

# **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*

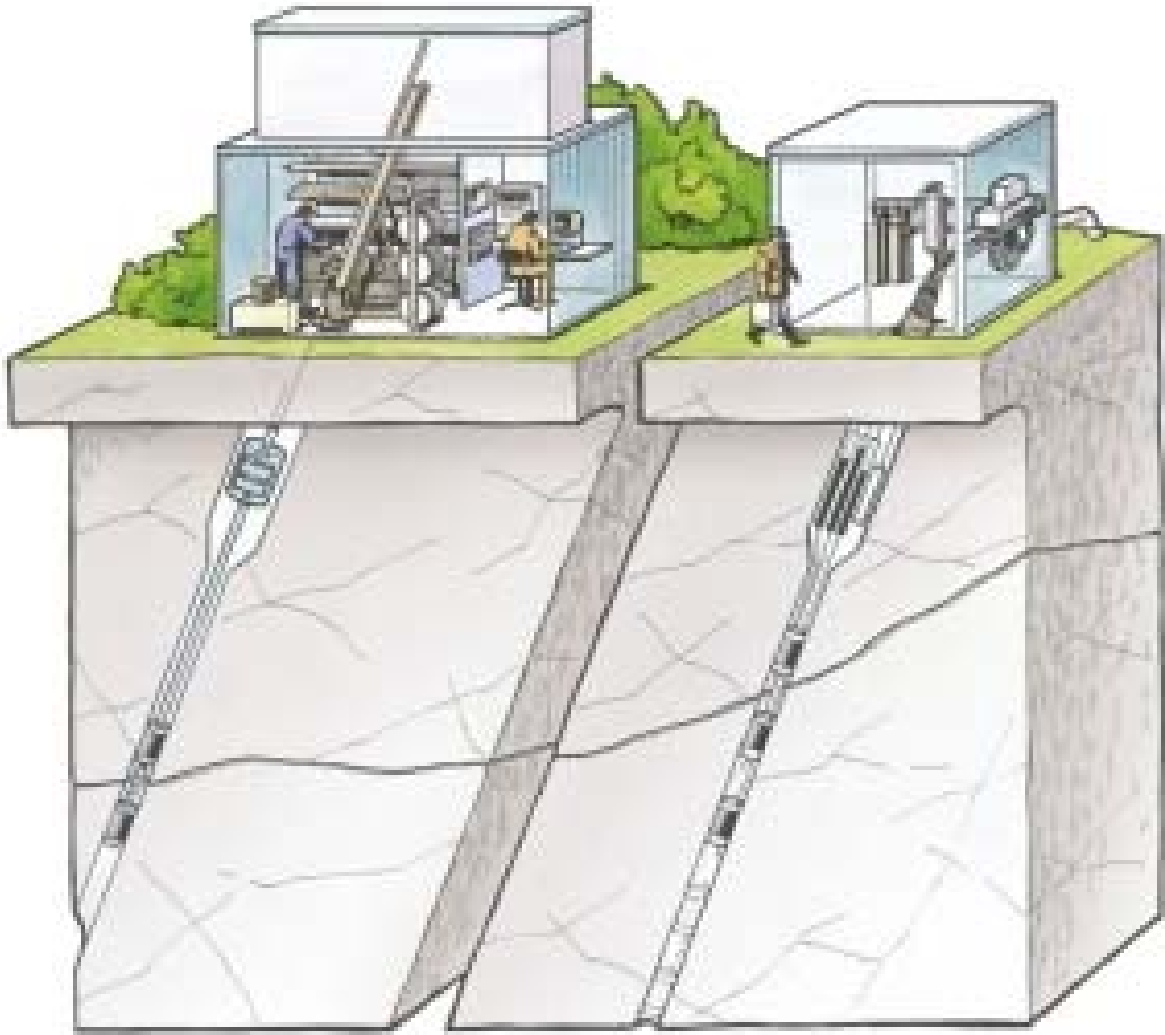
*Cable length calibration to account for stretching*

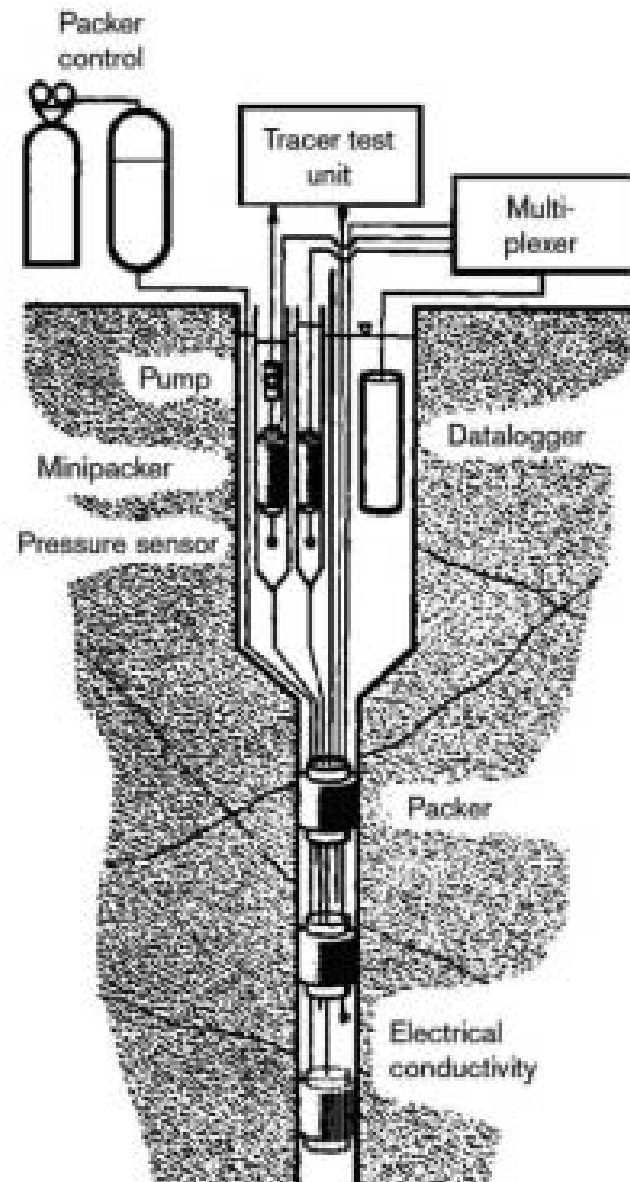
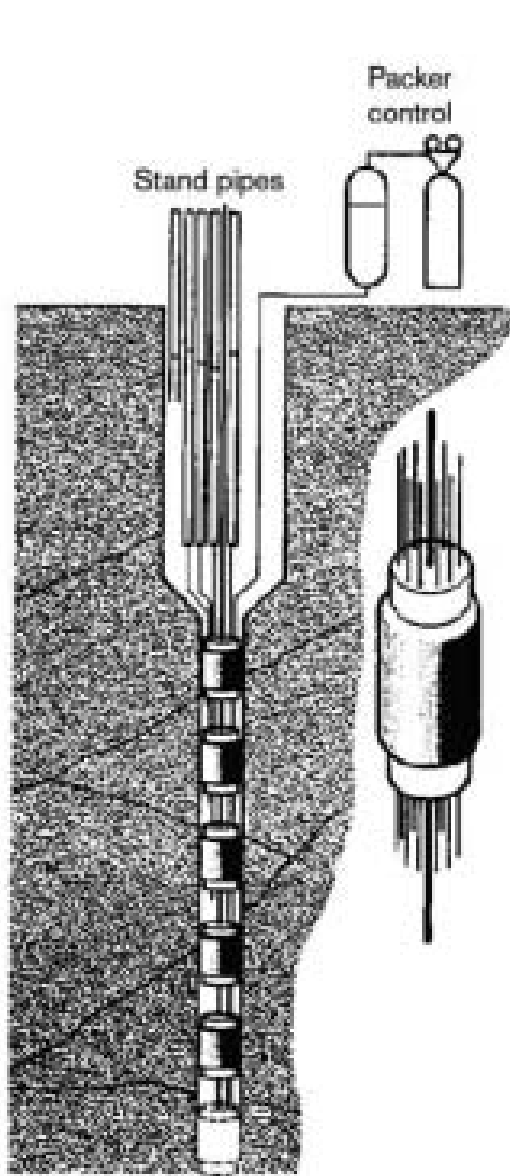


