Summary of Javelin Data Collected at GEMS, Lawrence KS, April and October 2010

Prepared for:

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Kansas Geological Survey

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Executive Summary

Vista Clara and KGS acquired borehole NMR and Geoprobe NMR data in and around the GEMS field site in Lawrence Kansas, in April and October 2010. This document summarizes the data that were collected and how these data were reduced to basic NMR signal responses that can be further analyzed by Stanford and KGS researchers.

The NMR data acquired using the Geoprobe NMR tool indicated significantly shorter T2 decay rates, and significantly lower derived K estimates, than NMR borehole logs in nearby wells that had been developed. The differences appear to be largest in the section of the sand/gravel aquifer below 17m.

Two new 2" PVC wells were installed and NMR logs performed both before and after well development. The NMR logs performed before development indicate significantly shorter T2, and significantly lower derived K estimates, than the NMR logs performed after development.

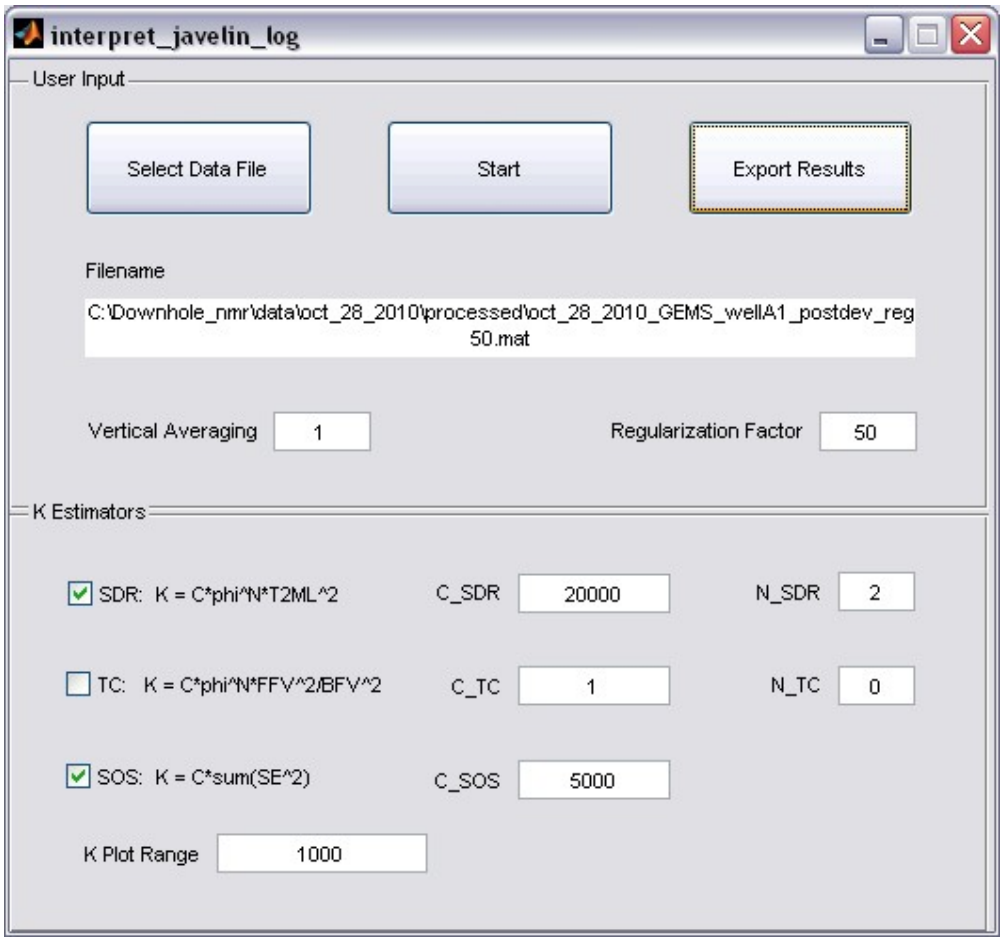
Data Reduction and Data Formats

Raw NMR logging data were initially reduced to averaged, filtered and calibrated spin echo amplitude samples for each depth level. These spin echo data sets are available as Matlab (*.mat) data files. Each *.mat file contains three variables:

- "depth": a vector of depth samples in meters
- "se_vector_wc": an NxM matrix of spin echo amplitudes, where N is the number of spin echo samples at each depth sample, and M is the number of depth samples
- "time": a vector of time samples (for the corresponding spin echo samples) in seconds

The processed spin echo data were further reduced and converted to water content and K estimates using the program "interpret_javelin_log", which is a Matlab-based executable. A screenshot of this program is shown in the figure below. Interpreted data were exported as an ASCII format 8 column file in the following format:

Column	Data
1	Depth (m)
2	Total water content
3	Bound water content
4	Mobile water content
5	Log Mean T2 (s)
6	K_sdr (m/day)
7	K_tc (m/day)
8	K_SMSE (m/day)



The various K estimates are calculated as follows:

$$K_{SDR} = C_{SDR}\Phi_{total}^{N}(T2ML)^2$$

$$K_{TC} = C_{TC}\Phi_{total}^{N}\frac{\Phi_{mobile}^2}{\Phi_{bound}^2}$$

$$K_{SMSE} = C_{SMSE}\left(\frac{1}{N}\sum_{N} spinechos\right)^2 .$$

In the data that we present here, and provide as ascii text files, we used the following K estimation parameters:

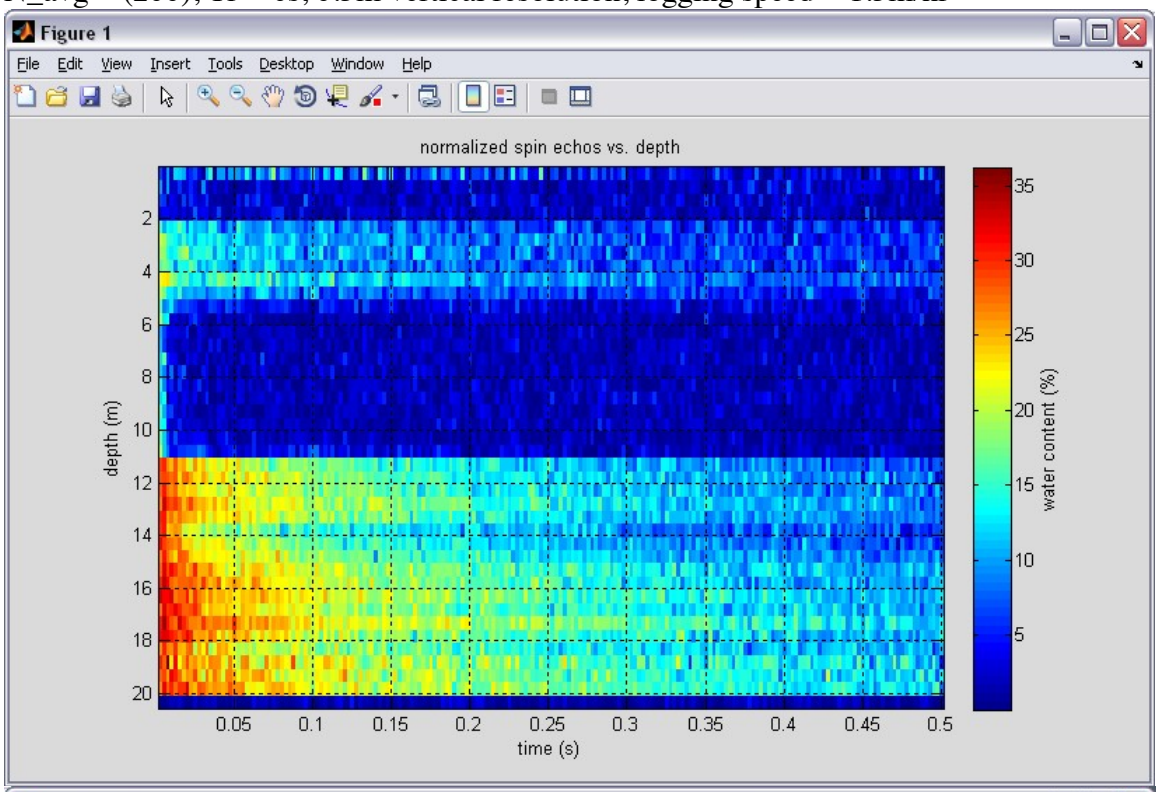
C_sdr = 20000, N_sdr = 2
C_tc = 1, N_tc = 0
C_smse = 5000

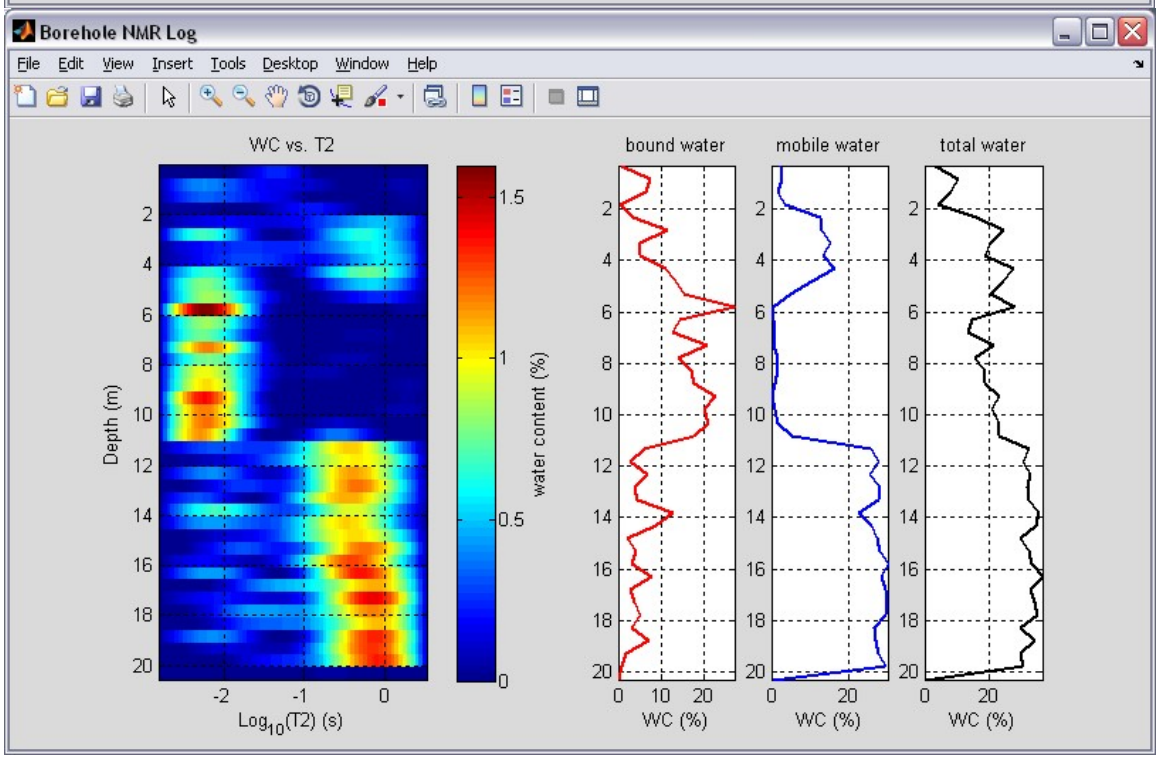
We found that the Timur Coates (TC) estimator produced very high variance, so we do not plot these K estimates here.

