Flowing Fluid Electric Conductivity (FFEC) Logging Method
for Determination of Hydraulic Properties of Fractures and Hydrologic Zones Intersected by a Borehole

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Objectives of Hydrologic Testing

- *In situ* measurements to determine hydrogeologic structures (conductive zones and faults/fractures)
- Measurements on permeability, porosity, mineralogy and water chemistry as a function of depth along boreholes, to determine relevant physio-chemical processes
- *In situ* evaluation of pressure heads and salinity, as well as natural regional flow, recharge and discharge zones: “state” of the hydrogeologic system

*Obtain data for estimating subsurface flow capacity and water quality as well as for flow and transport modeling*
Hydrological Testing Methods

- Constant-rate tests
  - Pump test (or pressure transient tests)
  - Flow loggings methods
- Constant-pressure tests — Injection tests
- Variable head/flow tests — slug tests

*Testing over whole open hole, or packer test with interval of 100m, 20m, 5m or smaller interval across known flowing fracture*

*Cable length calibration to account for stretching*
Other tests

- Interference testing — typically, 2 to 3 days of pumping and 1 to 2 days of recovery
- Long-term pump tests (including tracer tests)
  - 3-6 months pumping and 1-2 month recovery
  - Monitoring wells within 500-1000 m
- Dilution tests to measure ambient flow
  - Natural flow or during long term pumping
- Long-term monitoring of pressure using a multi-packer system 4-10 sections
Fluid Logging Methods

- Heat Pulse Flowmeter
- Electromagnetic Flowmeter
- Posiva Difference Flowmeter
- Colloidal Borescope
- Flowing Fluid Electric Conductivity Logging Method

To measure inflows into the well as a function of depth — to identify hydraulic fractures
Principle of operation of the thermal-pulse flowmeter (Hess and Pailec, 1990)
Figure 4-3. Detail of the down-hole tool in difference flow logging (DIFF).
Flowing Fluid Electric Conductivity (FFEC) Logging Method

Multi-rate FFEC Logging Method
Outline of Talk on FFEC Logging Method

• Development of FFEC Logging method
  — Early development and applications 1990 and later
  — Recent development since 2003
• Application to deep well in crystalline rock
• Application to deep well in sedimentary rock
• Application to agricultural wells (Quinn and Su)
• Applications to shallow wells for wide range of applications (Bauer, COLOG)
It all started ca 20 years ago during a Hydrogeology Modelers’ Meeting in Sante Fe

Peter Hufschmied (NAGRA, Switzerland) and I had dinner at a Mexican restaurant, and we discussed with sketches on red napkins
Data from 1700-m Leuggern Borehole
750–1650 m; \( Q=20 \text{ L/min} \)
(Five fluid conductivity profiles over three days)
(FEC = Fluid electric conductivity)

Area under each peak $\approx q_i C_i \times \Delta t$

Skewness of peak upwards $\rightarrow q_i$

Reproducing the two features $\rightarrow q_i$ and $C_i$; then $q_i \rightarrow T_i$
Analysis Method

• The numerical model BORE (Tsang, et al., 1990) was coded to calculate FEC profiles, given a set of inflow locations $z_i$, feed point flow rates $q_i$, and salinities $C_i$, by a finite difference numerical method

• Assumptions:
  - (a) feed points to act as mass sources or sinks
  - (b) fluid flow is steady, and
  - (c) complete mixing occurs across the wellbore cross-sectional area

• The BORE code is typically employed in a trial-and-error inverse process to obtain feed point parameters by comparing calculated FEC profiles to observed FEC logs
Developed a simple code “BORE”
Parameters obtained in match to field data

<table>
<thead>
<tr>
<th>Peak Number</th>
<th>$x_i$ (m)</th>
<th>$t_i$ (hours)</th>
<th>$q_i$ (10^{-6} m^3/s)</th>
<th>$C_i$ (kg/m^3)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
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<td>16</td>
<td>0.65</td>
<td>0.50</td>
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<td>0.43</td>
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<td>0.75</td>
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<tr>
<td>9</td>
<td>843</td>
<td>11</td>
<td>17</td>
<td>0.95</td>
</tr>
</tbody>
</table>

$K = 1.0 \times 10^{-3}$ m$^2$/s and $Q = 1.3$ L/min
Since this initial development, widely used in Nagra Program

According to Jorg Hadermann (PSI), a member of Nagra Board of Directors:

In a Board meeting, Nagra stated that Flowing Fluid EC Logging has saved Nagra millions of Swiss Francs !!!
Work after Initial Success

- Define test procedure; apply to shallow systems
- Improved analysis method: BORE-II code
- Mass integral method
- Signature of peaks to indicate flow conditions
Flowing FEC Logging Method

1. **Wellbore water is first replaced** by de-ionized water (or water of constant salinity distinctly different from that of formation water).