# Other tests

- **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**





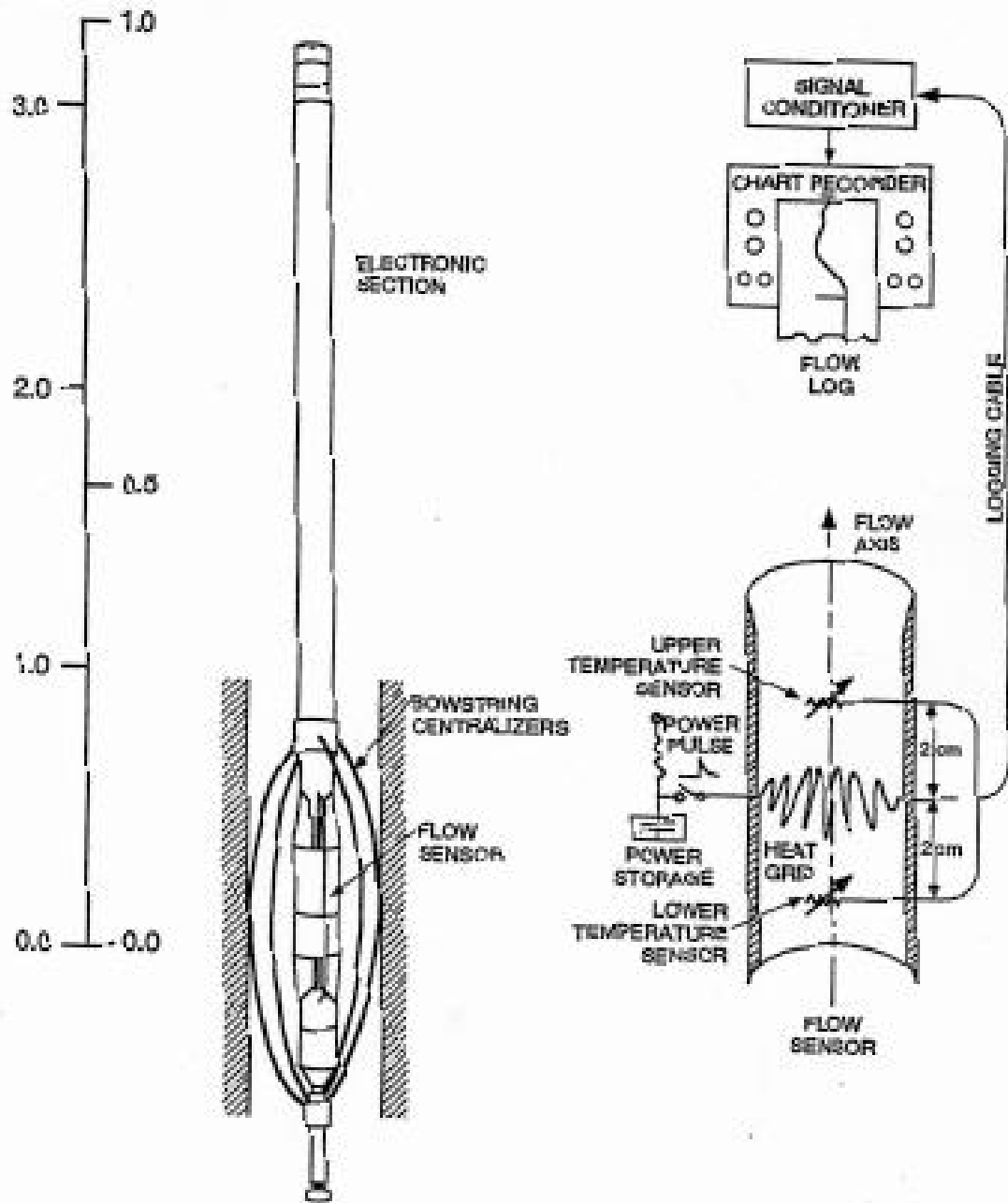


# Fluid Logging Methods

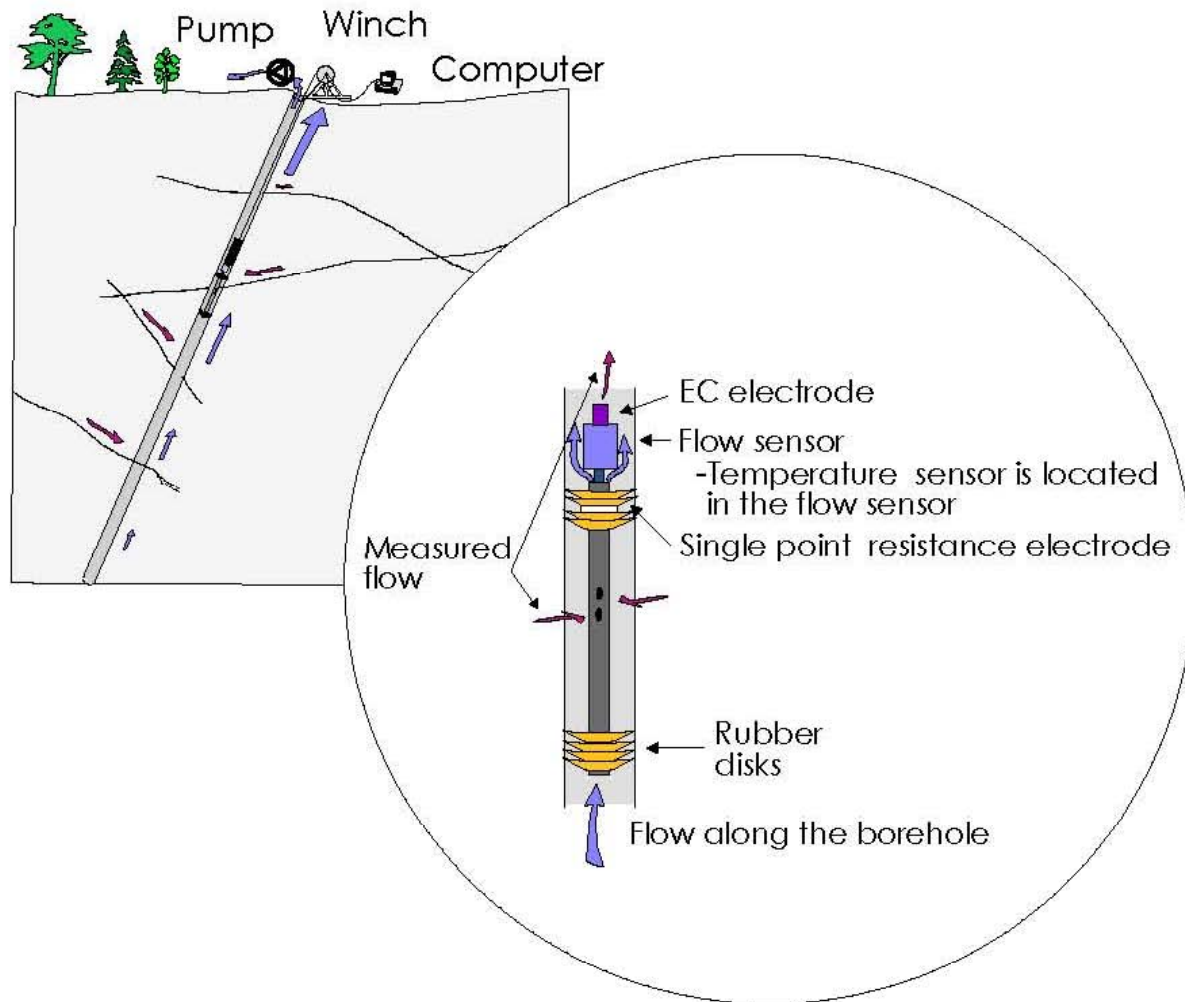
- Heat Pulse Flowmeter
- Electromagnetic Flowmeter
- Posiva Difference Flowmeter
- Colloidal Borescope
- Flowing Fluid Electric Conductivity Logging Method

*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 Fallet, 1990)*



**BERKELEY** *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*

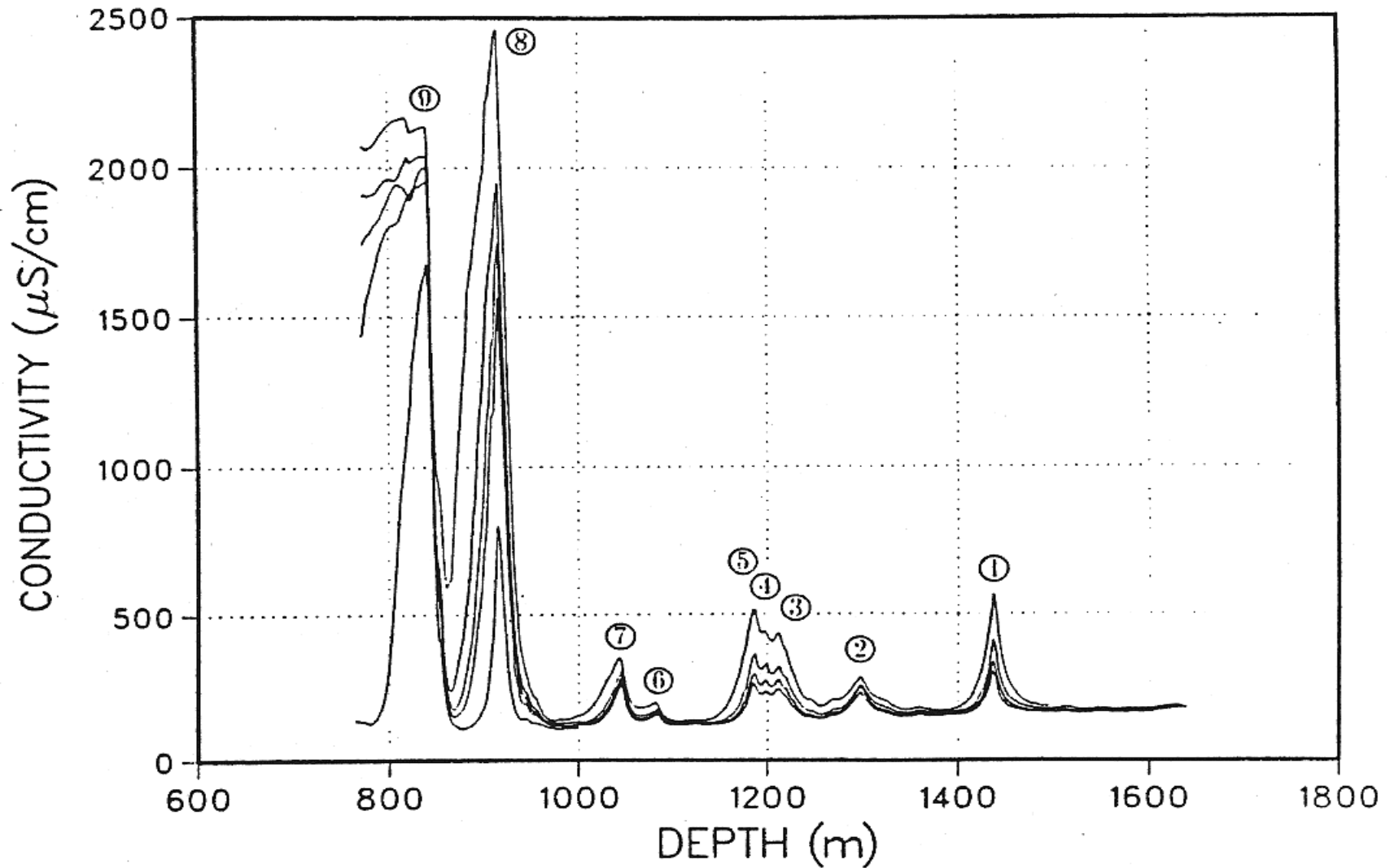
*Peter Hufschmied (NAGRA,  
Switzerland) and I had dinner at a  
Mexican restaurant, and we  
discussed with sketches on red  
napkins*

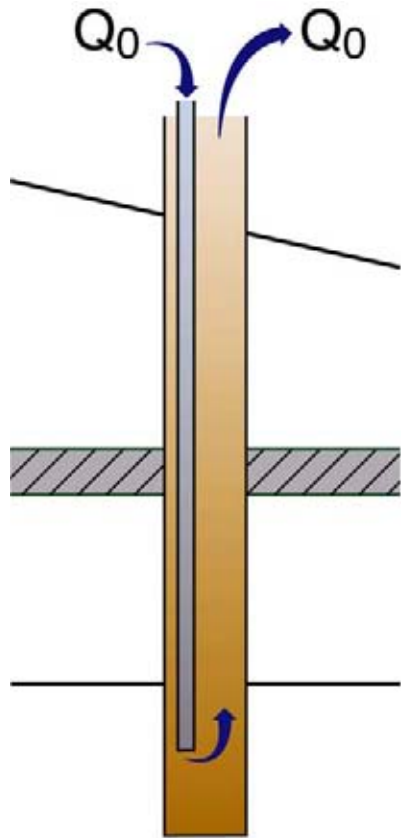


# Data from 1700-m Leuggern Borehole

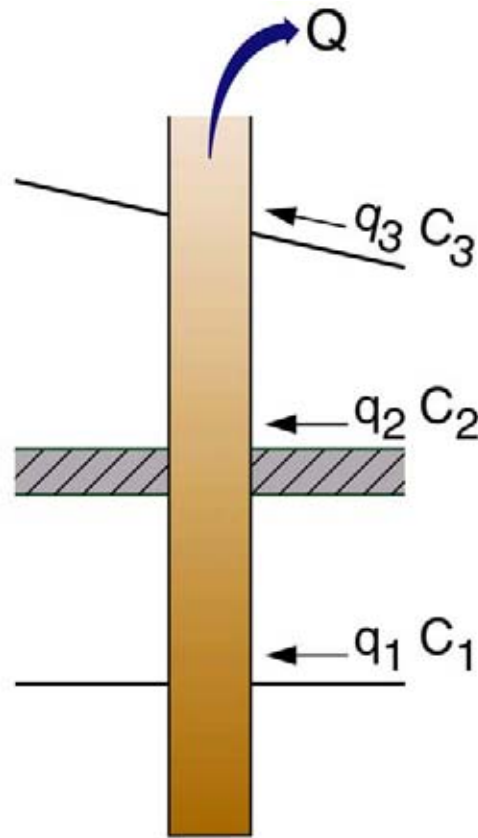
750–1650 m; **Q=20 L/min**

*(Five fluid conductivity profiles over three days)*

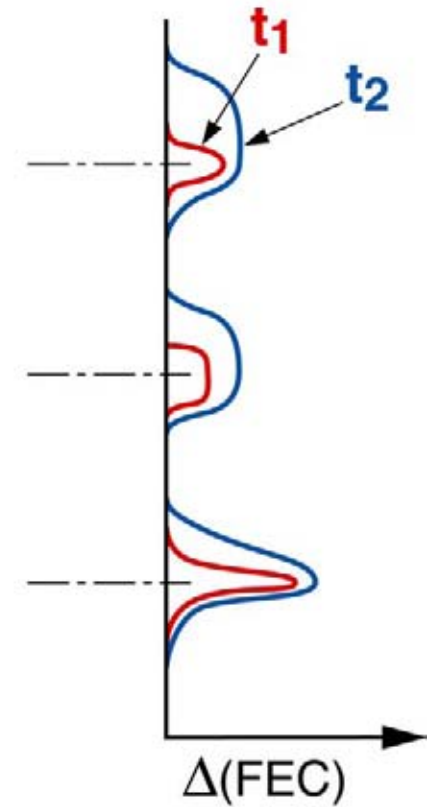




Initial Replacing  
Borehole Water



FEC Logging  
(several times) while  
Pumping at Q



ESD06-001



*(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**

Peak Number	$x_i$ (m)	$t_i$ (hours)	$q_i$ ( $10^{-6} \text{ m}^3/\text{s}$ )	$C_i$ ( $\text{kg}/\text{m}^3$ )
1	1440	16	0.65	0.50
2	1300	15	0.60	0.45
3	1215	16	0.55	0.45
4	1200	27	0.25	0.40
5	1188	27	0.65	0.43
6	1085	24	0.20	0.37
7	1048	24	0.60	0.48
8	918	13	0.75	5.50
9	843	11	17	0.95

$K = 1.0 \times 10^{-3} \text{ m}^2/\text{s}$  and  $Q = 1.3 \text{ L}/\text{min}$