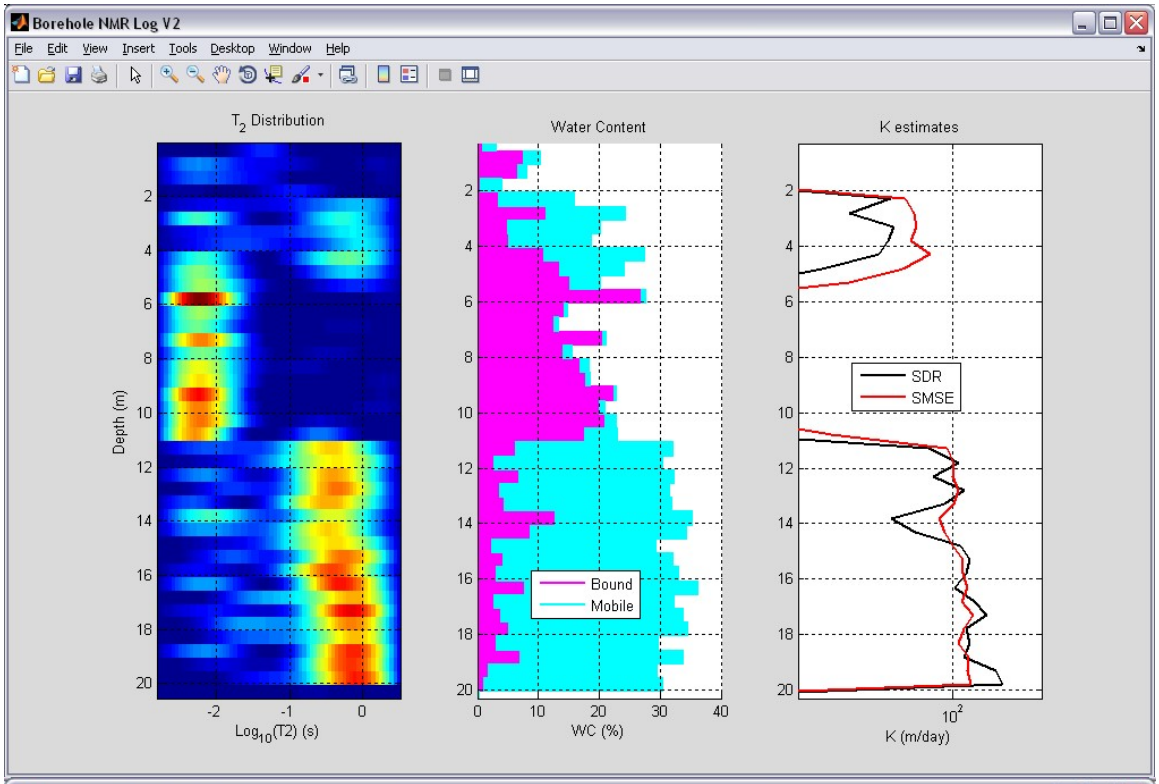
April 19, 2010

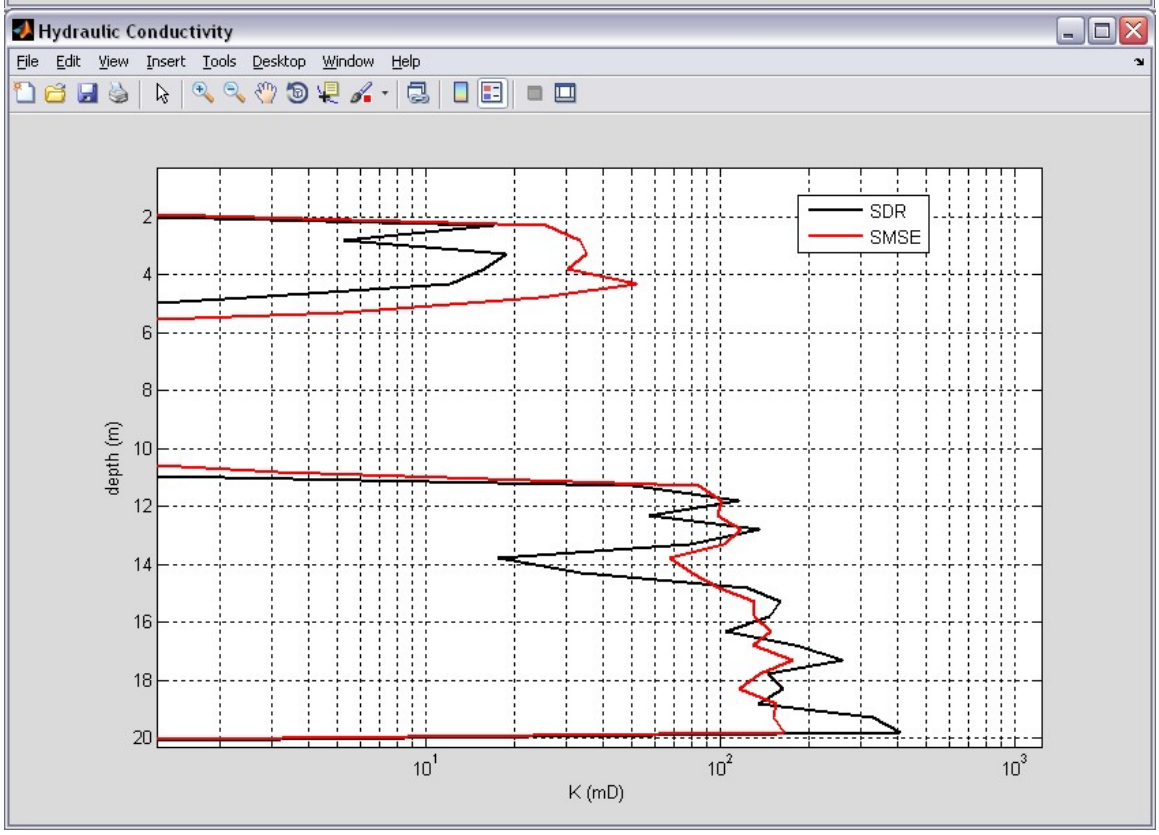
Javelin Log of GEMS Well 4S, using 3.5” diameter borehole NMR tool

