0.5 mL/min) at t = 45 h decreases the salt mass inflow rate suddenly (sharp drop at changing point) and then stabilizes to be parallel to the original flow of 1 mL/min, and similarly a sharp rise in salt mass was observed with enhanced local water flow from 1 to 5 mL/min. However, for a case of high initial local water flow rate of 20 mL/min, an increase to 30 mL/min at 45 h causes relatively small deviation from the linear trend. It is due to the fact that the wellbore water was nearly saturated with formation water at 45 h under such a high regional flow rate, so that the enhanced water flow did not cause much increase in salt concentration in the monitoring well, especially in a log-log plot.

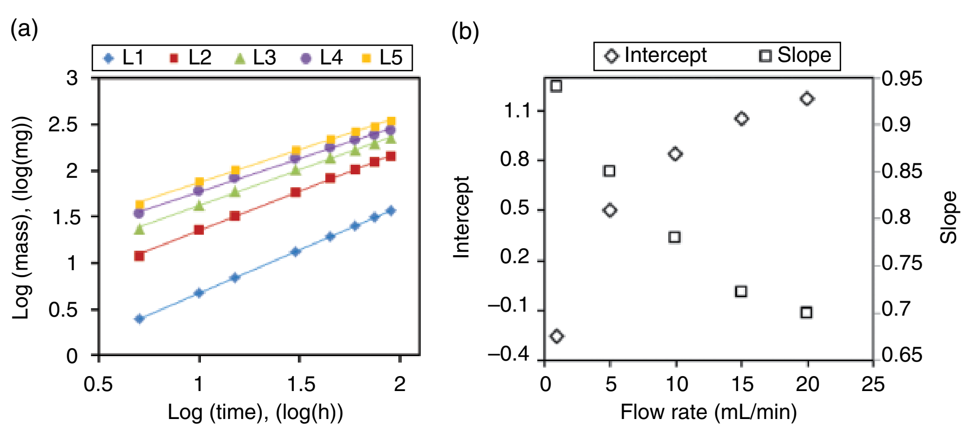

Figure 4.3 (a) Total salt mass present in the well as a function of time during the monitoring period (in log-log scale) for different flow rate in the individual layers: L1: 1 mL/min, L2: 5 mL/min, L3: 10 mL/min, L4: 15 mL/min, and L5: 20 mL/min. The solid points show the calculated values and the lines show the linear fitting. (b) Intercept and slope of linear fits of log-log plots of total salt mass with time.

4.3.3. Feasibility of Determining the Local Flow Rates at Different Times from the FFEC Log Profiles

In order to understand the rate of increase in salt mass with time for different flow rates of formation water surrounding the monitoring well, two plots were made: first a plot of the intercept of the mass-time log-log plot versus the flow rate, and second a plot of the slope of the mass-time log-log plot versus the flow rate (Figure 4.3b). Figure 4.3b indicates that the intercept a in Equation 4.3 increases with an increase in flow rate (i.e., the intercept is higher for high transmissive layers). It shows that the slope b in Equation 4.3 decreases with an increase in flow rate. This can be understood since the entering rate of formation water into the well through a highly transmissive zone is much faster in the beginning (i.e., just after the replacement of wellbore water with deionized water), but that rate decreases with time. However, the responses of formation water flow into the well through less transmissive zones are slower in the beginning, which might have improved after the stabilization of the entrance of formation water through higher transmissive layers (Figure 4.2). Now, we can use the FFEC log profile at 45 h and subtract that from the later FFEC profiles at the new flow rate (we call this the normalized case). The new profiles thus obtained can be analyzed as before in terms of a plot of log M versus log t, where t is now measured from the changed time of 45 h. This observation suggests an alternative analysis procedure for cases of flow rate changes within the monitoring period.