2. Next, **well is shut in** and an electric conductivity probe is lowered into the borehole to scan the FEC as a function of depth.

3. Pump the well at **constant rate Q, during which a series of 5 or 6 FEC logs** are obtained (over a few-hour to 1-2 day period).

4. At depth locations \( z_i \) where water enters the borehole (feed points), the logs display peaks. These points give depths of inflow points or zones (typical resolution of about 10 cm).

5. The peaks grow with time and are skewed in the direction of water flow. Area under a peak is proportional to \( q_i C_i \) (where \( q_i \) is inflow rate at a particular feed point) and the skewness of the peak depends on \( \Sigma q_i \) over inflow points below (or upstream) of it.

6. Thus, by analyzing these logs, it is **possible to obtain the flow rate** \( q_i \), **salinity C as measured by FEC, and initial ambient pressure heads** \( h_i \) of each individual fracture or feed point \( i \).
Applications to Shallower Boreholes

FEC logs from the Raymond field site in California (Cohen, 1995, Karasaki et al., 2000).
Analysis Method

• 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.

• BORE II can handle both inflow and outflow points at the well, with flow going up or down.

• BORE II can analyze regional natural flow across the well; probably better than Drost’s method.
Mass Integral \( M(t) \) Method (1)

- Integrate \( C(z,t) \), or FEC profile, over \( z \) of logged interval to get salinity mass per unit area
- Then multiply by wellbore cross-sectional area to obtain salinity mass in wellbore section at time \( t \): \( M(t) \)
- \( M(t_2) - M(t_1) \) is total salinity enters the borehole over \( t_2 - t_1 \)
Mass Integral $M(t)$ Method (2)

- If $q_i$ and $C_i$ constant for all feed points; and additionally if all feed points are inflow points, $M(t)$ will be linear.
- Deviations of $M(t)$ from linearity provide information on validity of model assumptions:
  - $M(t)$ concaves up
    - $q_i$ increasing in time (transient response to pumping)
    - $C_i$ increasing in time or $t_0 > 0$ (DI water moves into fractures during recirculation)
  - $M(t)$ concaves down
    - $q_i$ decreasing in time
    - Outflow points are present
- For more accurate results from fitting, focus on FEC profiles collected during period when $M(t)$ is linear.
FFEC Logs: Signature of peaks

- Constant C
- Increasing C
- Inflow with $C_0$
- Isolated Peaks
- Interfering Peaks
- Inflow and Outflow
- Thin Horizontal Flow
- Thick Horizontal Flow
- Inflow and Outflow

Sections:
- Sect. 2.1.1
- Sect. 2.1.2
- Sect. 2.1.3
- Sect. 2.1.4
- Sect. 2.1.5
- Sect. 2.1.6
- Sect. 2.2
Method revisited and extended in 2002

Multi-rate Flowing Fluid Electric Conductivity Logging Method
Combining FFEC logging analysis with two pumping rates: Q and Q+ ΔQ

\[ q_i = \frac{2\pi T_i^* (h_i - h_{wb})}{\ln(r_i / r)} = T_i (h_i - h_{wb}) \]

\[ \frac{T_i}{T_{tot}} = \frac{\Delta q_i}{\Delta Q} \]

\[ \frac{(h_i - h_{avg})}{(h_{avg} - h_{wb})} = \frac{q_i / Q}{\Delta q_i / \Delta Q} - 1 \]
Use of Three Rates $Q$, $Q/2$ and $2Q$

- Generally recommend three pumping rates to be used in three tests, Test 1, Test 2 and Test 3
- BORE-II analysis yields three sets of $q_i$, with one set of $C_i$ and $x_i$
- Combining results of three possible pairs out of the three tests, i.e., (Test 1 and Test 2), (Test 2 and Test 3), and (Test 3 and Test 1) gives three sets of $T_i$ and $h_i$, as well as one set of $C_i$
- This allows internal check and enhances confidence
Remarks: Input to Modeling

- It has been noted for fractured rocks and also for an heterogeneous porous medium, that $k$, salinity, and $h$ (ambient pressure of a hydrogeologic unit) can vary strongly spatially. Information is needed to identify hydraulic structure of the subsurface.