N_avg = (200), Tr = 6s, 0.5m vertical resolution, logging speed = 1.5m/hr



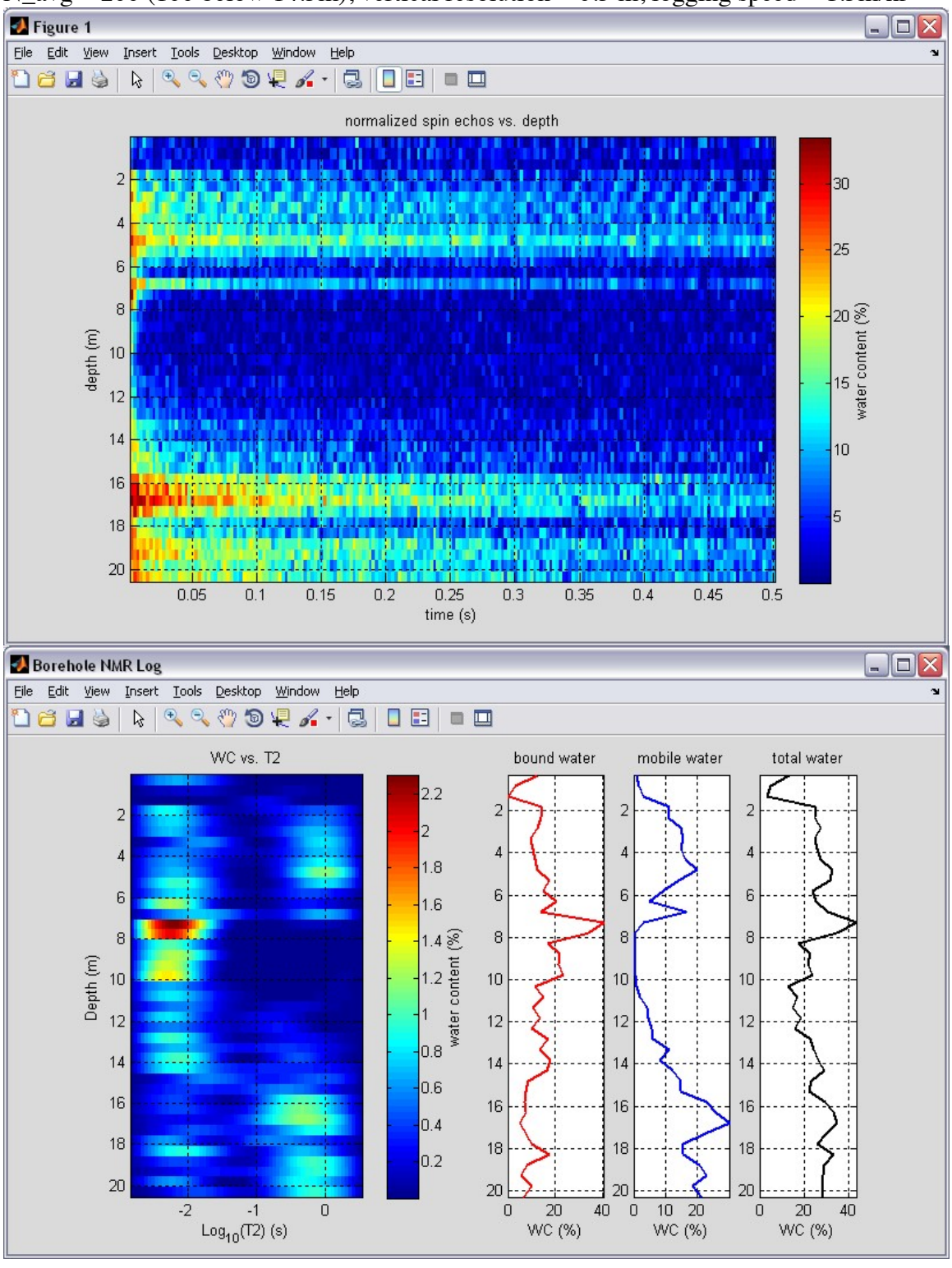


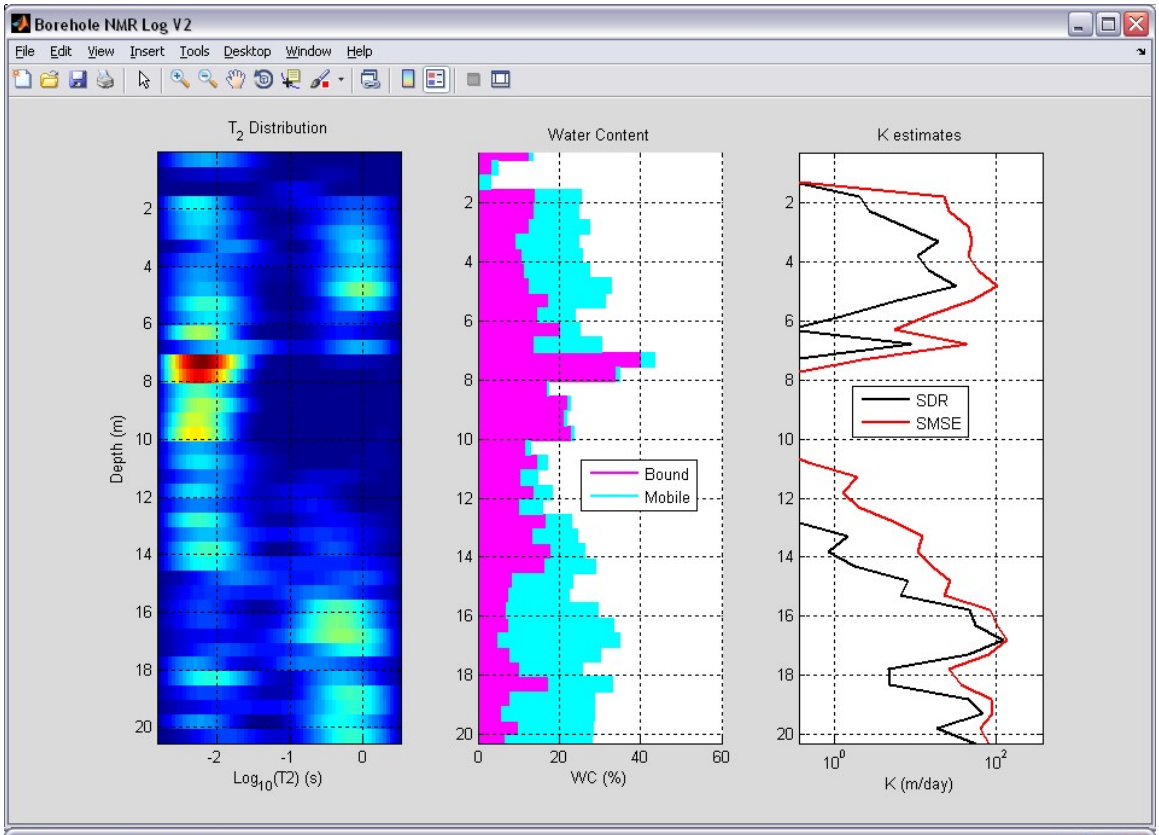

Borehole NMR Log V2
File Edit View Insert Tools Desktop Window Help
T2 Distribution
Water Content
K estimates
Depth (m)
Log10(T2) (s)
WC (%)
K (m/day)
Bound
Mobile
SDR
SMSE

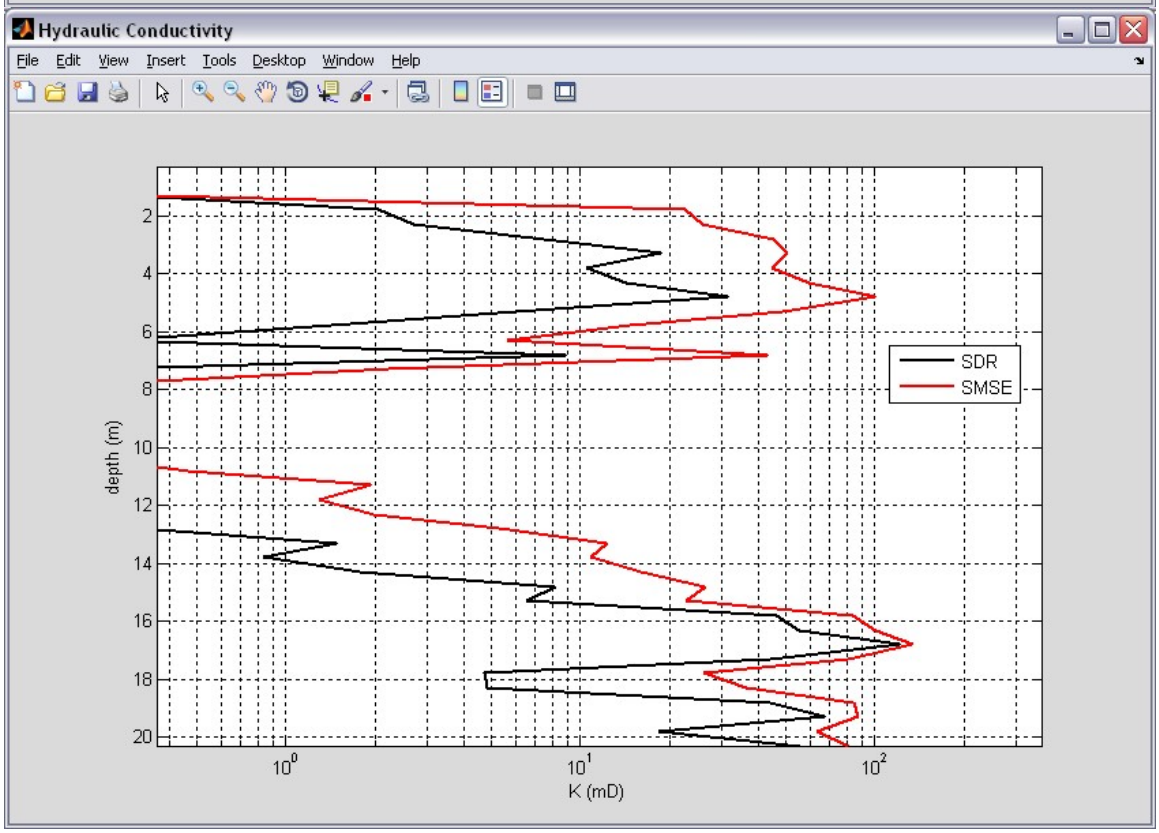

Hydraulic Conductivity
File Edit View Insert Tools Desktop Window Help
depth (m)
K (mD)
SDR
SMSE

April 21, 2010

Javelin Log of GEMS Well 4N, using 3.5" diameter borehole NMR tool
N_avg = 200 (100 below 14.5m), vertical resolution = 0.5 m, logging speed = 1.5m/hr




Borehole NMR Log V2
File Edit View Insert Tools Desktop Window Help
T2 Distribution
Water Content
K estimates
Depth (m)
Log10(T2) (s)
WC (%)
K (m/day)
Bound
Mobile
SDR
SMSE


Hydraulic Conductivity
File Edit View Insert Tools Desktop Window Help
depth (m)
K (mD)
SDR
SMSE

Oct 14, 2010 (First Use of Geoprobe NMR Logging Tool)

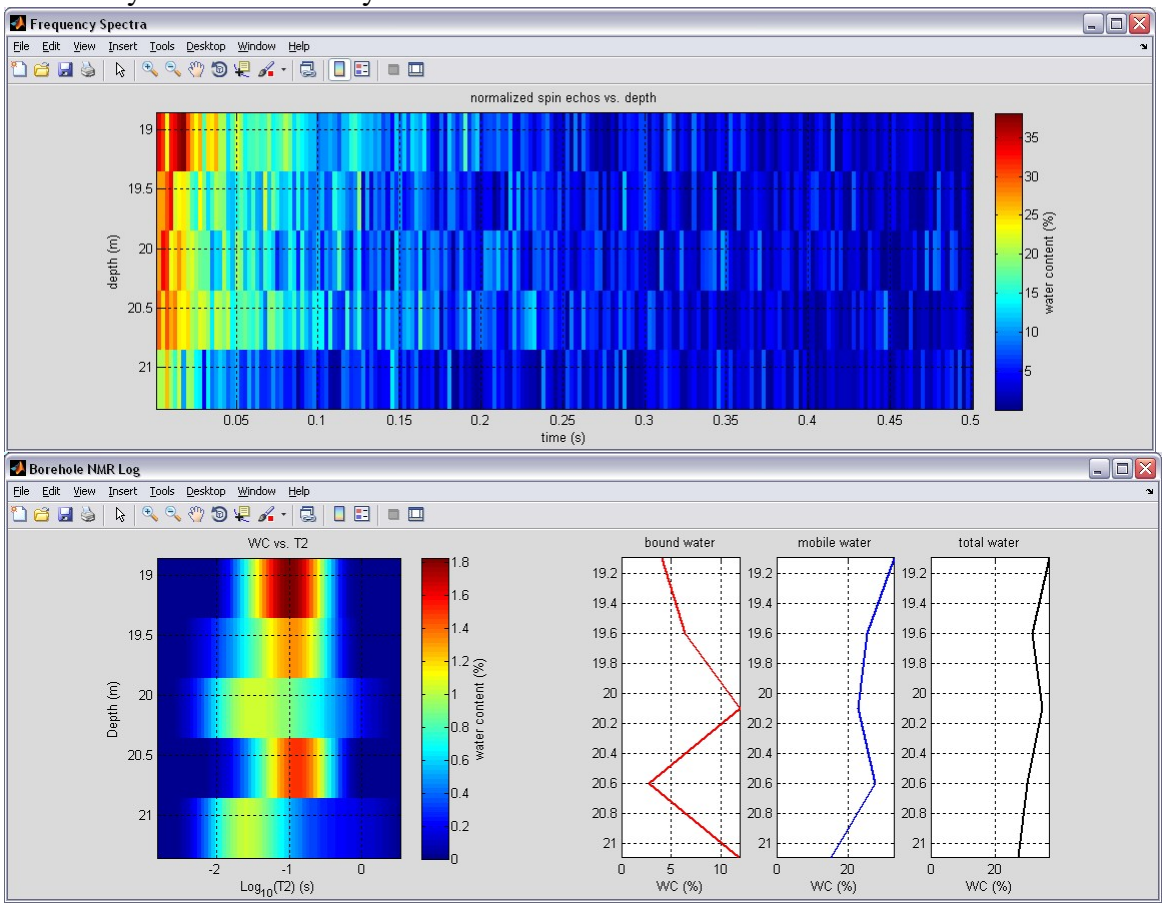
Static Tests of Geoprobe NMR tool in GEMS Well 4N
depth = 16.45 m from ground surface
N_avg = 50, vertical resolution = 0.5 m, fo = 295 kHz, echo spacing = 2.0 ms