4.3.4. Sensitivity Analysis

The analysis method has been tested for the impact of wellbore diameter of the monitoring well. It was found that the saturation time for wellbore water is increased for larger wellbore diameter. Thus, for the FFEC method, a larger well diameter will allow the measurement of higher flow rates and its temporal change. Other engineering considerations along this line will be explored in an ongoing study to evaluate and improve the possible range of local flow rates that can be conveniently monitored by the FFEC logging method for the Heletz test site.

We also tested the effect of dispersion coefficient (D_w) within the borehole, which controls the mixing of inflow water from the formation with the wellbore water. Figure 4.4 shows the effect of D_w on the total salt mass as a function of time in the monitoring well. The simulations are performed in a single conductive layer by assuming a constant flow rate and three different D_w values, namely, D5: 4×10^{-5} m²/s, D6: 4×10^{-6} m²/s, and D7: 4×10^{-7} m²/s. The results (Figure 4.4) indicate that for early time the effect of D_w is not so important, and therefore the comparison of intercept and slope in Figure 4.3b is not sensitive to the

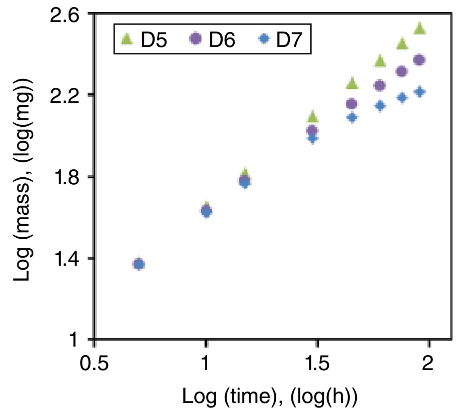

Figure 4.4 Comparison of total salt mass in the well versus time in a single layer on a log-log plot for different values of dispersion coefficient: D5: 4×10^{-5} m²/s, D6: 4×10^{-6} m²/s, and D7: 4×10^{-7} m²/s.

dispersion of salt along the length of the monitoring well over a range of three orders of magnitude in the dispersion parameter.

The sensitivity of the method in determining flow rates and their changes can be demonstrated by the analysis of data from a field case as presented in the next section.

4.3.5. Partial Demonstration of the Feasibility of the Approach Based on Field Data

It may be noted that up to now, FFEC logging has been used to provide profiles of fluid electric conductivity in the borehole at successive time intervals over a period of only one or two days for obtaining the hydraulic information of deep and shallow boreholes at field and commercial scale [*Doughty et al.*, 2008; *Doughty et al.*, 2013]. Thus, the FFEC method has not yet been tested for long-term monitoring of the natural flow of surrounding formation water through a wellbore. However, some long-term FFEC logging data are available from a deep borehole at Outokumpu, Finland, which was drilled primarily for geothermal studies by the Geological Survey of Finland and their partners. The borehole is 2516 m in depth and penetrates into Palaeoproterozoic metasedimentary, igneous, and ophiolite rocks, and studies were conducted to systematically understand the temperature variation over depth (in the range of 6°C to 38°C corresponding to the land surface to a depth of 2.5 km) and the heat flux due to long-term paleoclimatic disturbances, groundwater flow, and structural effects [*Kukkonen et al.*, 2011]. During this investigation, four electrical conductivity logs at different times over more than three years were also obtained [*Ahonen et al.*, 2011; *Kukkonen et al.*, 2011]. This data set, though not obtained according to our proposed long-term logging method, provides us an opportunity to