# 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

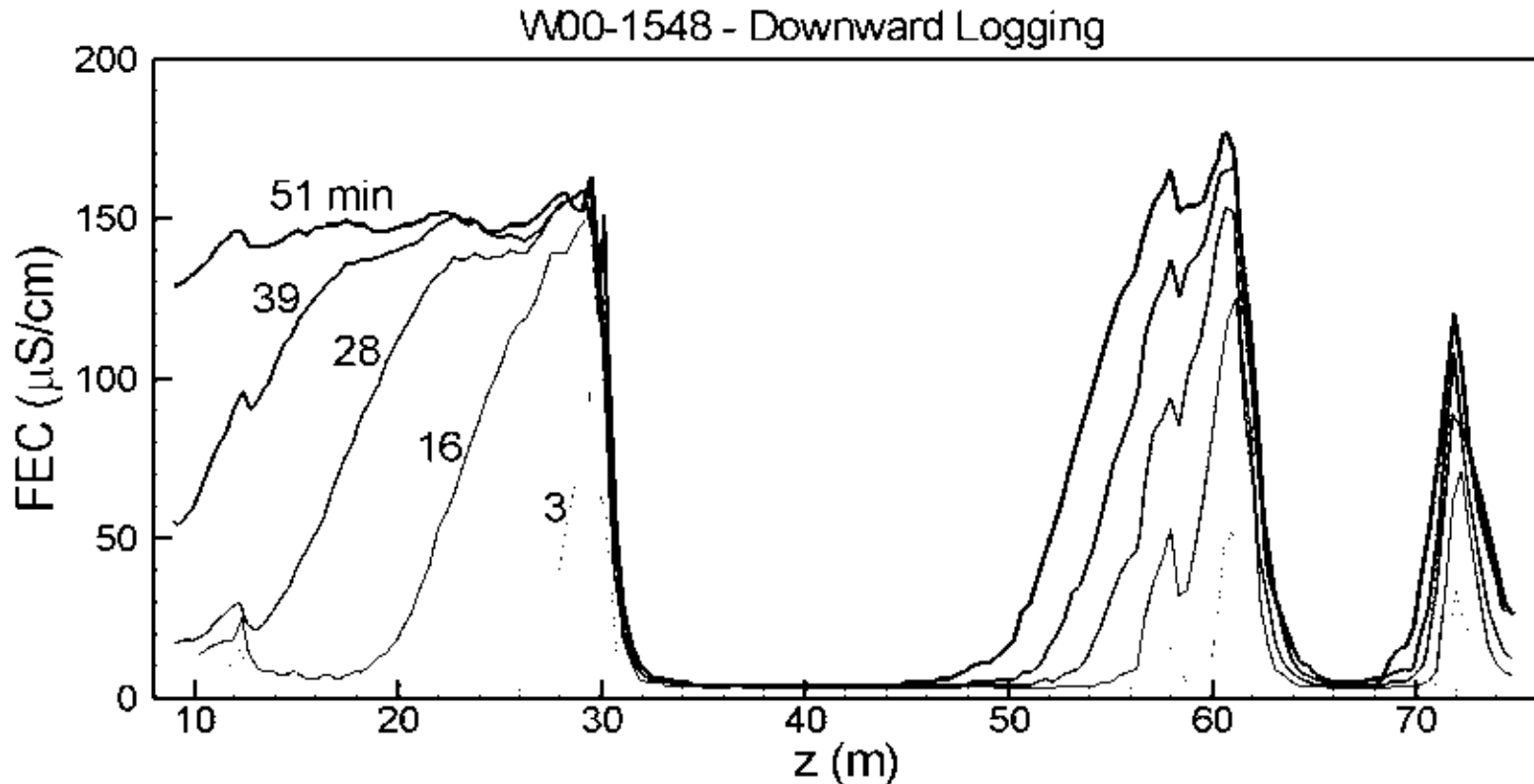
- Define test procedure; apply to shallow systems
- Improved analysis method: BORE-II code
- Mass integral method
- Signature of peaks to indicate flow conditions



# 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  $\sum q_j$  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).**



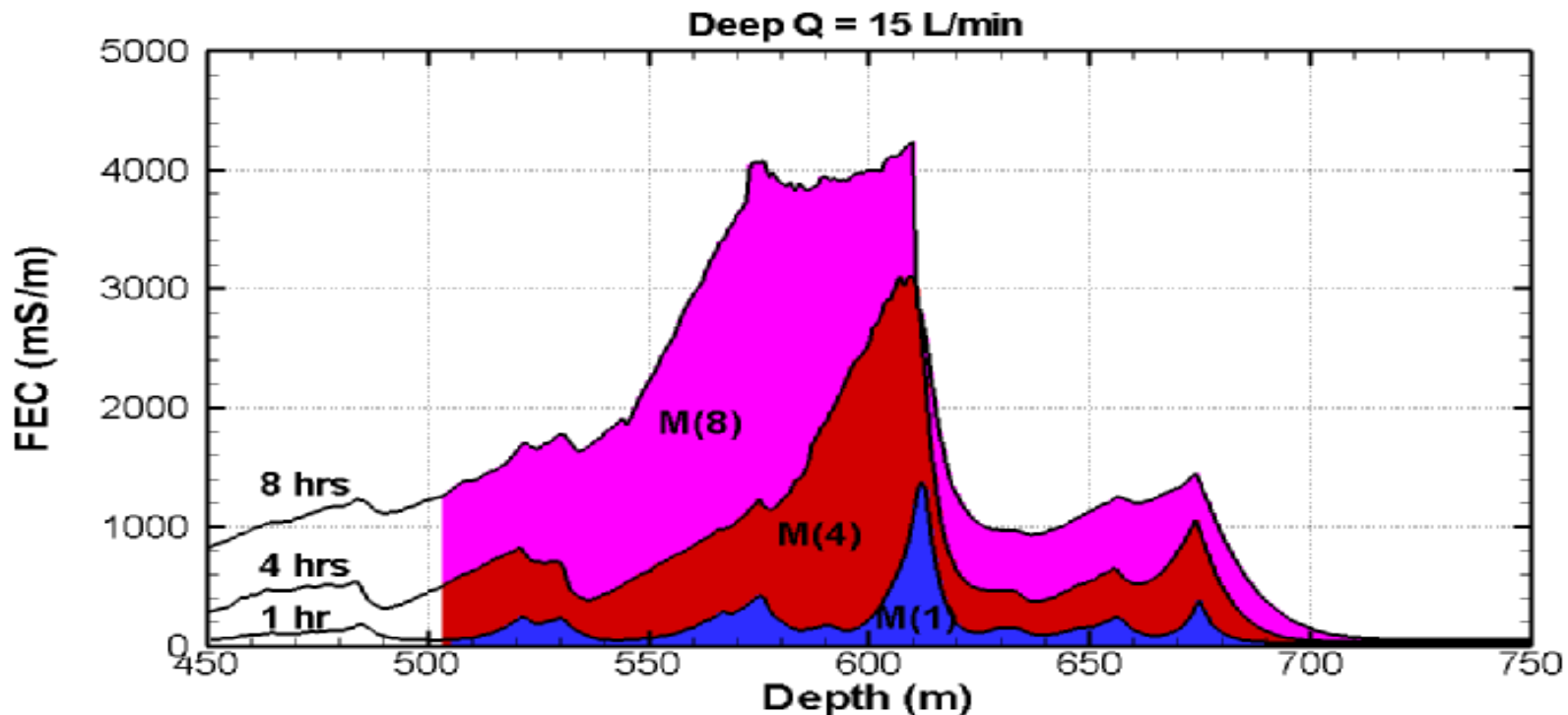
# Analysis Method

- 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)

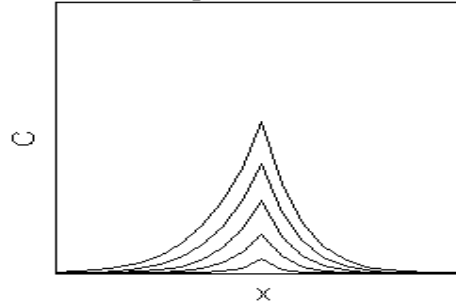
- If  $q_i$  and  $C_i$  constant for all feed points; and additionally if all feed points are inflow points,  $M(t)$  will be linear
- Deviations of  $M(t)$  from linearity provide information on validity of model assumptions
  - $M(t)$  concaves up
    - $q_i$  increasing in time (transient response 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

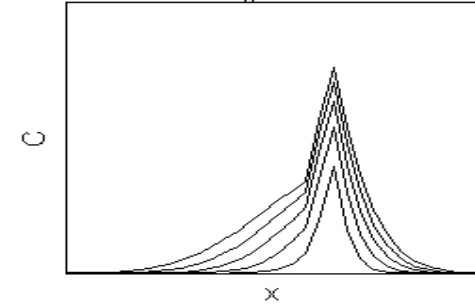
Constant C Sect. 2.1.1



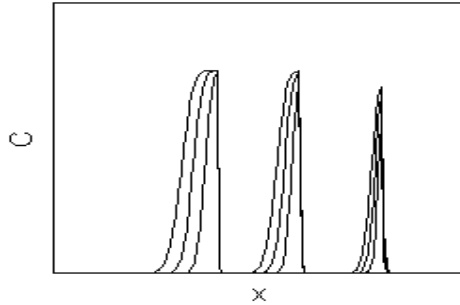
Increasing C Sect. 2.1.3



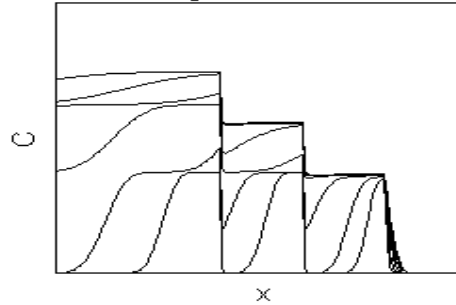
Inflow with  $C_0$  Sect. 2.1.4



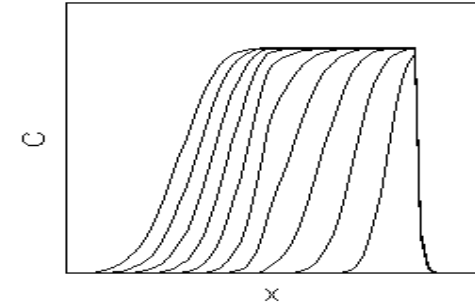
Isolated Peaks Sect. 2.1.1



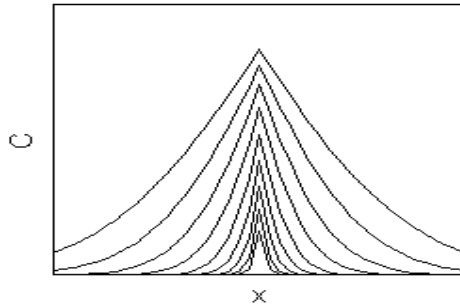
Interfering Peaks Sect. 2.1.1



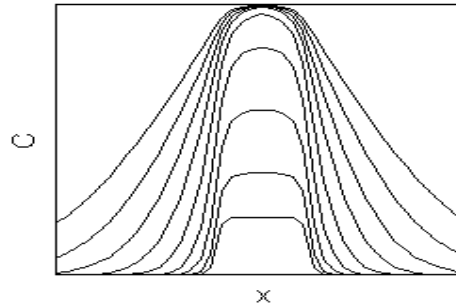
Inflow and Outflow Sect. 2.1.5



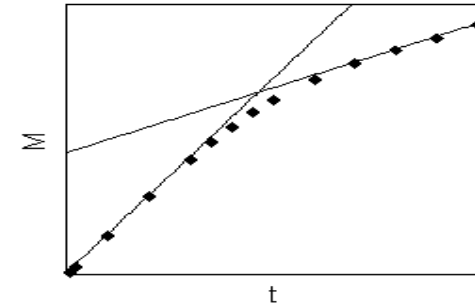
Thin Horizontal Flow Sect. 2.1.6



Thick Horizontal Flow Sect. 2.1.6



Inflow and Outflow Sect. 2.2



**Method revisited and extended in 2002**

# **Multi-rate Flowing Fluid Electric Conductivity Logging Method**



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# Combining FFEC logging analysis with two pumping rates: $Q$ and $Q + \Delta Q$

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

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

$$\frac{(h_i - h_{avg})}{(h_{avg} - h_{wb})} = \frac{q_i / Q}{\Delta q_i / \Delta Q} - 1$$