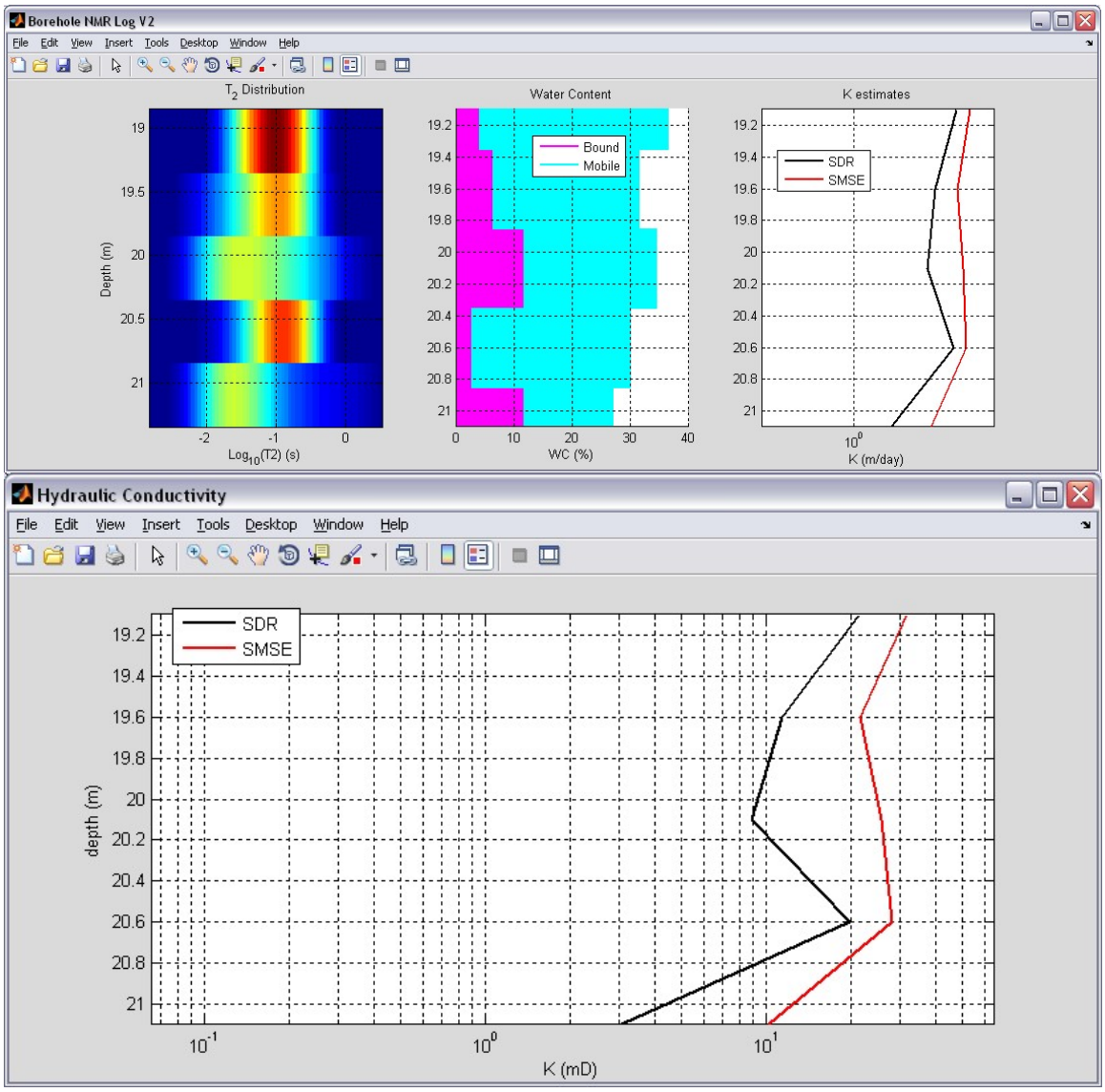
Test #	Fo (kHz)	TWC (%)	BWC (%)	MWC (%)	MLT2 (s)	K_sdr (m/day)	K_smse (m/day)
1	294	33.39	8.57	24.81	0.1560	54.3	107.5
2	294	29.74	3.22	26.52	0.2652	124.4	105.5
3	294	28.07	0.79	27.27	0.3569	117.2	111.0
4	245	25.24	0.16	25.08	0.3826	186.5	93.0
5	245	37.20	12.65	24.55	0.0967	25.9	93.5
6	245	31.00	5.39	25.61	0.1913	70.34	96.5

Table 1: Static test of Geoprobe NMR tool in GEMS Well 4N, at depth of 16.45 m. Note the low variance on the second K estimator (K_smse).

Oct 14, 2010

Geoprobe NMR log on East side of GEMS
N_avg = 120, vertical resolution = 0.5 m, fo = 295 kHz, echo spacing = 2.0 ms
Data collection was stopped after the first 5 depth records, because we all thought the time decays were abnormally short.




Borehole NMR Log V2
File Edit View Insert Tools Desktop Window Help
T2 Distribution
Depth (m)
Log10(T2) (s)
Water Content
Bound
Mobile
WC (%)
K estimates
SDR
SMSE
K (m/day)
Hydraulic Conductivity
File Edit View Insert Tools Desktop Window Help
SDR
SMSE
depth (m)
K (mD)

Oct 15, 2010 (Investigation of Geoprobe NMR Measurement Effects)

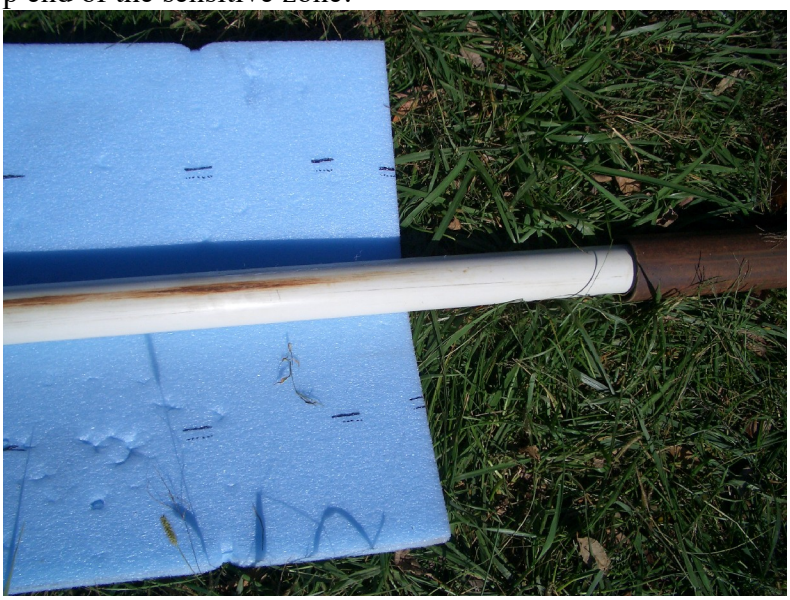
We performed a number of experiments to try to determine why the Geoprobe NMR log from Oct. 14 produced reasonable water content, but unexpectedly low T2 values. We hypothesized a number of possible reasons for this:

1. The steel Geoprobe rods in the close vicinity to the NMR sensor were distorting the B0 and B1 fields to the point that it was effecting the distribution of tip angles, and hence shortening the spin echo train.
2. The Geoprobe rods were leaving magnetic particles in the formation, which were shortening the T2 of the bulk water itself.
3. The particles left by the geoprobe rods were causing some other pore-scale iron reaction that was decreasing the T2.
4. The Geoprobe was compacting the formation, causing the pores to get measurable smaller.
5. The wells that had been drilled and then developed through intensive pumping produced artificially long T2 times, because material had been removed and fines in particular had been removed.

Presence of geoprobe drill rods

We performed the following tests to determine whether the presence of the steel drill rods could be distorting the Bo and B1 fields enough to lower the measured T2.

1. **Mapping of B0 fields with Gauss meter.** We laid the geoprobe sensor on a foam pad, by itself, and mapped the contours of the 250kHz sensitive zone. Then we positioned a geoprobe steel rod with the collar in its approximate position for logging and remapped the static field contour for 250 kHz. **Result:** there was less than 1cm deviation of the sensitive zone contour, and this deviation was only measureable at the very top end of the sensitive zone.



2. **Bulk water experiments.** We filled a trash can with water, and performed NMR measurements with the NMR sensor being held by the Geoprobe machine. After the water had settled for 30 minutes, we measured a total water contents between 93% and 98% and T2 peaks between 650ms and 1000ms. Hence we concluded that the presence of the Geoprobe rods in the vicinity of the measurement did not have a significant effect of the T2 distribution.

3. **Measurements in Geoprobe-installed 2" well.** Next we performed NMR logging measurements in a 2" PVC well (GEMS well HT6, located about 5 feet away from well 4N) that had been installed using a Geoprobe machine. NMR measurements in well HT6, at depths of 17.0m and 20.0m, produced similar NMR responses to the previous NMR log of well 4N.

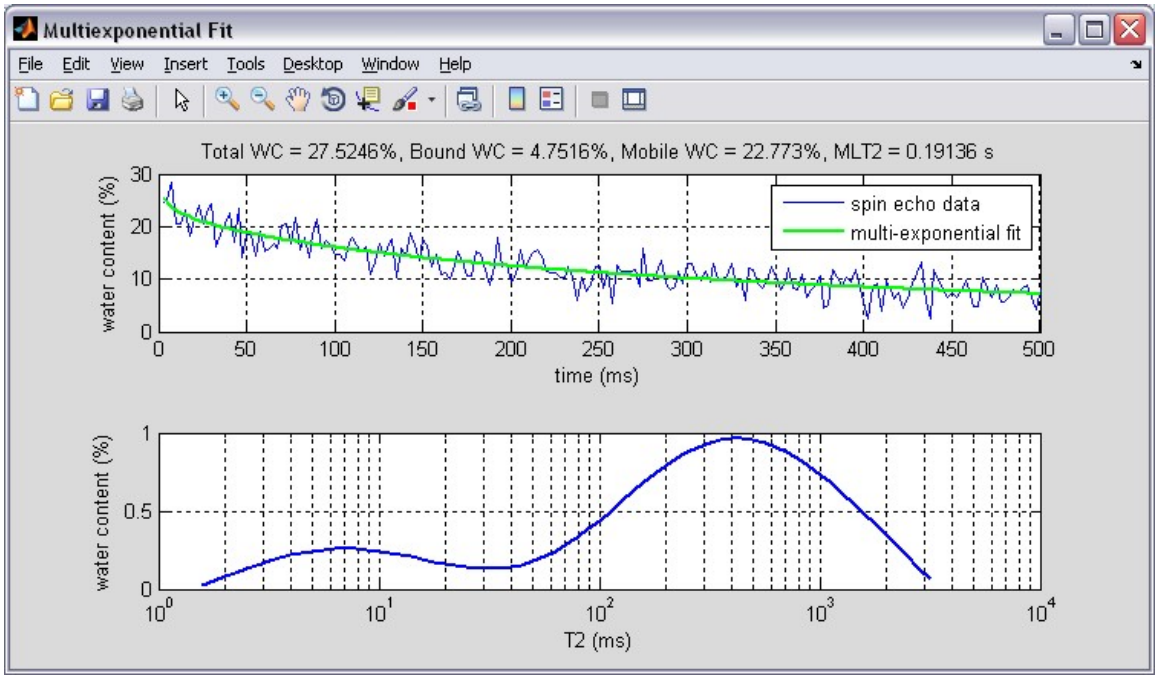


Figure 1: April 21, 2010, GEMS well 4N, 17.0m. K_smse = 76 m/day.