- Much information can be obtained from FFEC Logs from just 3 days of data
  - no special tools (contrast to heat pulse or Posiva flowmeters)
  - robust and efficient method

- Developed concept of Flow Compartmentalization based on observed $h$’s being different (confirmed by Kamaishi (JNC) data; Forsmark (SKB) data)

- Information on pressure head ($h$) distributions puts a new constraint to fracture hydrology modeling
Application to a Japanese Site
(Doughty et al., 2005)
3-day data sets from a 500-m well at Tono site, Japan

- Test 1 Q = 10 L/min (Day 1)
- Test 2 Q = 20 L/min (Day 2)
- Test 3 Q = 5 L/min (Day 3)

Each set has 7 logs at 1 hour apart ("Initial" log was taken 4-7 minutes after pumping started)
Examining Initial and Static Conditions

- Solid curves show “initial” conditions at about 4-7 minutes after pumping started.
- Dotted curves show “static” log just before pumping started, after the well was flushed with de-ionized water.
  - not constant FEC, as one would expect or hope for
  - very similar for all three tests
  - must be due to internal flow
Results from 3 days of data (19 conductive fractures)

- Salinity (FEC) as a function of depth
- Transmissivity (permeability) as a function of depth
- “Far-field” head as a function of depth
Further Validation

- Notice: “initial” log may represent results of internal wellbore flow with $Q = 0$

- Result of product of $C_i, T_i/T_{avg}$ and $(P_i-P_{wb})/P_{avg}-P_{wb}$

- Match surprisingly good!
## Table of Results: 19 Inflow Points over 260 m

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Ti/Ttot</th>
<th>Ti/Tbar</th>
<th>Test 2 (Pi-Pwb)/ (Pavg-Pwb)</th>
<th>Test 3 (Pi-Pwb)/ (Pavg-Pwb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>456</td>
<td>0.004</td>
<td>0.076</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>440</td>
<td>0.011</td>
<td>0.215</td>
<td>1.412</td>
<td>2.647</td>
</tr>
<tr>
<td>436</td>
<td>0.038</td>
<td>0.713</td>
<td>0.999</td>
<td>0.996</td>
</tr>
<tr>
<td>429</td>
<td>0.053</td>
<td>1.013</td>
<td>1.031</td>
<td>1.125</td>
</tr>
<tr>
<td>403</td>
<td>0.008</td>
<td>0.152</td>
<td>1.250</td>
<td>2.000</td>
</tr>
<tr>
<td>366</td>
<td>0.008</td>
<td>0.158</td>
<td>1.200</td>
<td>1.800</td>
</tr>
<tr>
<td>347</td>
<td>0.022</td>
<td>0.412</td>
<td>1.154</td>
<td>1.615</td>
</tr>
<tr>
<td>338</td>
<td>0.025</td>
<td>0.475</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>331</td>
<td>0.006</td>
<td>0.108</td>
<td>0.882</td>
<td>0.529</td>
</tr>
<tr>
<td>323</td>
<td>0.137</td>
<td>2.597</td>
<td>1.024</td>
<td>1.098</td>
</tr>
<tr>
<td>318</td>
<td>0.097</td>
<td>1.837</td>
<td>1.034</td>
<td>1.138</td>
</tr>
<tr>
<td>310</td>
<td>0.070</td>
<td>1.330</td>
<td>0.929</td>
<td>0.714</td>
</tr>
<tr>
<td>304</td>
<td>0.080</td>
<td>1.520</td>
<td>1.063</td>
<td>1.250</td>
</tr>
<tr>
<td>298</td>
<td>0.097</td>
<td>1.837</td>
<td>1.086</td>
<td>1.345</td>
</tr>
<tr>
<td>287</td>
<td>0.028</td>
<td>0.538</td>
<td>1.059</td>
<td>1.235</td>
</tr>
<tr>
<td>275</td>
<td>0.033</td>
<td>0.633</td>
<td>0.750</td>
<td>No inflow; low head</td>
</tr>
<tr>
<td>250</td>
<td>0.070</td>
<td>1.330</td>
<td>0.893</td>
<td>0.571</td>
</tr>
<tr>
<td>230</td>
<td>0.082</td>
<td>1.552</td>
<td>0.949</td>
<td>0.796</td>
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<tr>
<td>205</td>
<td>0.132</td>
<td>2.504</td>
<td>0.929</td>
<td>0.718</td>
</tr>
</tbody>
</table>
Some Comments