# Use of Three Rates $Q$ , $Q/2$ and $2Q$

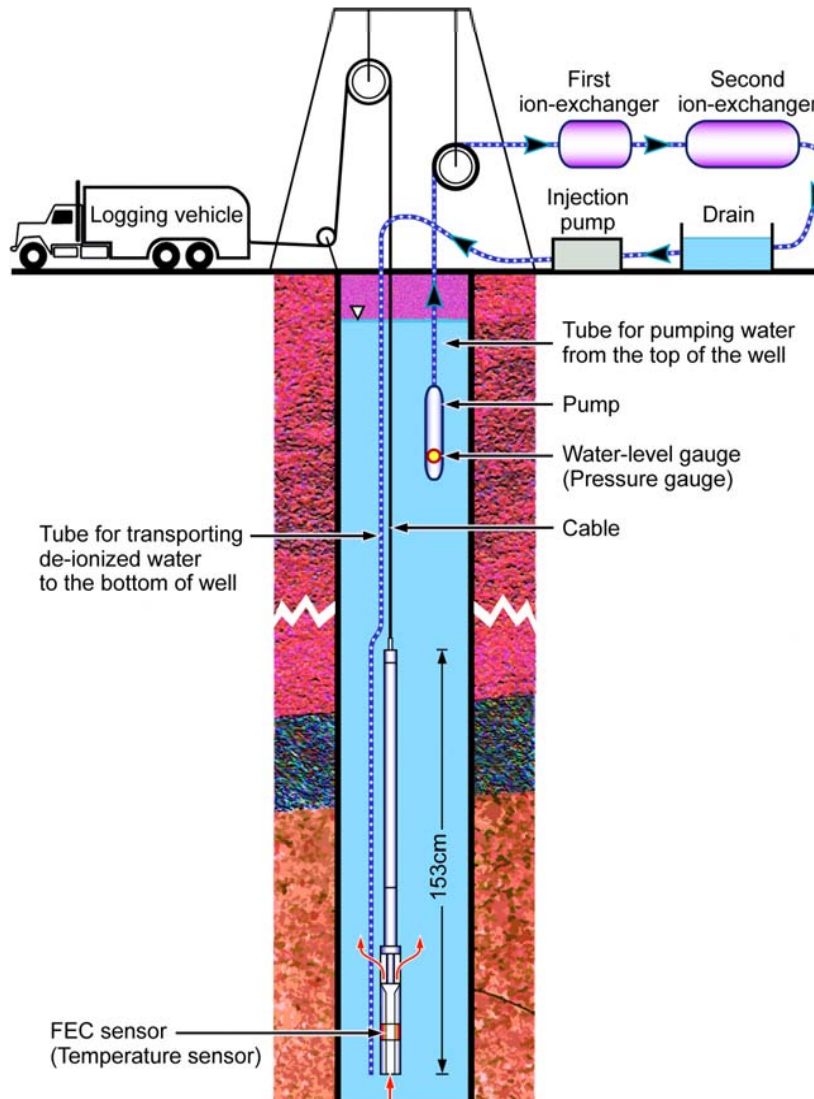
- Generally recommend three pumping rates to be used in three tests, Test 1, Test 2 and Test 3
- BORE-II analysis yields three sets of  $q_i$ , with one set of  $C_i$  and  $x_i$
- Combining results of three possible pairs out of the three tests, i.e., (Test 1 and Test 2), (Test 2 and Test 3), and (Test 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

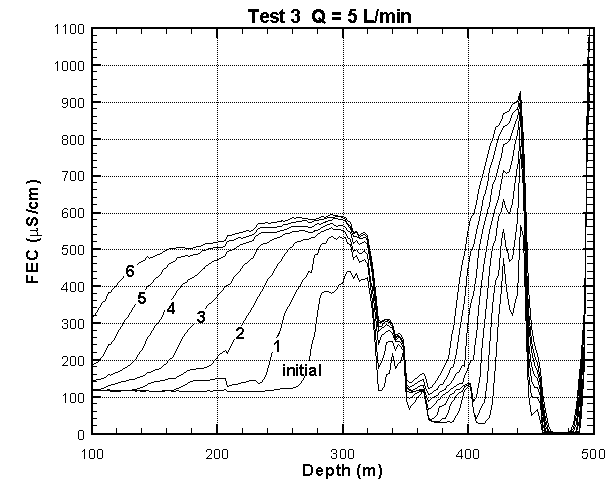
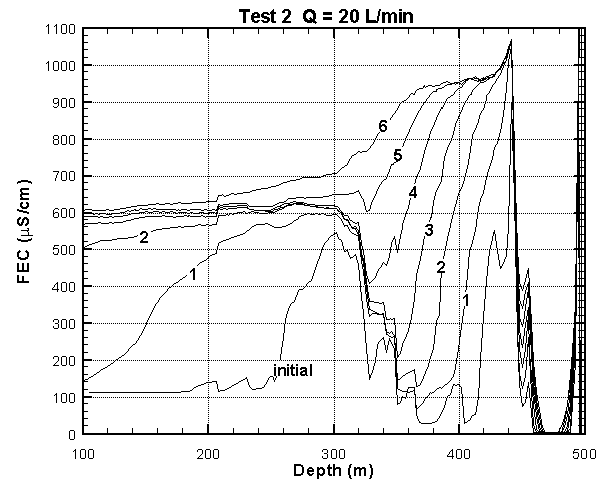
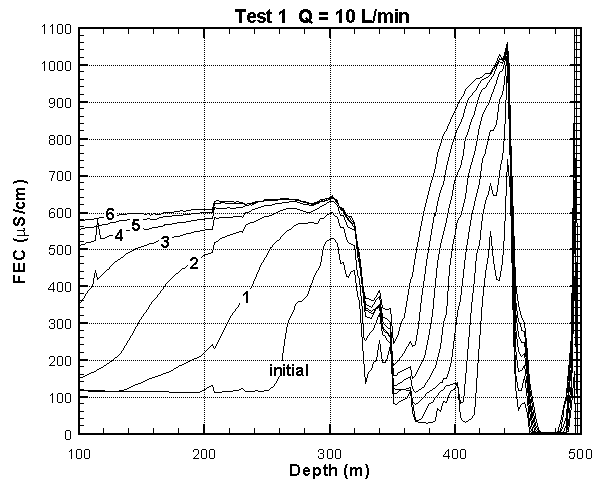
# Application to a Japanese Site (Doughty et al., 2005)



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# 3-day data sets from a 500-m well at Tono site, Japan

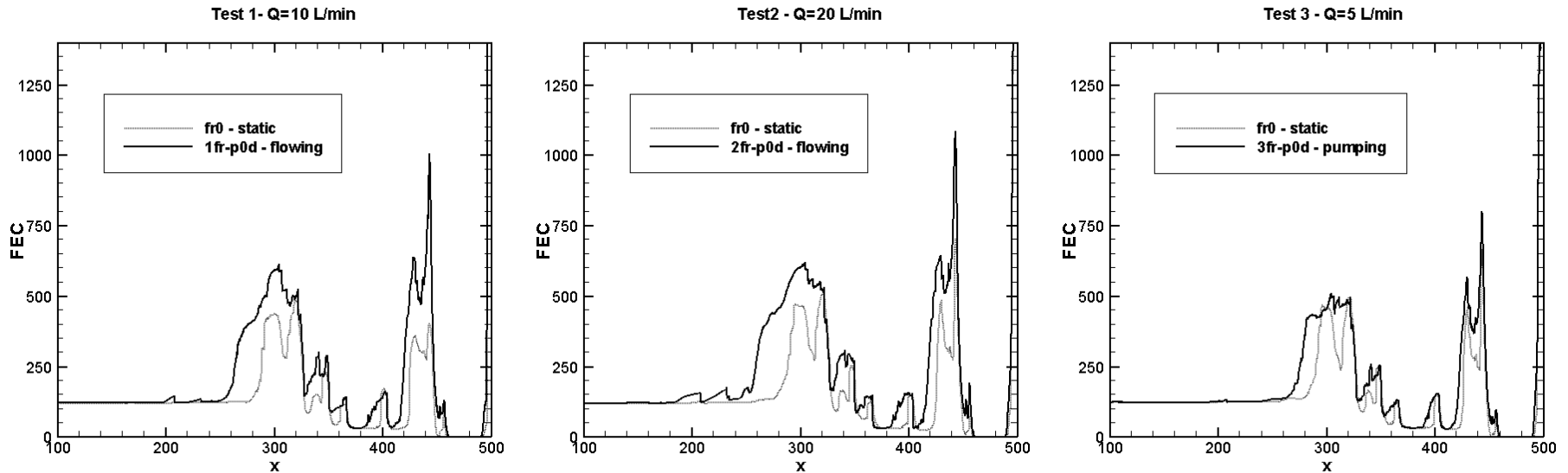


- Test 1 Q = 10 L/min (Day 1)
- Test 2 Q = 20 L/min (Day 2)
- Test 3 Q = 5 L/min (Day 3)

Each set has 7 logs at 1 hour apart (“Initial” log was taken 4-7 minutes after pumping started)



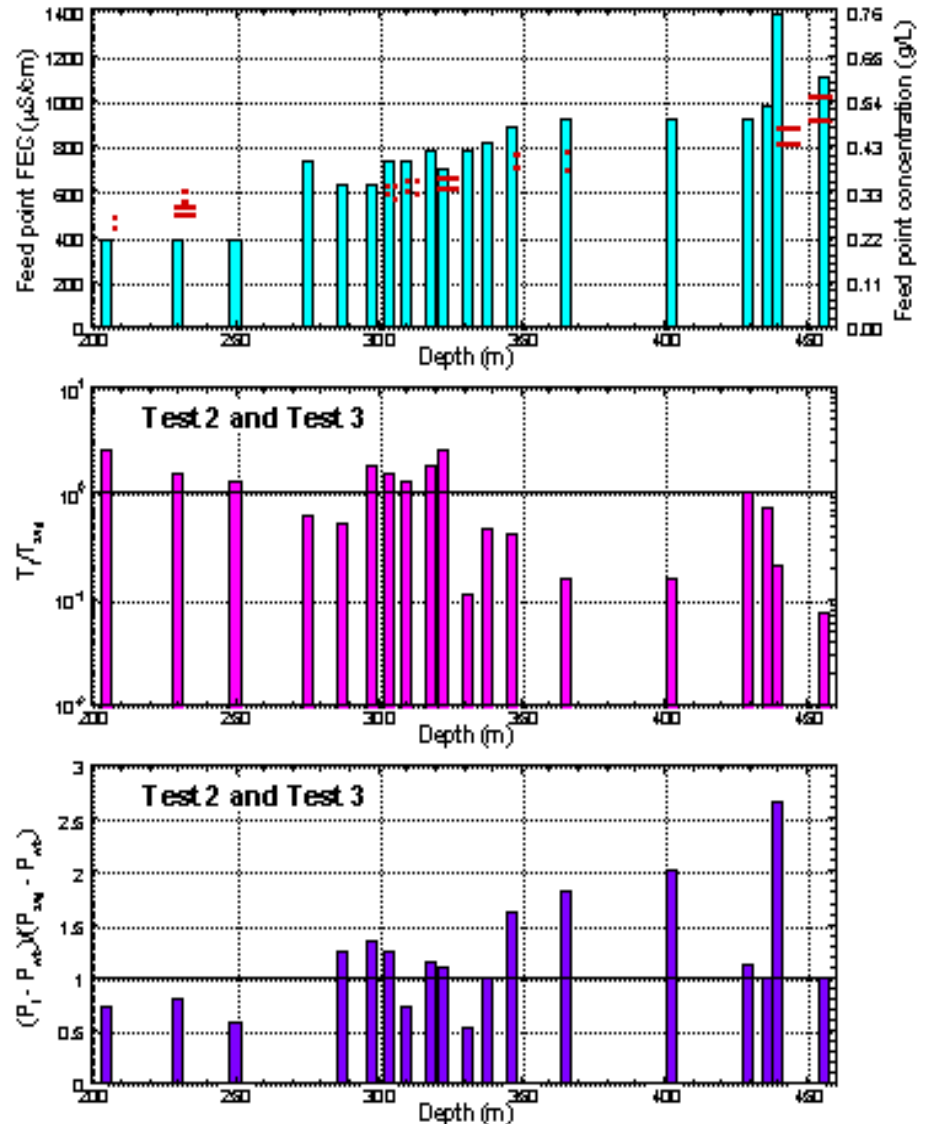
# Examining Initial and Static Conditions