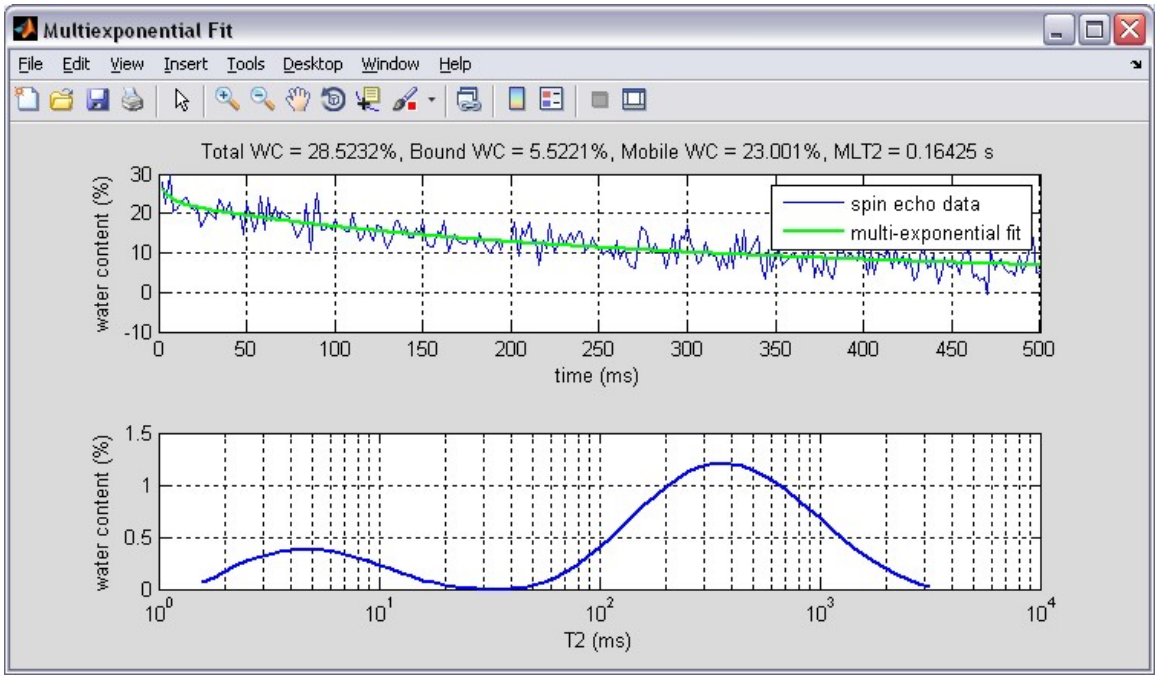


Figure 2: Oct 15, 2010, GEMS well HT6, 17.0m, 295 khz, K_smse = 77.5 m/day.

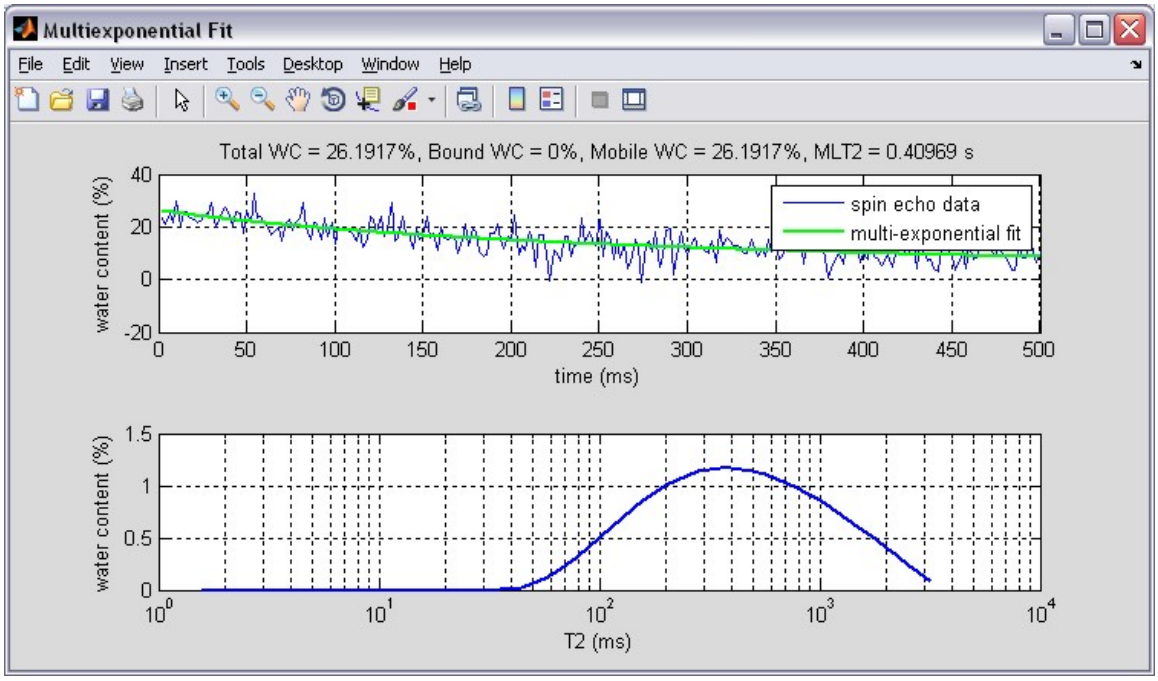


Figure 3: Oct 15, 2010, GEMS well HT6, 17.0m, 245 khz, K_smse = 106 m/day.

4.1 Flow Test Oct 15, 2010

We performed an NMR flow experiment in Well 4N. We lowered the 3.5" NMR probe into GEMS Well 4N to 16.5 m below the ground surface. We did basic detection experiments, first with no flow, and second with water pumped into the top of the well at 15 gal/min. There was no significant difference in the two resulting data sets.

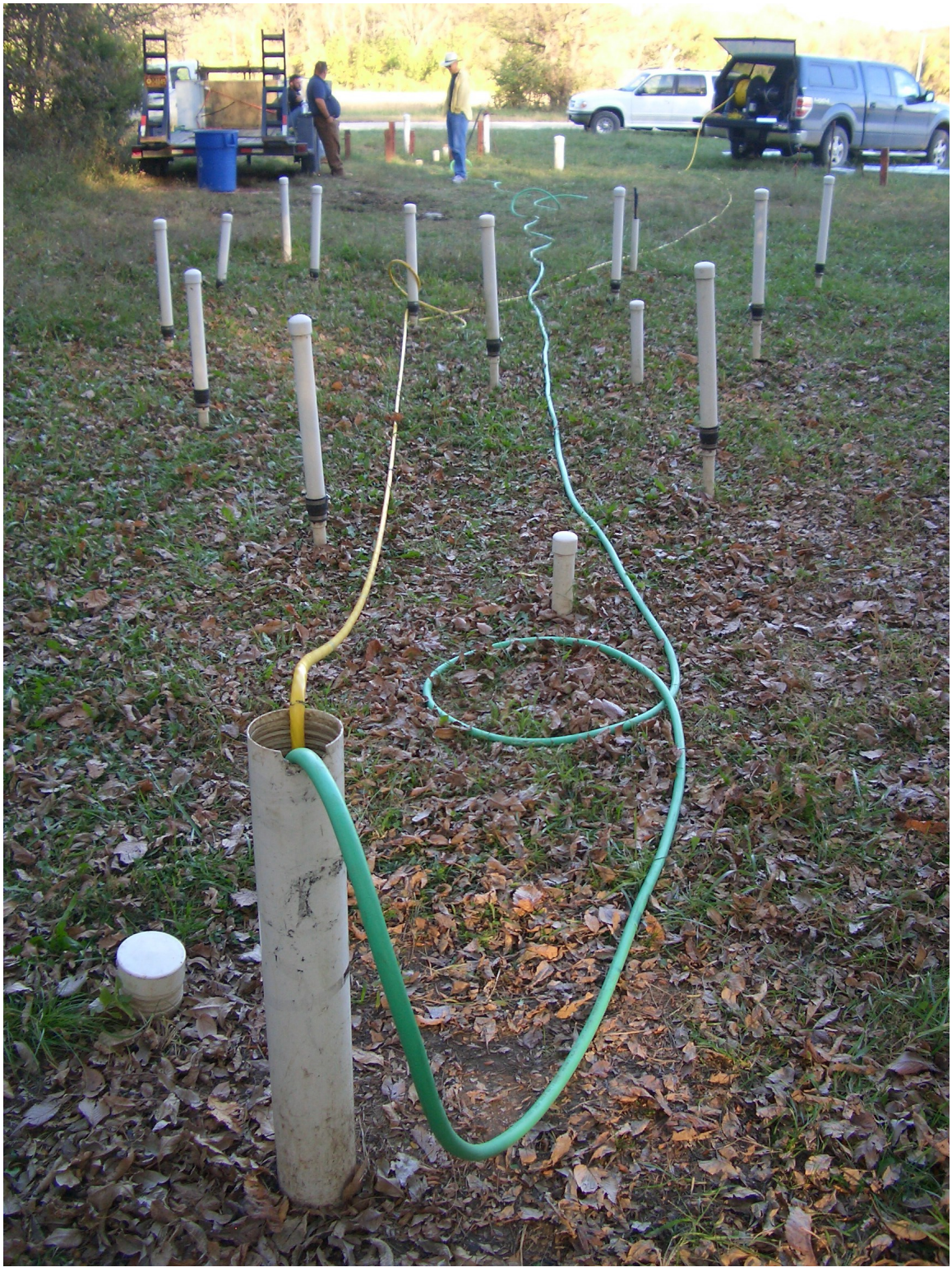


Figure 4: Water is pumped into Well 4N, while acquiring NMR data at depth = 16.5m.