• Results came out very well: much information was obtained from just three-days’ data
• Knowing $h_i$ is very useful
• Validation against two independent data provides much confidence: (a) $C_i$, independent data from water sampling; (b) $Q=0$, “static” FEC log data of internal wellbore flow
• Can improve matching, if we re-adjust $C_i$ for shallower fractures, and also if we allow $Q \neq \Sigma q$
Application to HDB-11 FFEC Logs
Horonobe, Japan

- Deep well in fractured sedimentary rock in Horonobe, Japan
- The well was drilled in three steps
- FFEC Logs were taken after drilling to 450 m
- FFEC Logs were again taken over a deeper well section after the second drilling step
Some Complications

- a section of the borehole having a variable wellbore diameter
- the presence of a free water surface in the borehole (i.e., the logged zone is not isolated with packers)
- flow of low-salinity water into fractures during the initial recirculation period
- periods of unknown pumping rate during FFEC logging
- a small increase in salinity all along the borehole during FFEC logging, probably the result of residual mud used in drilling the well
- a gradual borehole pressure decline during FFEC logging
HDB-11 Caliper Log

Well HDB-11

Depth (m)

Caliper (mm)

- CAL-X mm
- CAL-Y mm
Well HDB-11 FFEC Logging

- **Shallow Interval (150-450 m)**
  - $Q = 2 \text{ L/min}$
  - $Q = 10 \text{ L/min}$
  - $Q = 19.1 \text{ L/min}$

- **Deep Interval (450-800 m)**
  - $Q = 5 \text{ L/min}$
  - $Q = 10 \text{ L/min}$
  - $Q = 15 \text{ L/min}$
Shallow Zone: Model Fit to FFEC Data

- Three-day data
- Three pumping rates: 2, 10, 19.1 L/min
- Very good match for all peaks except very large peak at 150 m depth, which shows complicated behavior that cannot be analyzed
Shallow Zone: Results of Individual Tests
Shallow Zone: Multi-Rate Results
**Deep Zone: Model Fit to FFEC Data**

Fit is good
As before, \( \sum q_i << Q_{\text{form}} \) for all tests
- \( Q=5: \sum q_i=2.04 \quad Q_{\text{form}}=3.34 \)
- \( Q=10: \sum q_i=3.90 \quad Q_{\text{form}}=6.84 \)
- \( Q=15: \sum q_i=5.12 \quad Q_{\text{form}}=7.85 \)

System is strongly non-unique with respect to salinity
Analysis greatly benefits from one or more independent salinity measurements
Deep Zone: Multi-Rate Results
Summary of Results

Shallow tests

- Good results for small peaks
- Uppermost, big peak not analyzable

Deep tests

- Moderately good results, but analysis is highly nonunique with respect to increases in salinity (inferred values of $T_i/T_{tot}$ and $I\Delta P_i$ do not change appreciably)
- Need to understand why $\sum q_i << Q_{form}$
# Shallow Conducting Fractures (26)