- 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

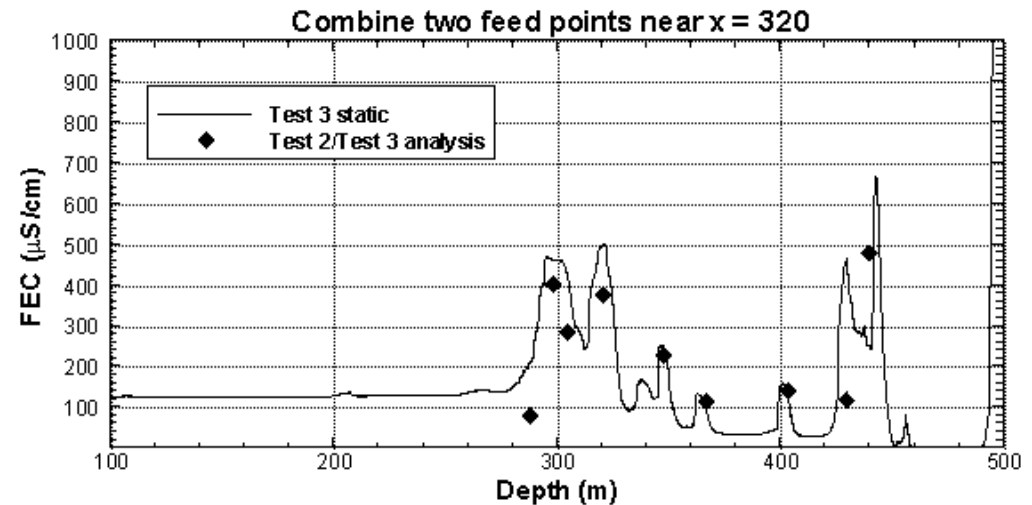
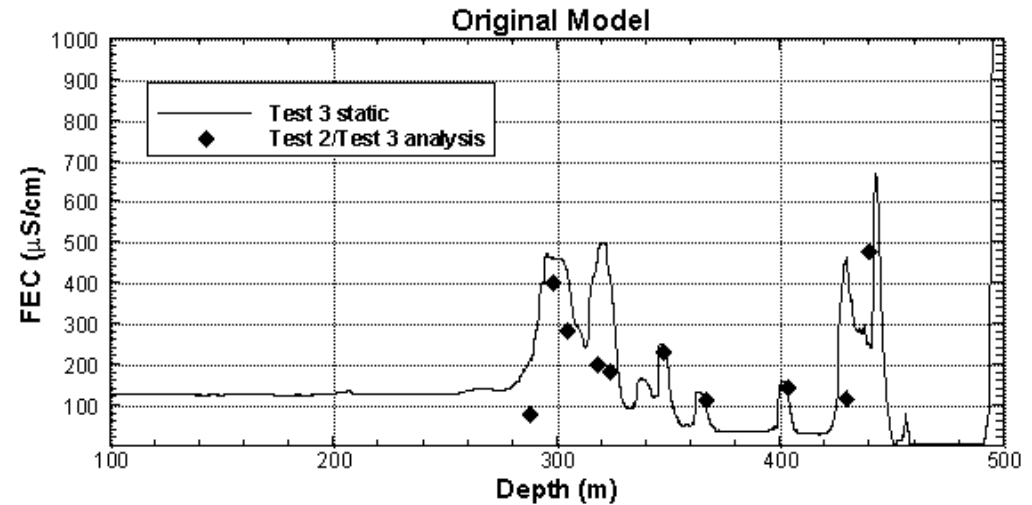
# Results from 3 days of data (19 conductive fractures)

- 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

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



# 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  $Q \neq \sum q$



# 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

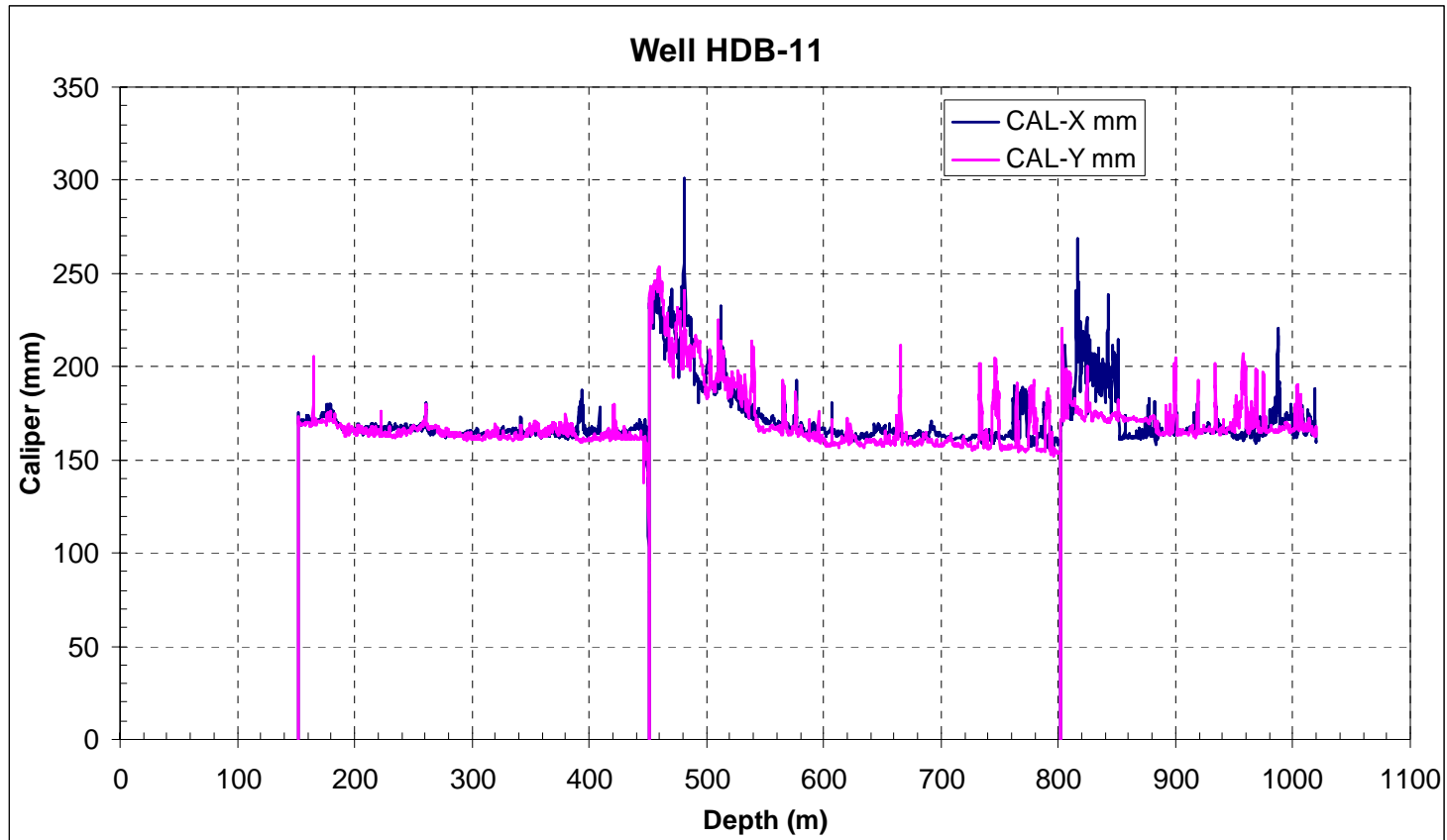


## Some Complications

- 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

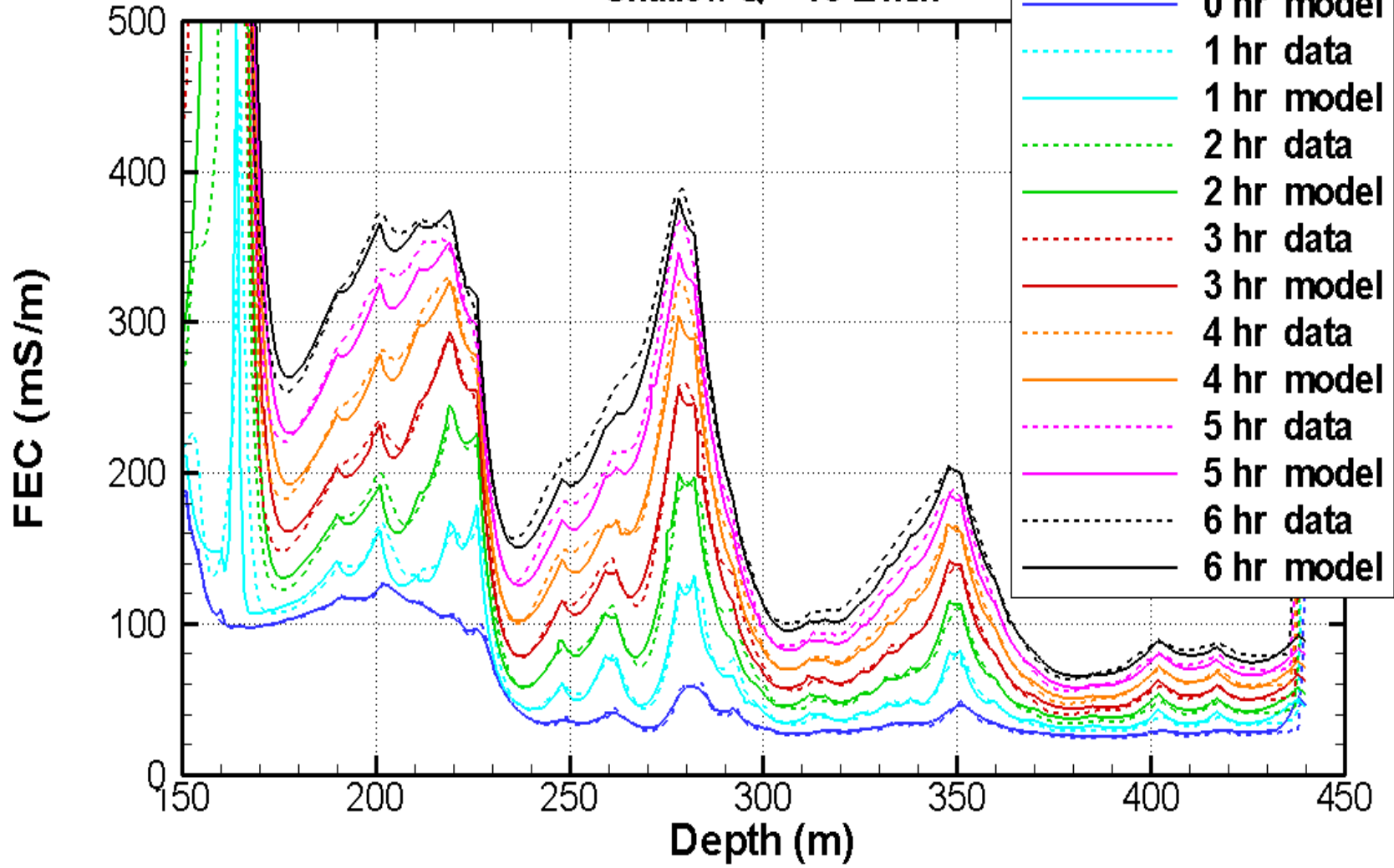


# Well HDB-11 FFEC Logging

- **Shallow Interval (150-450 m)**
  - $Q = 2$  L/min
  - $Q = 10$  L/min
  - $Q = 19.1$  L/min
- **Deep Interval (450-800 m)**
  - $Q = 5$  L/min
  - $Q = 10$  L/min
  - $Q = 15$  L/min