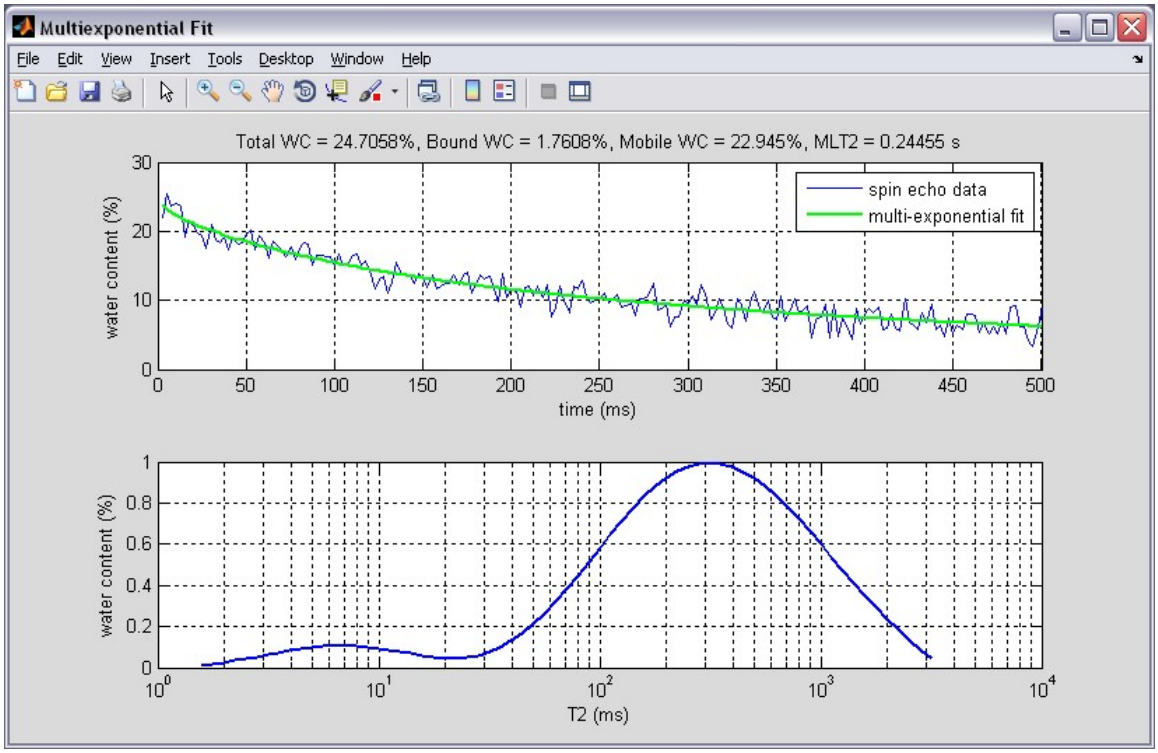


Figure 5: No flow, Oct 15, 2010, GEMS well 4N, 16.5m, 295 khz, K_smse = 65.5 m/day.

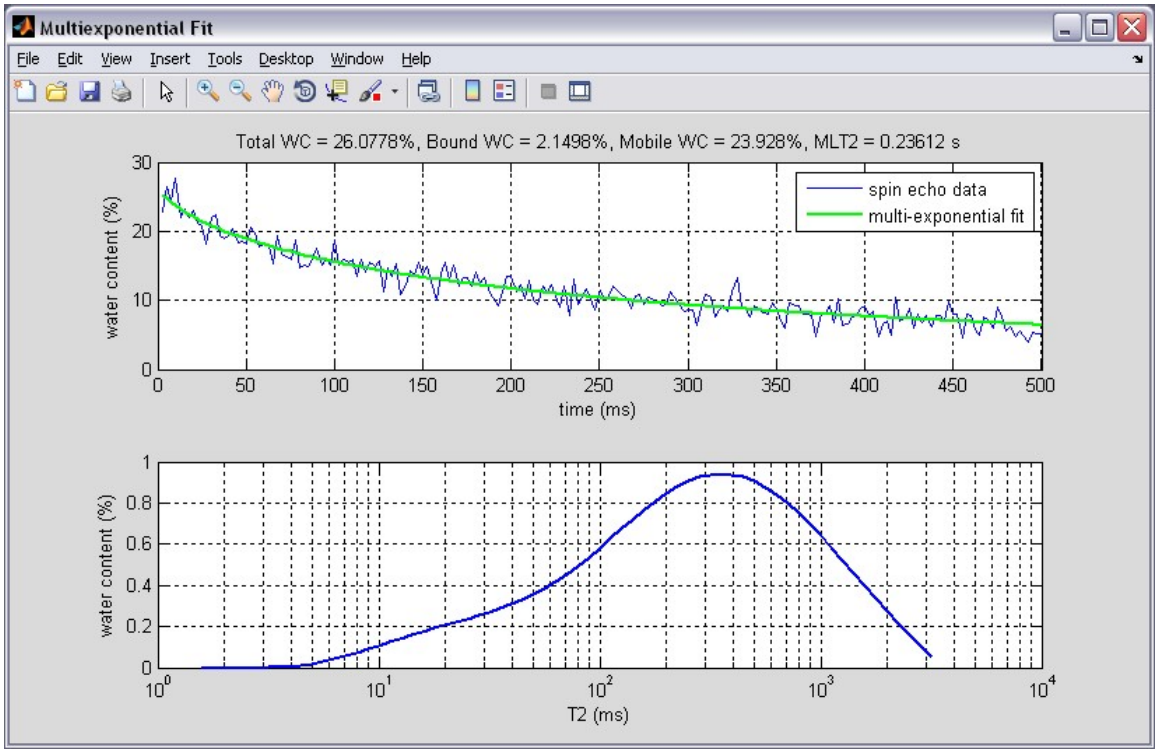


Figure 6: 15 gal/min, Oct 15, 2010, GEMS well 4N, 16.5m, 295 khz, K_smse = 68.5 m/day.

Oct 16, 2010 (more Geoprobe NMR investigations)

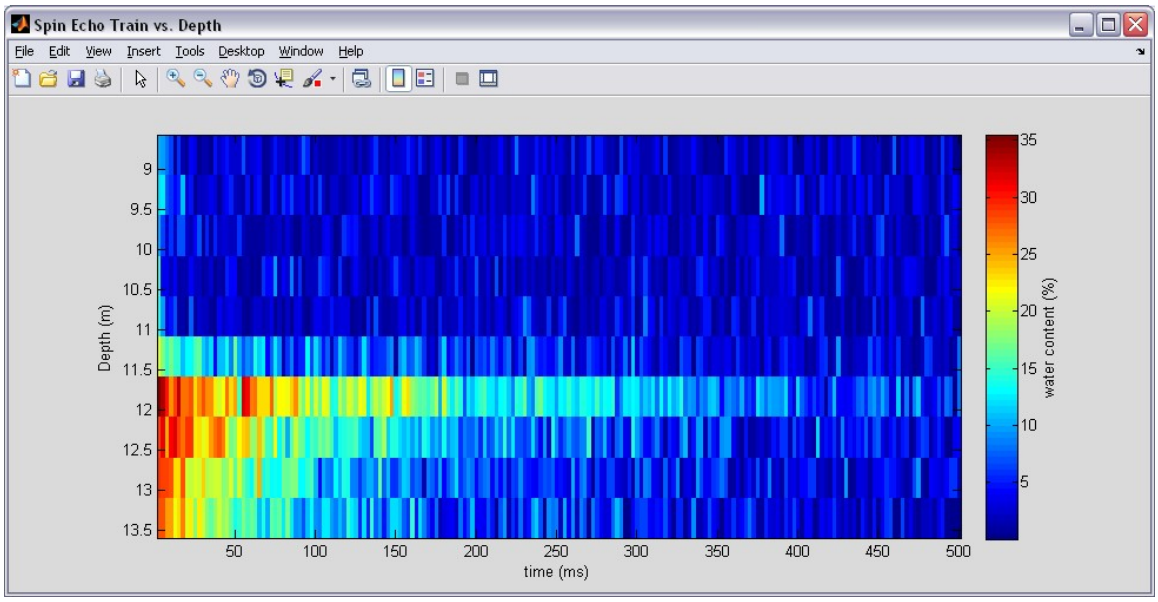
On this day we started logging GEMS "NMR1" with the geoprobe NMR logger, but aborted the operation when we again observed T2 values that we appeared to be unreasonably low.

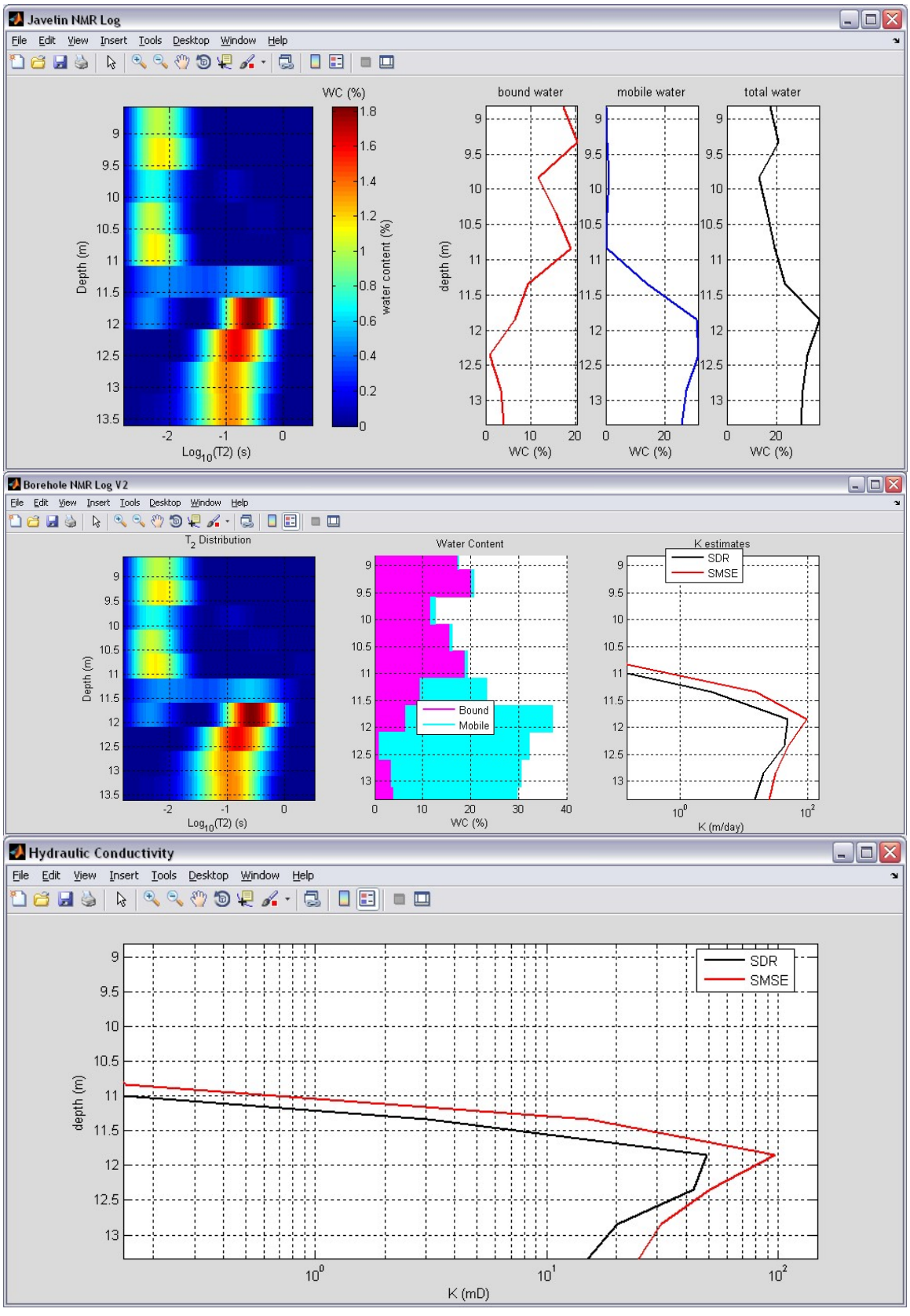
Depth (m)	Fo (kHz)	TWC (%)	BWC (%)	MWC (%)	MLT2 (s)	K_sdr (m/day)	K_smse (m/day)
20.9	294	26.74	16.30	10.44	0.0216	0.66	4.0
20.4	294	27.36	18.32	9.04	0.0181	0.50	1.6
19.9	294	25.37	15.29	10.09	0.0216	0.60	1.5

Table 2: Geoprobe "NMR1" partial log.