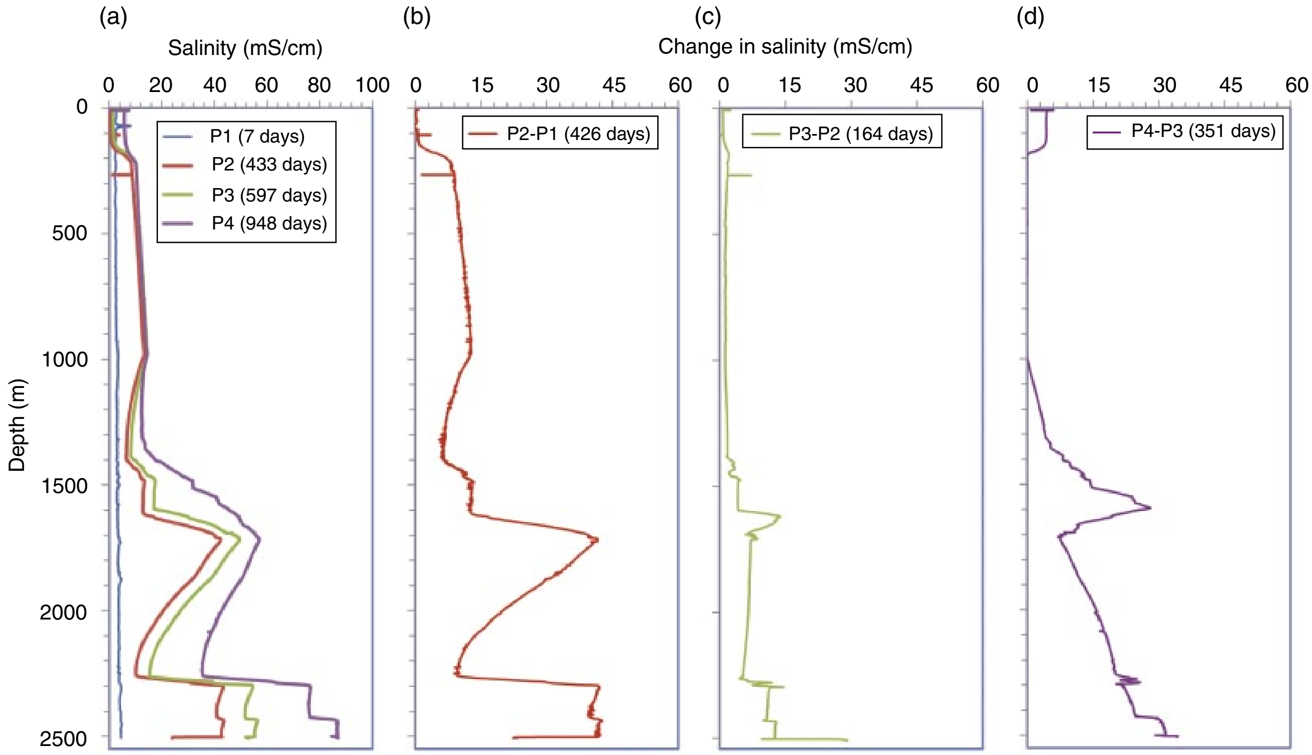

Figure 4.5 (a) Long-term (from February 2005 to September 2008) fluid electrical conductivity profiles (P1, P2, P3, and P4) in a deep borehole at the Outokumpu site during geothermal studies; differences between two adjacent profiles are shown in (b) P2-P1, (c) P3-P2, and (d) P4-P3.

demonstrate the feasibility of our approach for using FFEC logging to monitor change in formation water flow rate over a period of three years.

Figure 4.5a shows four FEC profiles (P1, P2, P3, and P4) from 8 m to 2516 m in a well at Outokumpu test site at 7 days, 433 days, 597 days, and 948 days, respectively, after drilling. A careful study of Figure 4.5a unveils that, in this case, inflows and outflows occur at different depths along the well. Further, it is found that the salinity of borehole water was already stabilized from well-top to 1000 m sometime between 7 and 433 days, but it was still increasing with time in the deeper part of the well. In this particular case, multiple fixed probes were not used (as we proposed in our method), but the FEC profiles were obtained using a moving probe to scan the well. First, these data demonstrate that consistent FEC profiles can be measured in the field over a long time period. Then we proceed to analyze the data. As only four profiles were obtained over the three and half year period, their analysis using FFEC method was challenging. A preliminary analysis of these FEC profiles is summarized below.