Shallow Q = 10 L/min

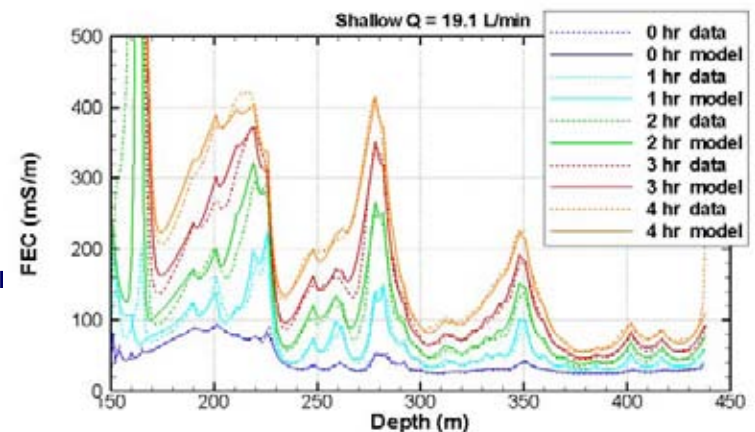
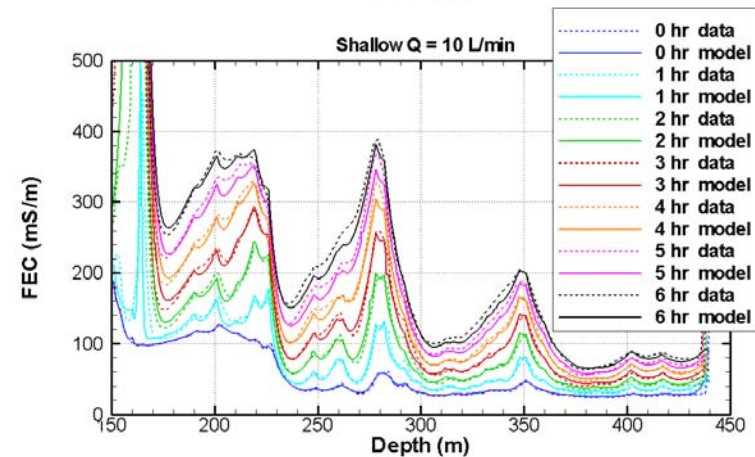
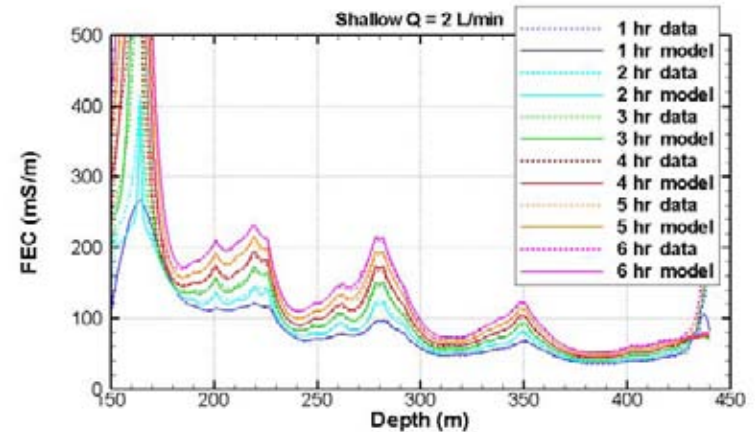


# Shallow Zone: Model Fit to FFEC Data

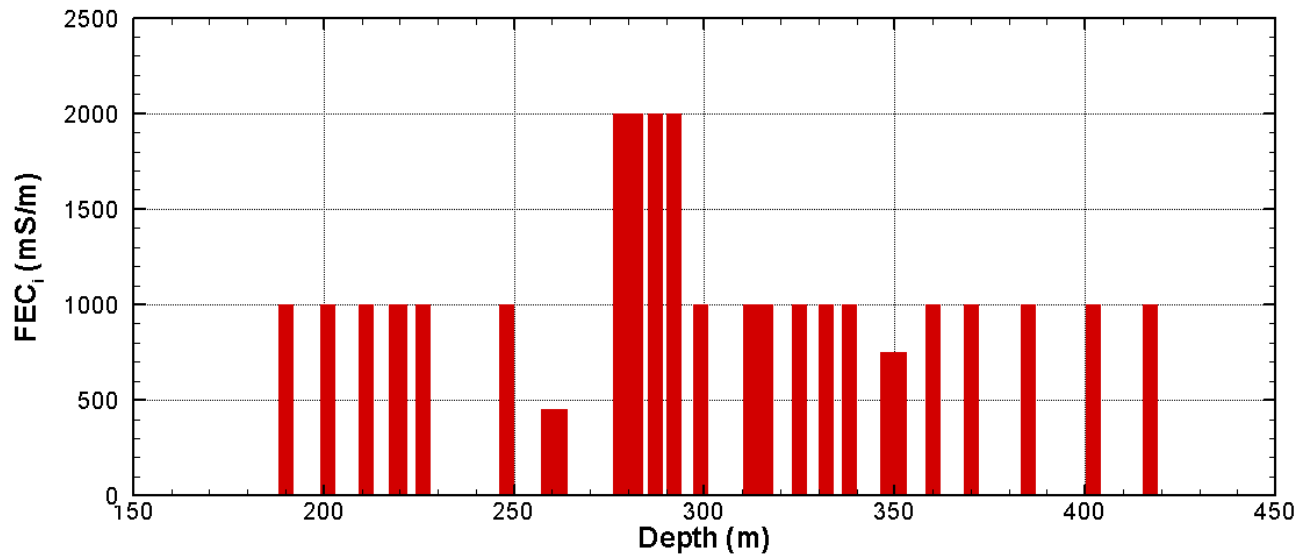
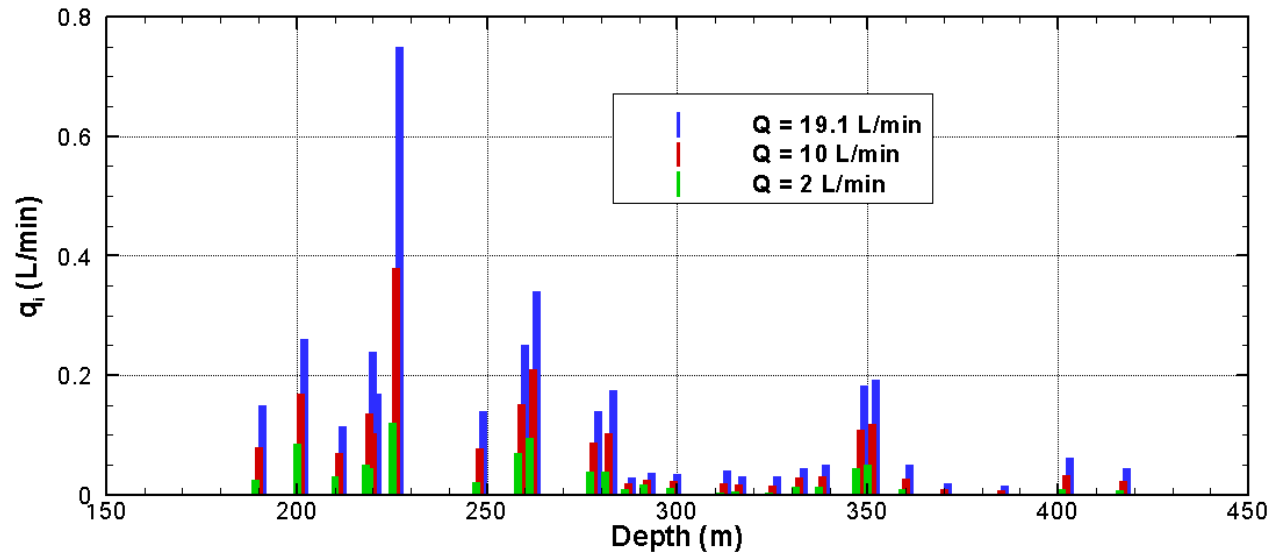
- Three-day data
- Three pumping rates: 2, 10, 19.1 L/min
- Very good match for all peaks except very large peak at 150 m depth, which shows complicated behavior that cannot be analyzed



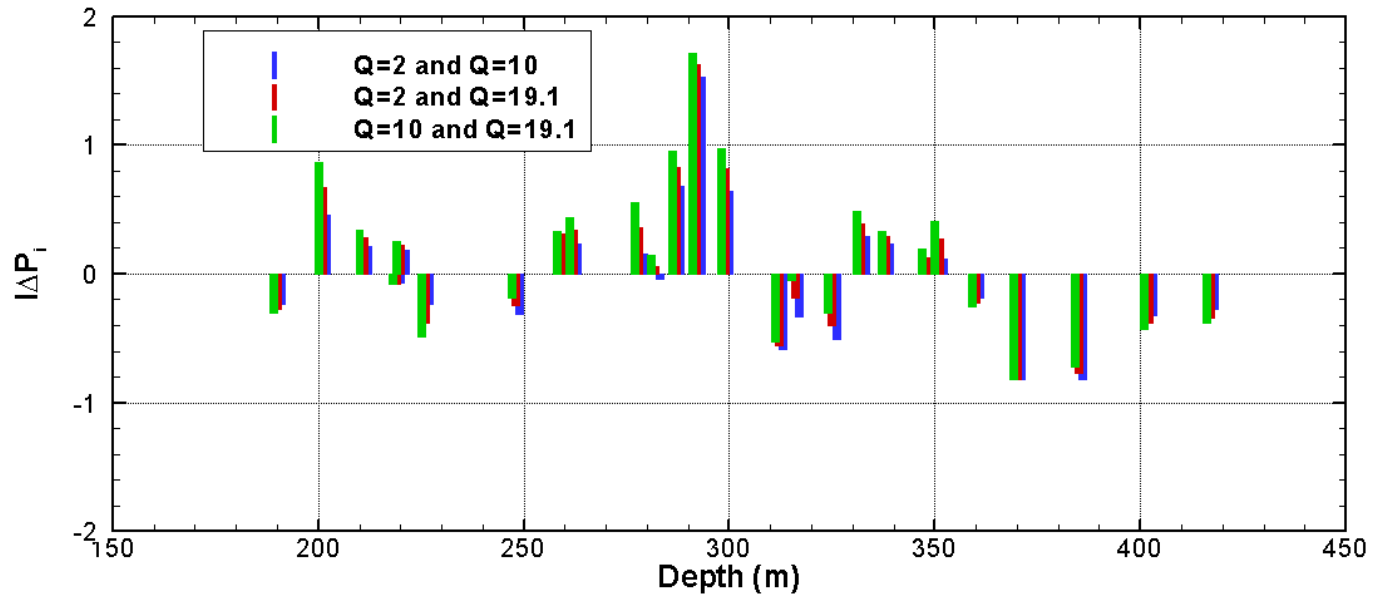
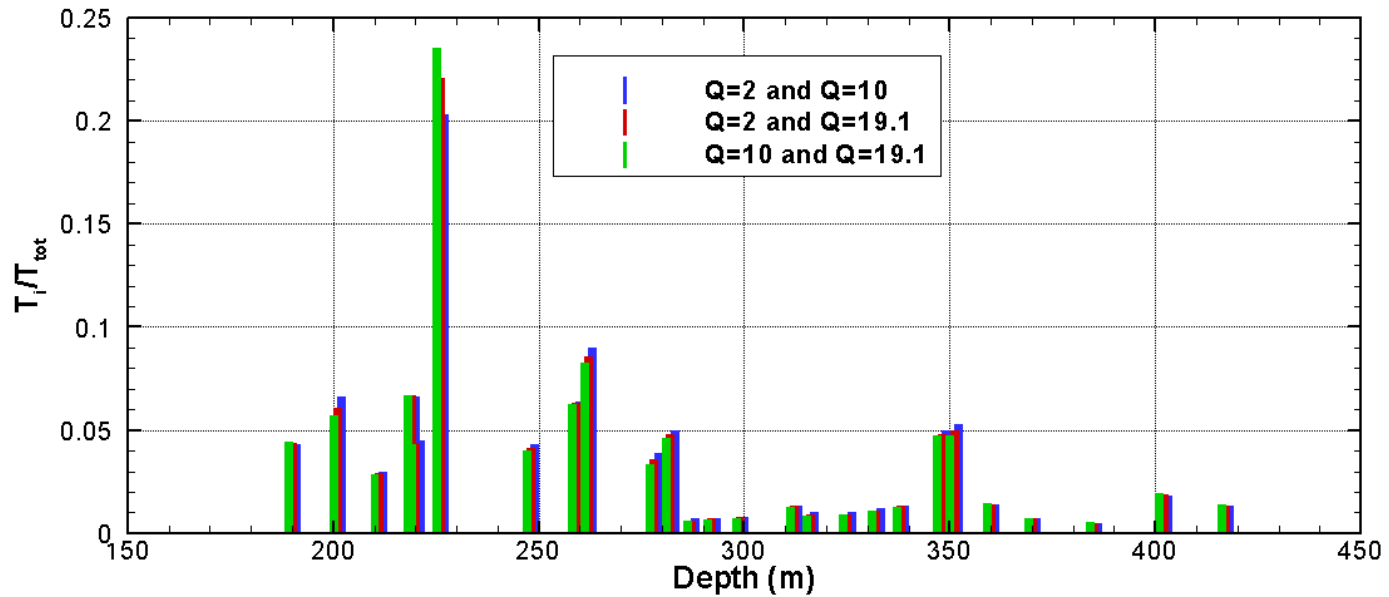
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# Shallow Zone: Results of Individual Tests