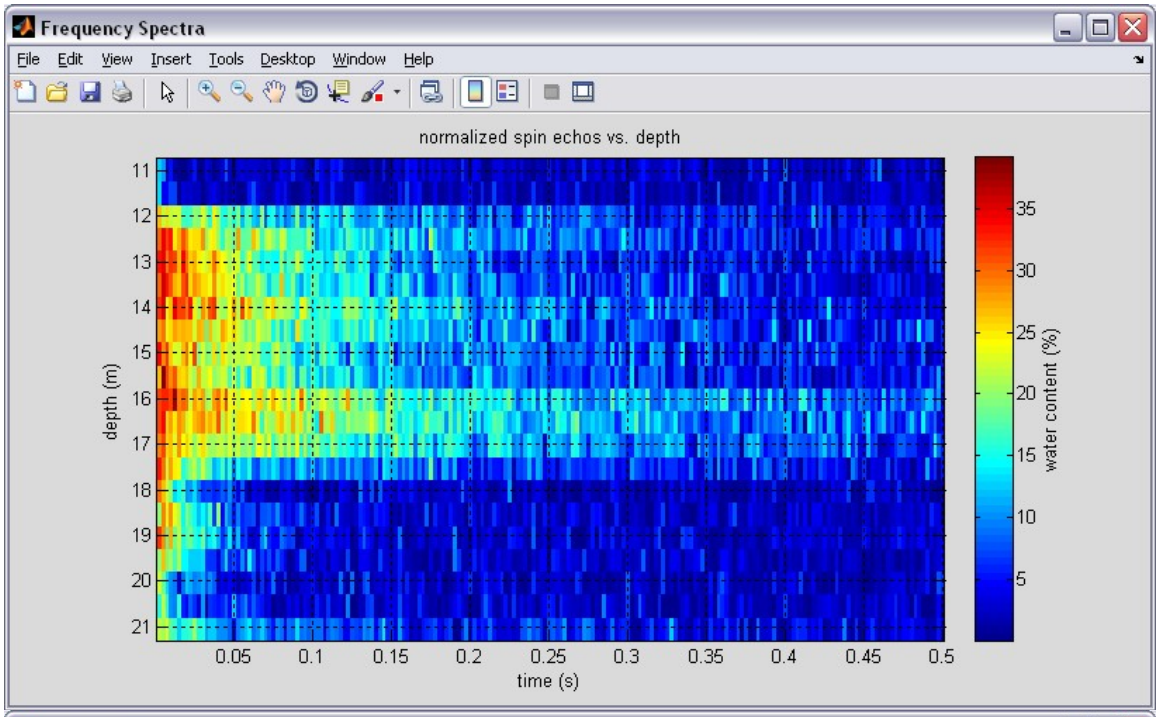
We performed more experiments with the water barrel and determined that the fine iron filings that were stuck to the NMR probe were not responsible for the unreasonably short T2 values.

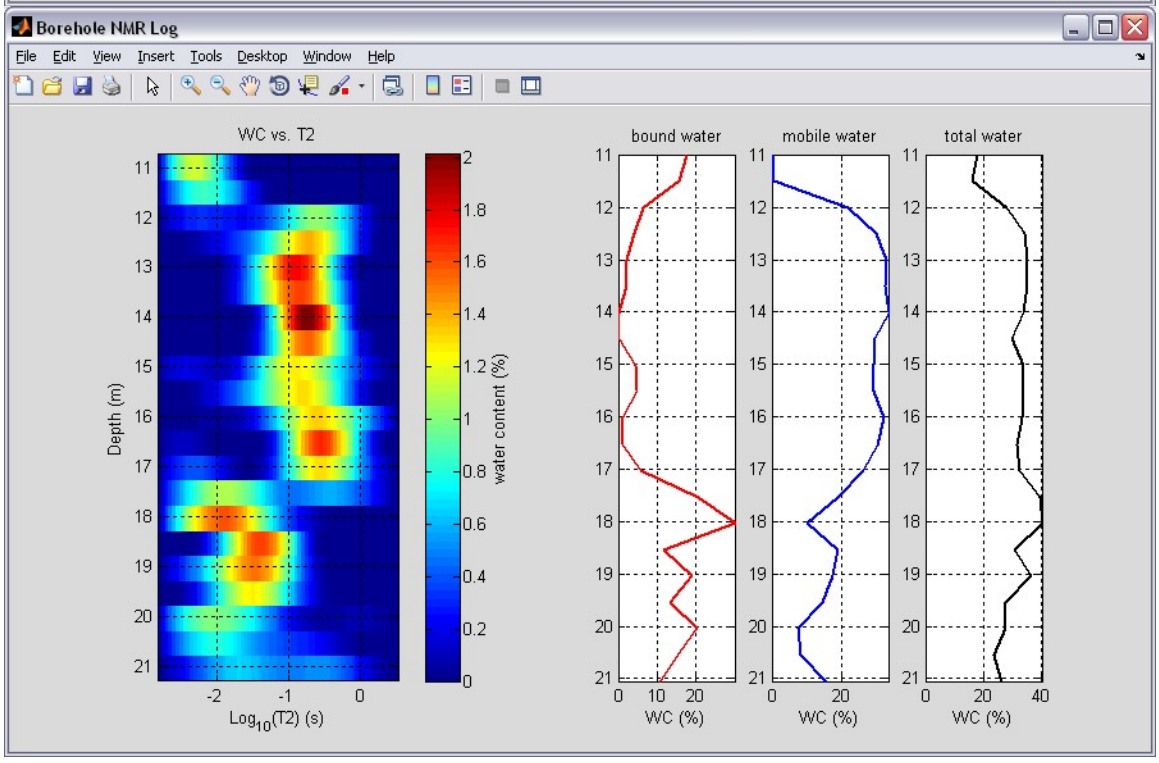
We drove the Geoprobe in again in a nearby location and performed a partial log from 13.35m to 8.78m. The results of this partial log seemed more reasonable, the T2's below 11m were on the order of 150ms, which is similar to what we see for T2* in the surface NMR data.