<table>
<thead>
<tr>
<th>Peak</th>
<th>Depth (m)</th>
<th>$T_i/T_{tot}$</th>
<th>IDP$_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>417</td>
<td>0.013</td>
<td>-0.338</td>
</tr>
<tr>
<td>2</td>
<td>402</td>
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<tr>
<td>4</td>
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<td>0.007</td>
<td>-0.816</td>
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<tr>
<td>5</td>
<td>360</td>
<td>0.014</td>
<td>-0.224</td>
</tr>
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<td>6</td>
<td>351</td>
<td>0.050</td>
<td>0.268</td>
</tr>
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<td>348</td>
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<td>0.130</td>
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<td>338</td>
<td>0.013</td>
<td>0.287</td>
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<td>9</td>
<td>332</td>
<td>0.011</td>
<td>0.393</td>
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<td>325</td>
<td>0.009</td>
<td>-0.403</td>
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<td>-0.186</td>
</tr>
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<td>312</td>
<td>0.013</td>
<td>-0.554</td>
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<tr>
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<td>299</td>
<td>0.008</td>
<td>0.814</td>
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<table>
<thead>
<tr>
<th>Peak</th>
<th>Depth (m)</th>
<th>$T_i/T_{tot}$</th>
<th>IDP$_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>292</td>
<td>0.007</td>
<td>1.626</td>
</tr>
<tr>
<td>15</td>
<td>287</td>
<td>0.006</td>
<td>0.828</td>
</tr>
<tr>
<td>16</td>
<td>282</td>
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<td>18</td>
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<td>0.342</td>
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<td>19</td>
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<td>0.306</td>
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<td>0.225</td>
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<td>24</td>
<td>211</td>
<td>0.029</td>
<td>0.283</td>
</tr>
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<td>201</td>
<td>0.061</td>
<td>0.668</td>
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<tr>
<td>26</td>
<td>190</td>
<td>0.044</td>
<td>-0.276</td>
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## Deep Conducting Fractures (18)

<table>
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<tr>
<th>Peak Number</th>
<th>Depth (m)</th>
<th>$T_i/T_{tot}$</th>
<th>$I \Delta P_i$</th>
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<tbody>
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<td>633</td>
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<td>629</td>
<td>0.021</td>
<td>-0.371</td>
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<td>6</td>
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<td>0.011</td>
<td>-0.732</td>
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</tr>
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<td>9</td>
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<td>1.587</td>
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<td>3.573</td>
</tr>
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<td>-0.332</td>
</tr>
<tr>
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<td>530</td>
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<tr>
<td>17</td>
<td>473</td>
<td>0.016</td>
<td>-0.246</td>
</tr>
<tr>
<td>18</td>
<td>463</td>
<td>0.009</td>
<td>-0.292</td>
</tr>
</tbody>
</table>
Comparison with Independent Data

Salinity

- Comparison with fluid resistivity data from HDB-1 and HDB-2
- Comparison with EC of groundwater squeezed from core samples

Packer Tests

- 6 intervals, spacing ranging from 10 to 80 m
- Need to develop calculational methods for converting detailed individual fracture results to packer interval results for comparison to packer test data
- Need $T_{tot}$ and $P_{avg}$
Salinity and Electric Resistivity in other HDB Wells

HDB-1

HDB-2

- Unit conversion: 1 ohm-m → 1 S/m = 1000 mS/m
- Range of FEC (150–700 m): 600 – 8000 mS/m
- Range acc. to Pickett (?): 400 – 22000 mS/m
Independent HDB-11 Data

Range of salinity squeezed from core: 2000 mS/m – 3500 mS/m
Compare Model and Packer Test Results

T fit is good for both zones

Head fit is good for shallow zone

Model head is more variable than packer-test head for deep zone
Concluding Remarks (1)

• Much information was obtained from just one to three days of field measurements
• Can measure depths of inflow zones, flow transmissivities, salinity, and initial pressure heads; as well as regional flow velocity
• Much less time and effort than packer tests
• No special tools (contrast to Heat Pulse Flowmeter, Posiva Flowmeters, or Multi-packer Tool)
• Method is robust and efficient
Concluding Remarks (2)

• Developed concept of Flow Compartmentalization based on observed h’s being different (confirmed by Kamaishi (JNC) data; Forsmark (SKB) data)

• Information on pressure head (h) distributions puts a new constraint to fracture hydrology modeling
References


• Christine Doughty and Chin-Fu Tsang, Koichiro Hatanaka, Satoshi Yabuuchi and Hiroshi Kurikami, Application of direct-fitting, mass-integral, and multi-rate methods to analysis of flowing fluid electric conductivity logs from Horonobe, Japan. Submitted to Water Resources Research, under revision to be published, November 2007.