# Shallow Zone: Multi-Rate Results



# Deep Zone: Model Fit to FFEC Data

Fit is good

As before,  $\sum q_i \ll Q_{\text{form}}$  for all tests

—  $Q=5$ :  $\sum q_i=2.04$   $Q_{\text{form}}=3.34$

—  $Q=10$ :  $\sum q_i=3.90$   $Q_{\text{form}}=6.84$

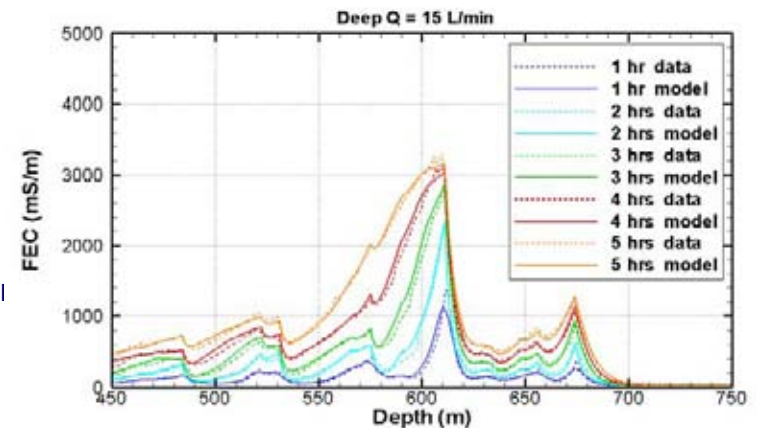
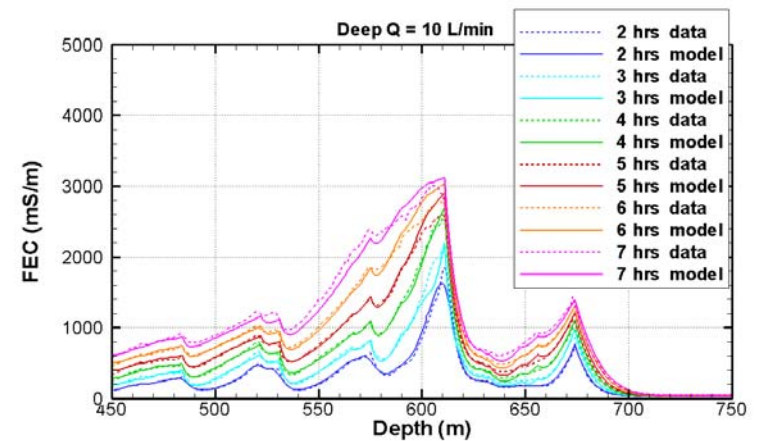
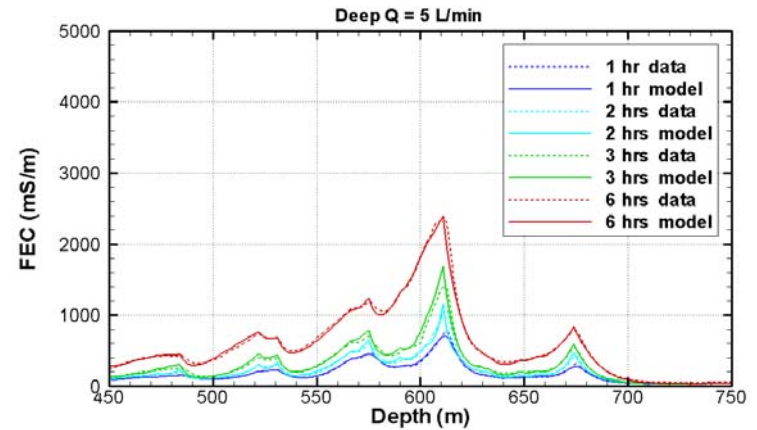
—  $Q=15$ :  $\sum q_i=5.12$   $Q_{\text{form}}=7.85$

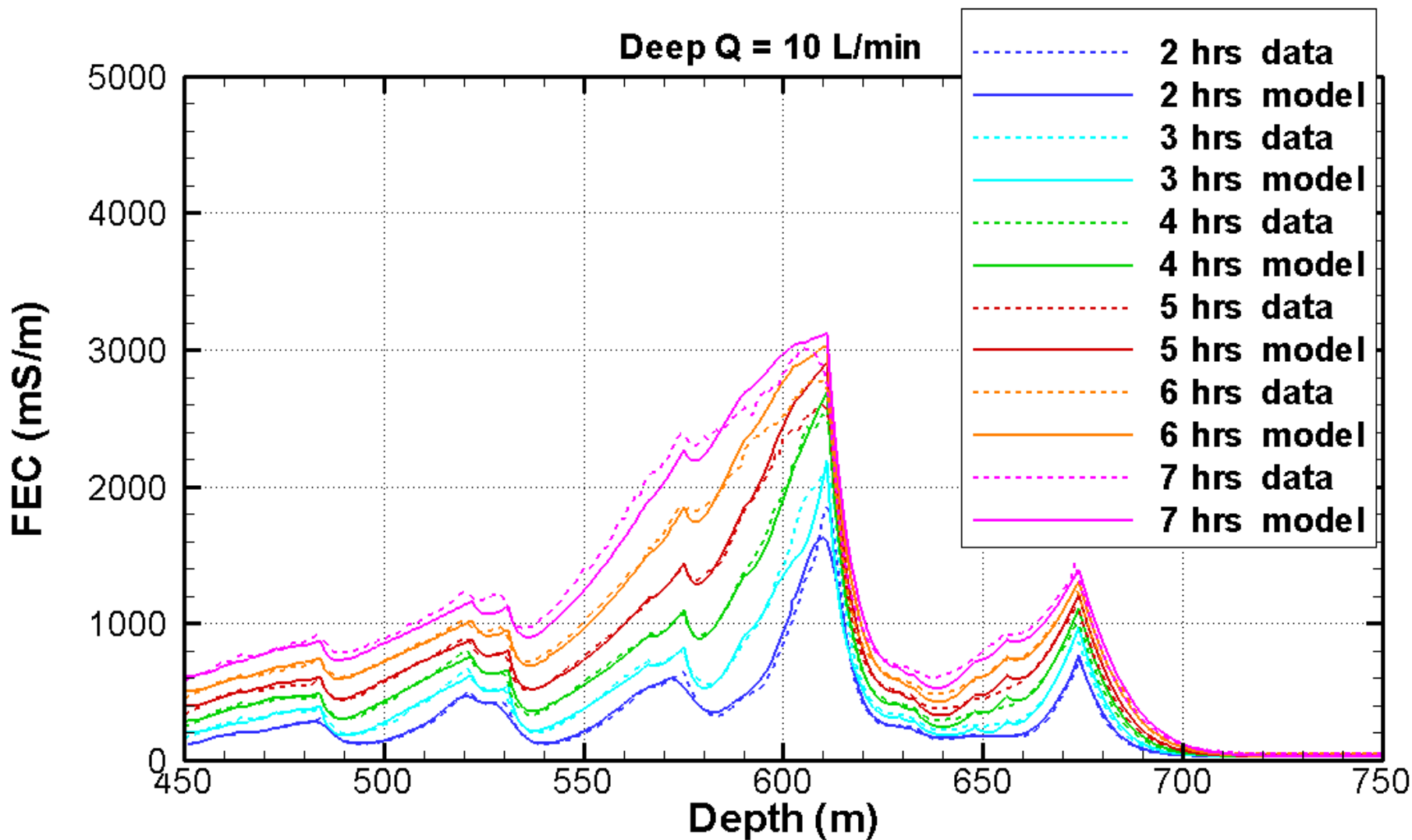
System is strongly non-unique with respect to salinity

Analysis greatly benefits from one or more independent salinity measurements

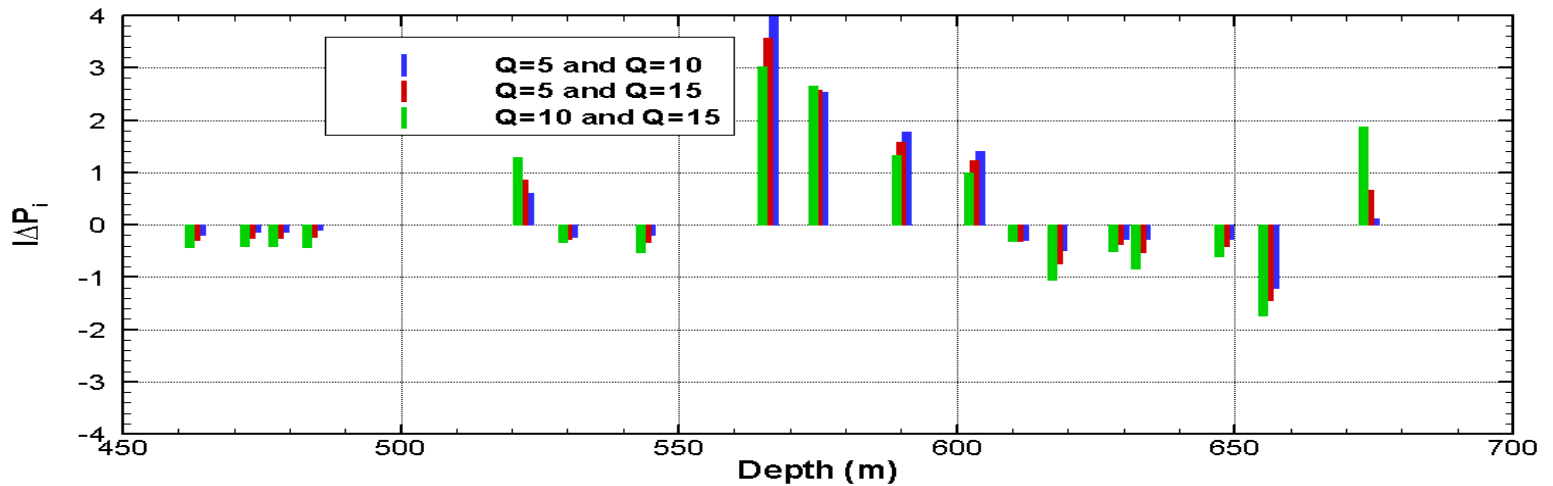
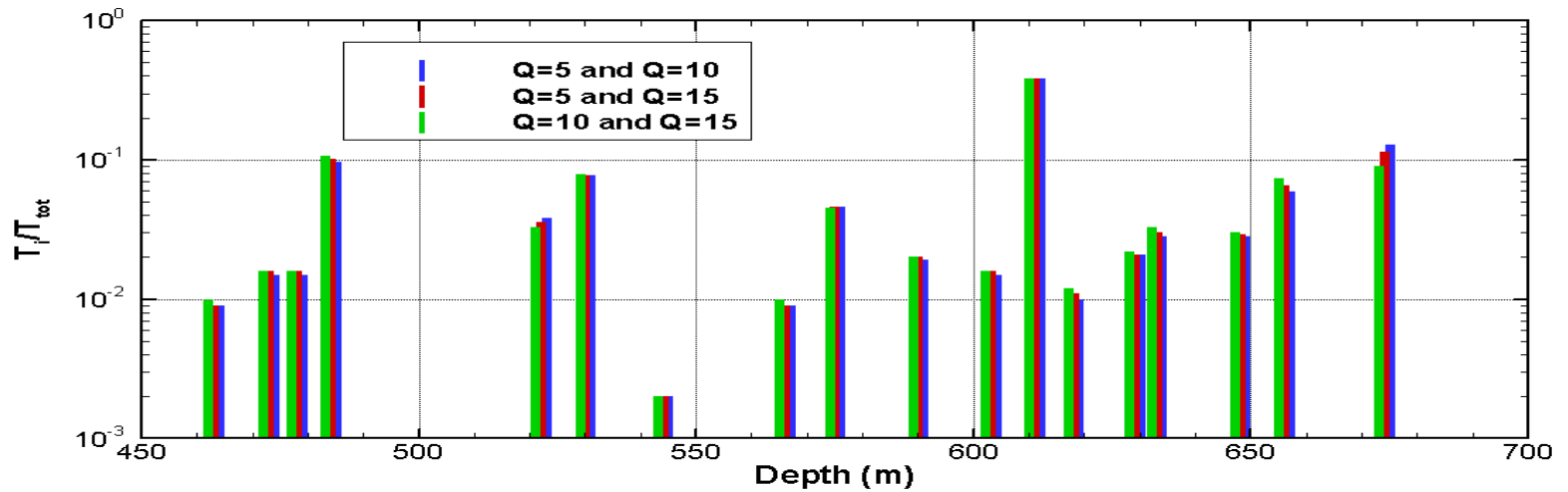


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# Deep Zone: Multi-Rate Results



# 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  $T_i/T_{\text{tot}}$  and  $I\Delta P_i$  do not change appreciably)
- Need to understand why  $\sum q_i \ll Q_{\text{form}}$