In order to understand the inflow and outflow locations, change in water flow rates, and change in salinity of formation water along the well depth, we obtained the difference between two adjacent profiles (P2-P1, P3-P2, and P4-P3), as shown in Figure 4.5 parts b, c, and d. A study of the FEC profiles and the "differences" profiles indicates the occurrence of inflow points representing high conductive layers or fractures at the locations of the peaks. It is also possible to see that though the inflow zones may exist continuously at a shallower part of the well (<1000 m), the profile stabilized as wellbore water salinity was approaching to the formation water salinity after about one year (433 days). In addition, we could observe a linear increase in salinity with depth of the well (see profile P4-P3 for depth below 1000 m), which may imply a constant rate of (relatively smaller) background salinity diffusion from the formation water to the borehole over an extended interval of the well.

After accounting for the background salinity diffusion along the well, and assuming a depth-dependent salinity of formation water that is constant with time (ranging from 12 mS/cm near the land surface to 300 mS/cm at the depth of the bottom of the well), we were able to simulate all the FEC peaks and their respective development by fitting using the BORE II code (Figure 4.6). The results on inflow locations of the peaks, their flow rates, and salinity of formation water are presented in Table 4.1. The calculated results for the peak flow rates were constant with time for the peaks of the profiles P2-P1, P3-P1, and P4-P1, except

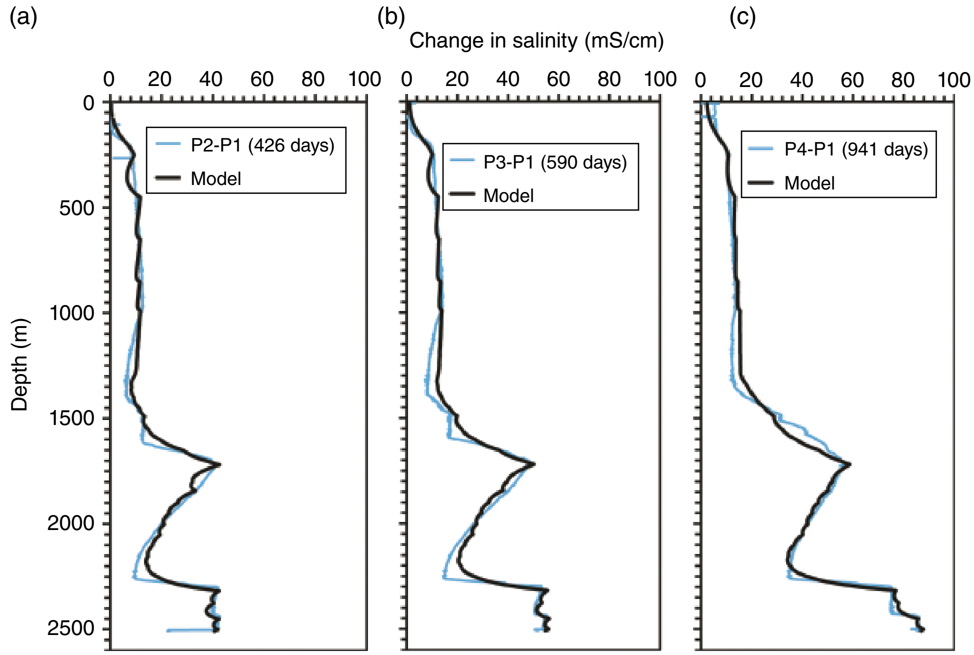

Figure 4.6 Application of FFEC analysis method to the profiles from the Outokumpu site after considering the first profile (P1) as a baseline. The figures show the data and model fit for (a) P2-P1, (b) P3-P1, and (c) P4-P1.

Table 4.1 Results of a preliminary analysis of long-term FFEC data in a deep borehole of Outokumpu site. Flow rates in bold face indicate cases where flow rates changed over the different time intervals.

		Flow Rate (mL/min)		
Well Depth (m)	Salinity (mS/cm)	P2-P1 (426 days)	P3-P1 (590 days)	P4-P1 (941 days)
200	12	OF	OF	OF
250	12	35	35	35
450	15	45	45	45
650	15	40	40	40
850	18	30	30	30
990	25	14	14	14
1300	50	OF	OF	OF
1490	90	**2**	**3**	**3**
1650	120	3	3	3
1718	140	**7**	**7**	**6**
1718	140	OF	OF	OF
1840	160	**3**	**2**	**2**
2300	250	OF	OF	OF
2315	260	**4**	**5**	**6**
2450	280	2	2	2
2500	290	2	2	2
2550	300	OF	OF	OF

OF = outflow from the wellbore.

for the four inflow points at 1490 m, 1718 m, 1840 m, and 2315 m (Table 4.1). At these four depths, the changes in flow rate for the time interval between the two adjacent FEC profiles are shown in Table 4.2, which shows the average flow rates at these depths over the first 426 days, then over the next 164 days, and finally over the next 351 days. Thus, Table 4.2 indicates a decreasing flow rate at 1718 m but increasing flow rates at 2315 m and 2450 m. The flow rate appears to increase and then decrease at 1490 m. The preliminary analysis of these long-term data demonstrates the feasibility of our proposed approach of using FFEC logging data to monitoring salinity changes, from which to obtain the long-term temporal flow rates changes in the formation. The results in Tables 4.1 and 4.2 also show that the sensitivity of the method in determining the local inflow rates is down to a few mL/min.

Table 4.2 Changes in flow rates at different well depths from data over different time intervals.

		Flow Rate (mL/min)		
Well Depth (m)	Salinity (mS/cm)	P2-P1 (426 days)	P3-P2 (164 days)	P4-P3 (351 days)
1490	90	2	4	3
1718	140	7	7	4
2315	260	4	7	8
2450	280	2	2	3

4.4. CONCLUDING REMARKS

It has been shown that the FFEC logging method for long-term (about three years) monitoring of FEC in a deep borehole is possible [*Kukkonen et al.*, 2011], and that these data can be successfully analyzed using the FFEC analysis method. In this chapter, a modified FFEC logging procedure is suggested for passive, long-term monitoring of the flows of formation water across the well through different transmissive layers and their temporal changes over a long time period. The modified procedure may be summarized as follows. (1) A series of electrical conductivity probes can be attached onto an injection tubing and installed in a monitoring well. (2) A data scanner connecting all the probes can be placed just above the series of probes to collect data from the probes in series. (3) The scanner would transmit data to a surface data logger at any time as demanded by a signal from the surface. (4) At a monitoring time t_m (which could be months or years), the borehole water is replaced by simultaneous injection to well bottom and pumping at well top at the same rate. (5) The display and analysis of data can be performed at selected times after wellbore water replacement, at $t_m + \Delta t$, $t_m + 2\Delta t$, $t_m + 3\Delta t$, etc., where Δt can be minutes or hours. (6) Finally, the profiles obtained from these collected data can be analyzed using our model. The results and sensitivity analyses presented in this chapter show that the amount of formation water entering into the monitoring well during the monitoring period, in a log-log plot, increases linearly with time if there are no temporal flow rate changes. Changes in "regional" water flow during this period can also be monitored by analyzing the deviation from linearity of the log-log plot. The appropriate range of flow rates that can be monitored is dependent on the wellbore diameter among other engineering parameters. Plans for testing and optimizing the proposed FFEC method for monitoring "regional" water flow rates are being developed for field validation for the large-scale $ScCO_2$ injection to be conducted at the Heletz test site, during which the range of flow rates that can be monitored as a function of design parameters will be further studied.

ACKNOWLEDGMENTS

We would like to acknowledge the funding from European Community's Seventh Framework Programme FP7/2007-2013 under Grant Agreement No. 227286 (as part of MUSTANG project) for supporting this research. We would like to thank Dr. Ilmo T. Kukkonen, Geological Survey of Finland (currently at the University of Helsinki), for providing the well logging data used in Figure 4.5a in this chapter. The second and third authors would also like to express their appreciation to Paul A. Witherspoon, for his mentoring over many years and for his generous encouragement to new ideas.

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