# Shallow Conducting Fractures (26)

Peak	Depth (m)	$T_i/T_{tot}$	IDP <sub>i</sub>
1	417	0.013	-0.338
2	402	0.019	-0.380
3	385	0.005	-0.768
4	370	0.007	-0.816
5	360	0.014	-0.224
6	351	0.050	0.268
7	348	0.048	0.130
8	338	0.013	0.287
9	332	0.011	0.393
10	325	0.009	-0.403
11	316	0.009	-0.186
12	312	0.013	-0.554
13	299	0.008	0.814

Peak	Depth (m)	$T_i/T_{tot}$	IDP <sub>i</sub>
14	292	0.007	1.626
15	287	0.006	0.828
16	282	0.048	0.058
17	278	0.036	0.358
18	262	0.086	0.342
19	259	0.063	0.306
20	248	0.041	-0.242
21	226	0.221	-0.381
22	220	0.044	0.225
23	219	0.067	-0.076
24	211	0.029	0.283
25	201	0.061	0.668
26	190	0.044	-0.276

# Deep Conducting Fractures (18)

Peak Number	Depth (m)	$T_i/T_{tot}$	$I \Delta P_i$
1	674	0.114	0.672
2	656	0.065	-1.438
3	648	0.029	-0.411
4	633	0.030	-0.518
5	629	0.021	-0.371
6	618	0.011	-0.732
7	611	0.384	-0.301
8	603	0.016	1.229
9	591	0.020	1.587
10	575	0.046	2.584
11	566	0.009	3.573
12	544	0.002	-0.332
13	530	0.078	-0.271
14	522	0.036	-0.856
15	484	0.101	-0.227
16	478	0.016	-0.246
17	473	0.016	-0.246
18	463	0.009	-0.292



# 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

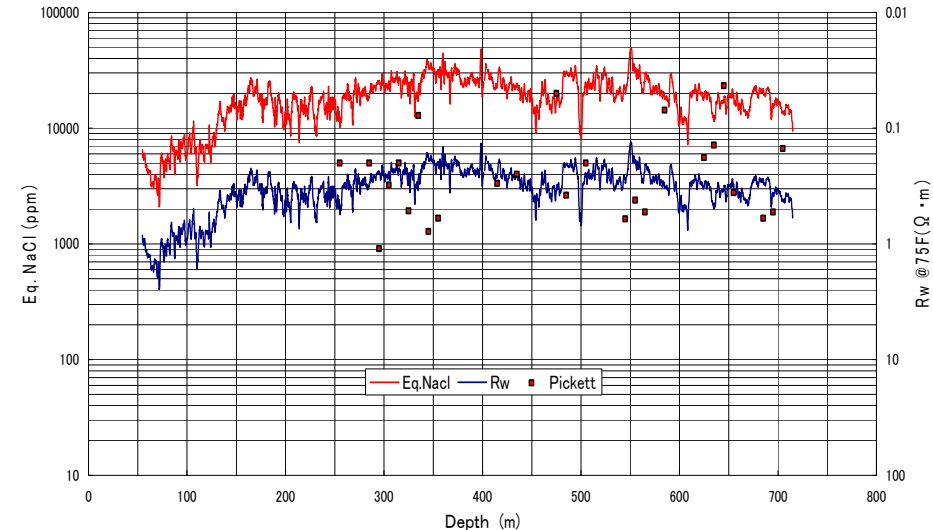
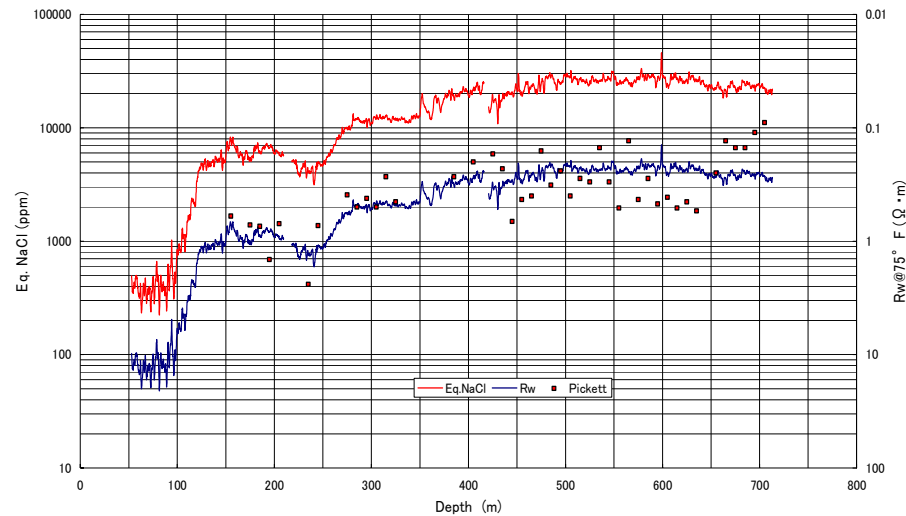
- 6 intervals, spacing ranging from 10 to 80 m
- Need to develop calculational methods for converting detailed individual fracture results to packer interval results for comparison to packer test data
- Need  $T_{\text{tot}}$  and  $P_{\text{avg}}$



# Salinity and Electric Resistivity in other HDB Wells

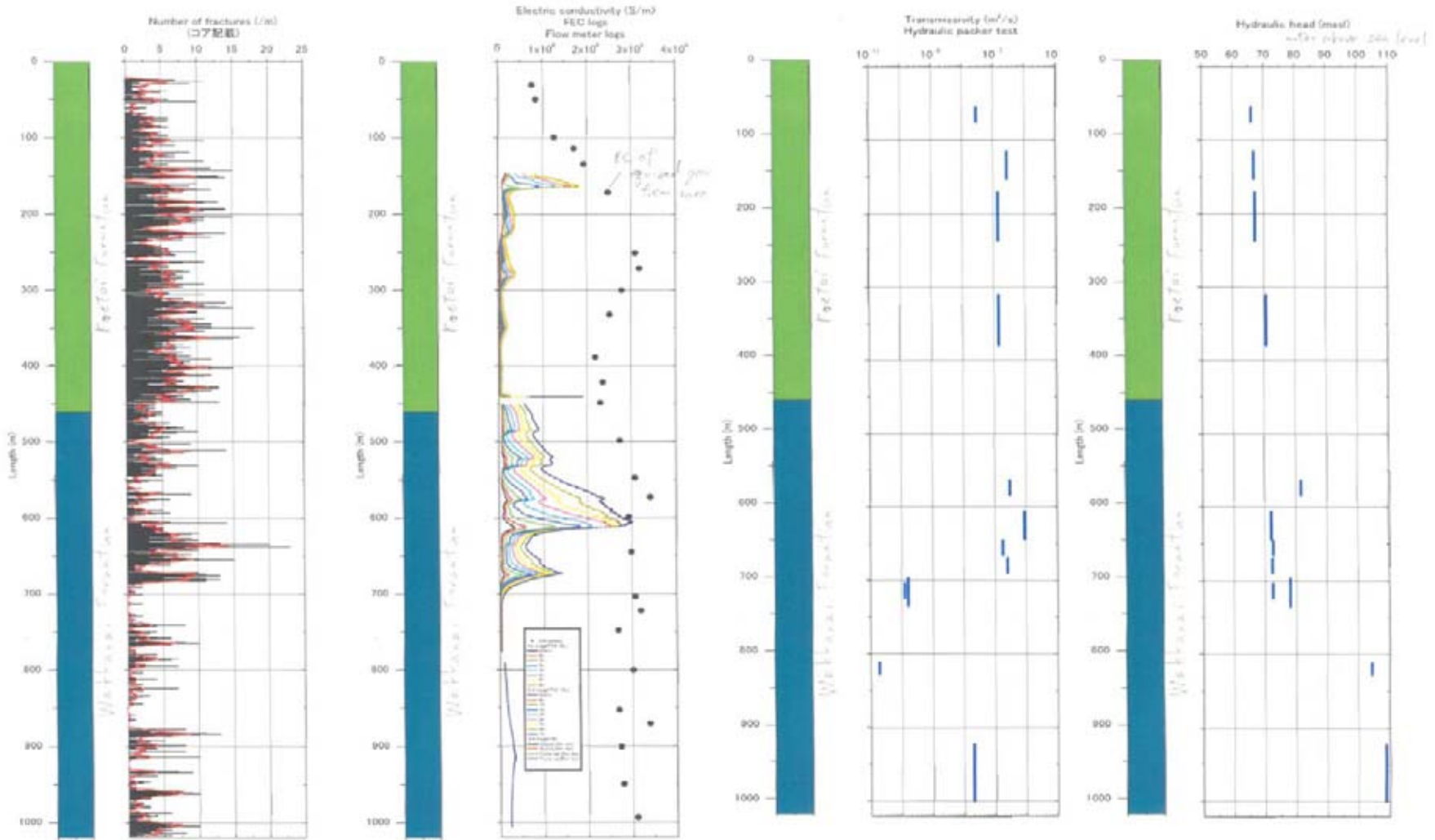
## HDB-1

## HDB-2



- Unit conversion:  $1 \text{ ohm-m} \rightarrow 1 \text{ S/m} = 1000 \text{ mS/m}$
- Range of FEC (150–700 m): 600 – 8000 mS/m
- Range acc. to Pickett (?): 400 – 22000 mS/m

# Independent HDB-11 Data



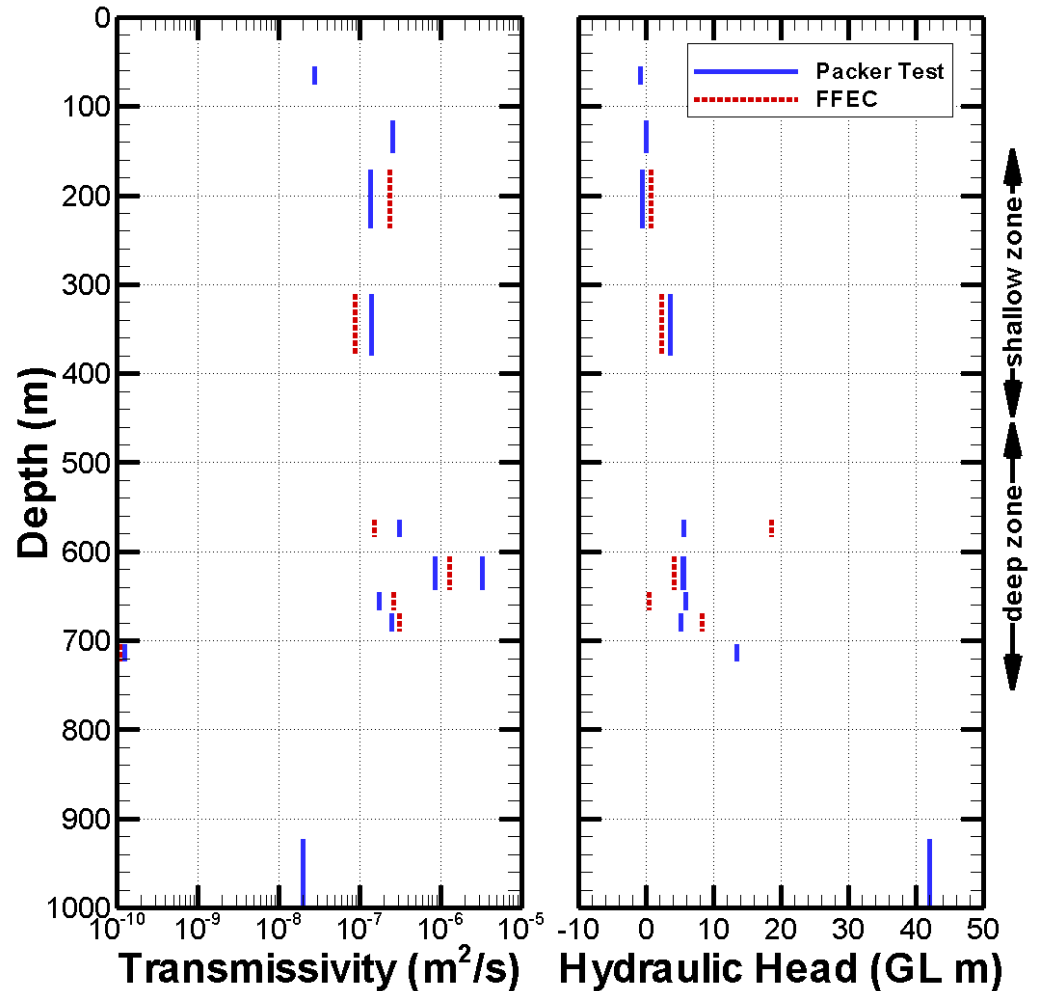
**E**  
Range of salinity squeezed from core: 2000 mS/m – 3500 mS/m

# 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**



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