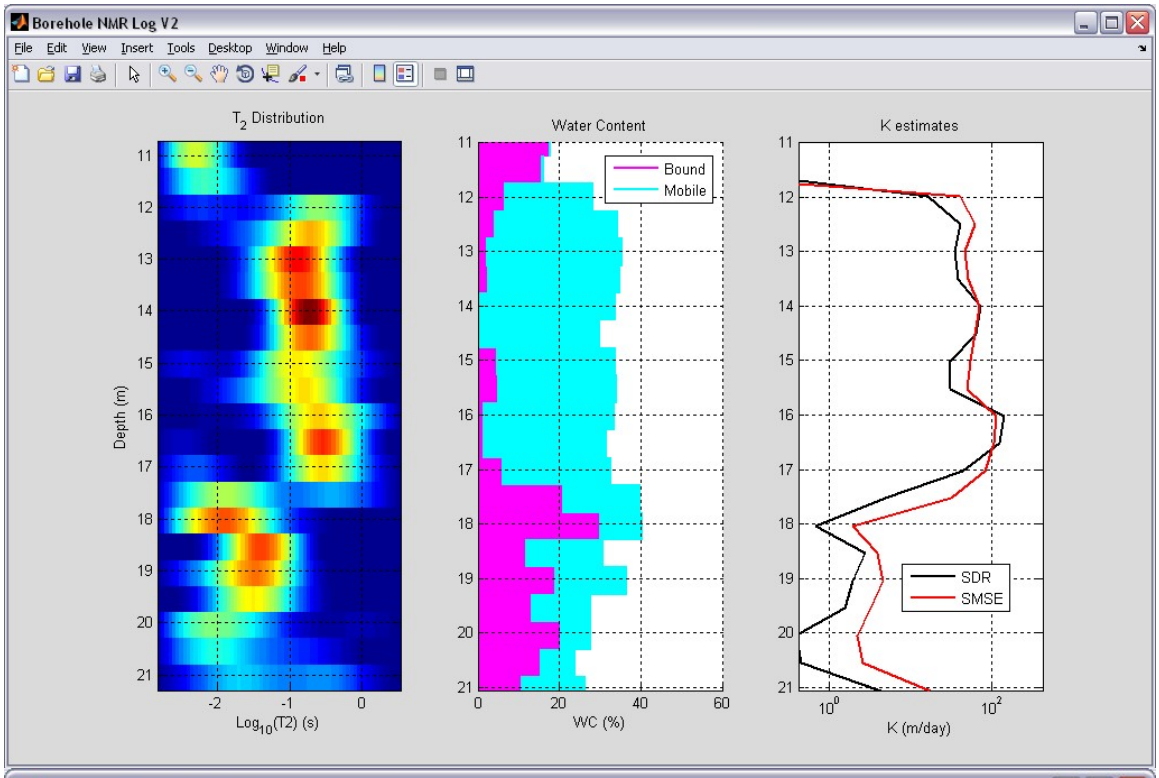


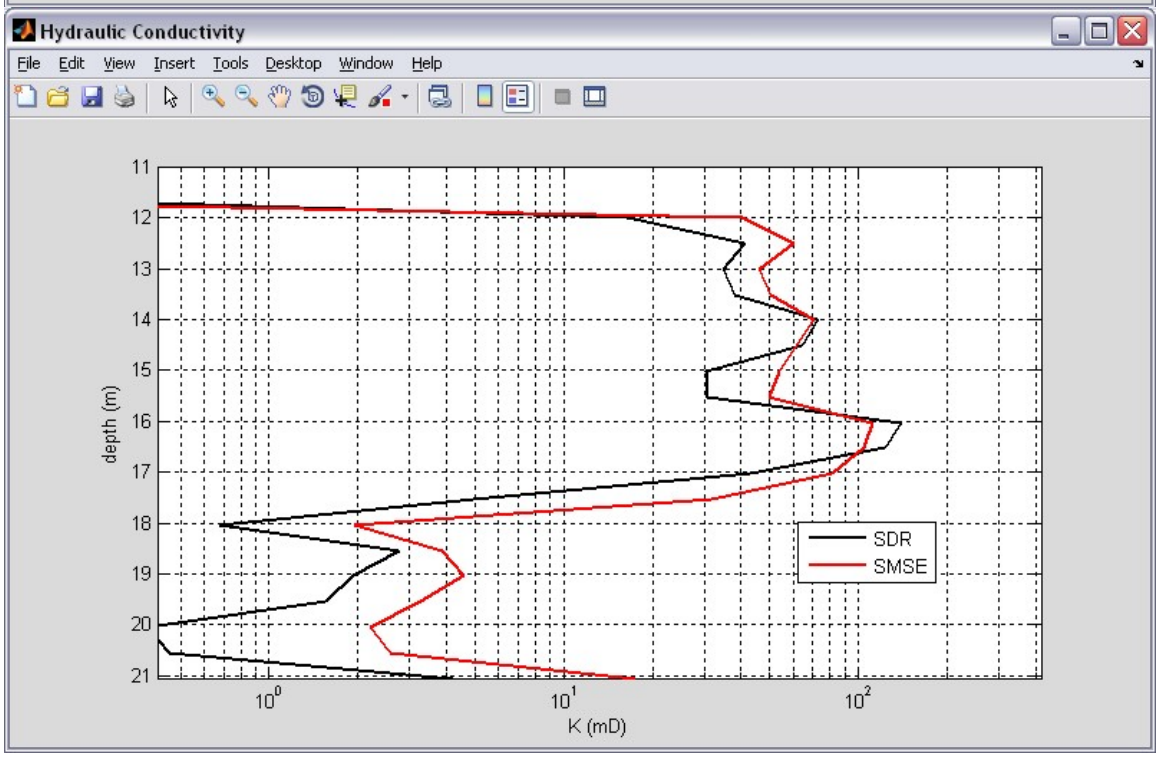

Javelin NMR Log
File Edit View Insert Tools Desktop Window Help
WC (%)
Depth (m)
Log10(T2) (s)
water content (%)
bound water
mobile water
total water
depth (m)
WC (%)
Borehole NMR Log V2
T2 Distribution
Water Content
Bound
Mobile
K estimates
SDR
SMSE
K (m/day)
Hydraulic Conductivity
depth (m)
K (mD)

Oct 17, 2010 (Geoprobe log of NMR2)

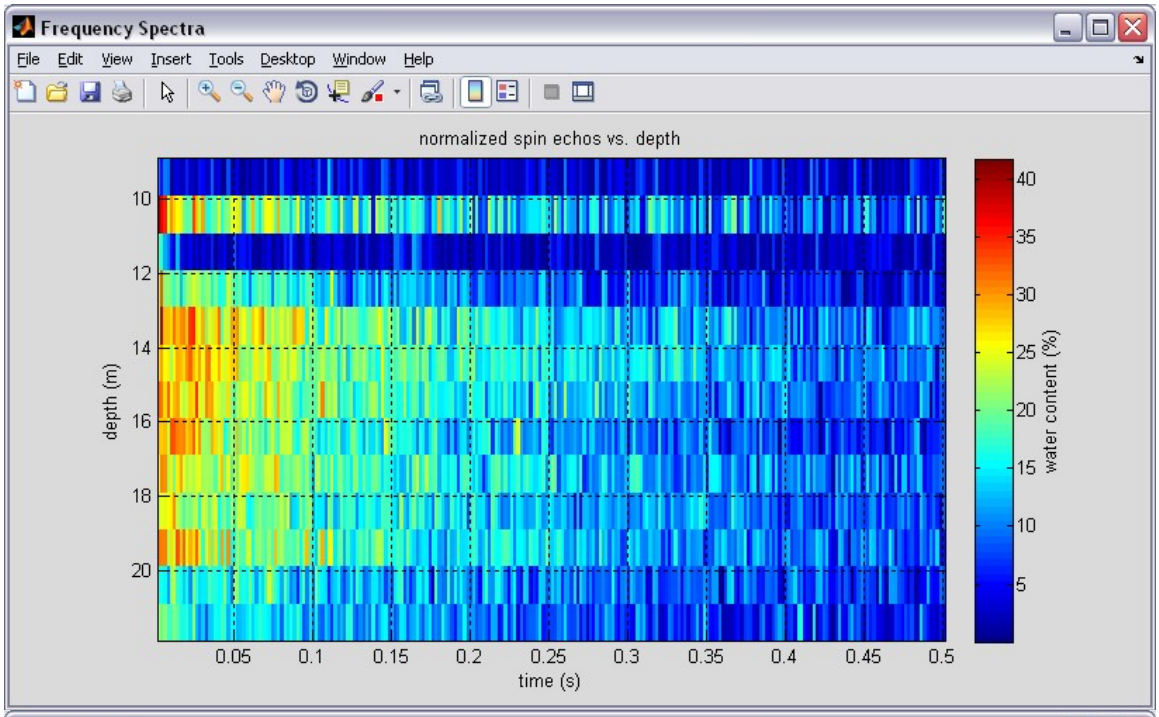


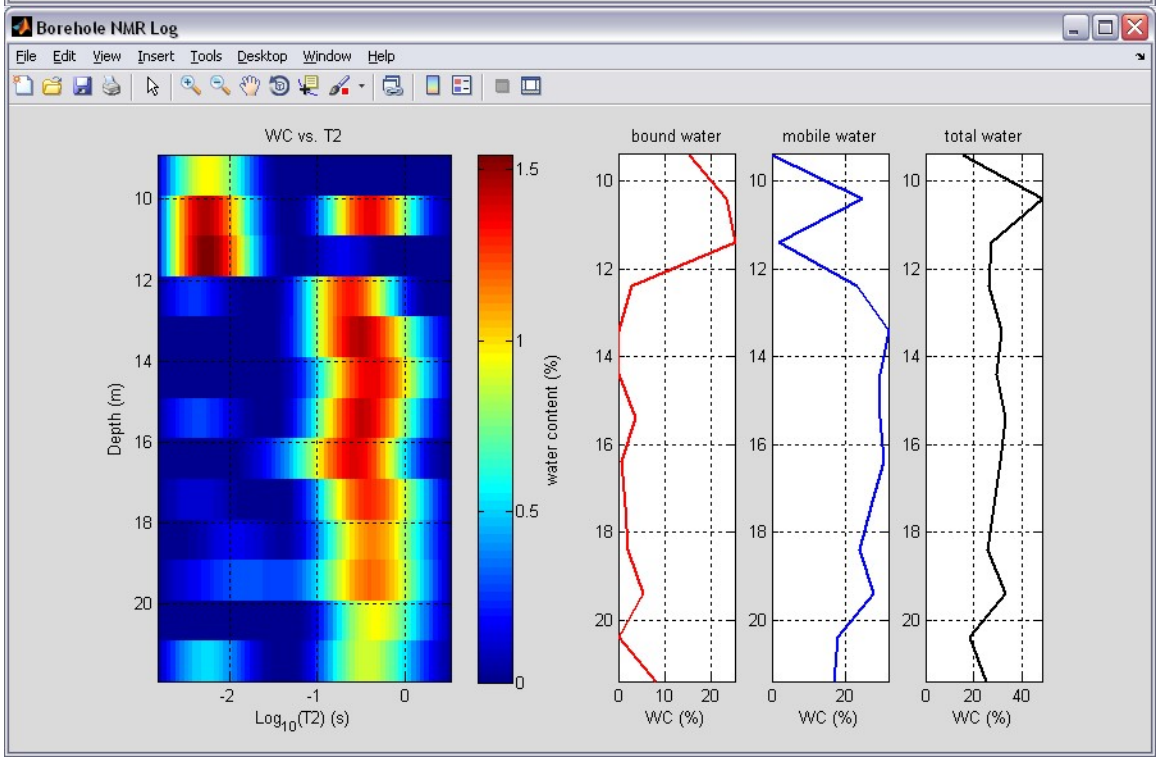


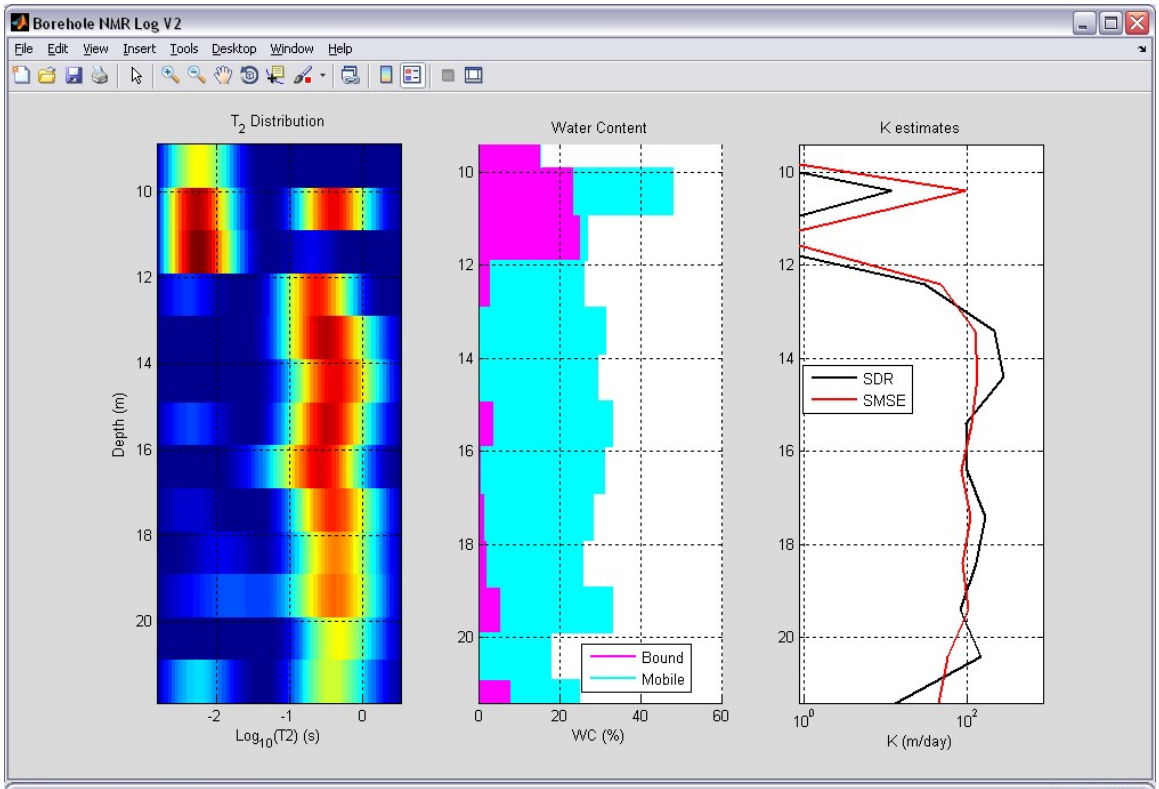

Borehole NMR Log V2
File Edit View Insert Tools Desktop Window Help
T2 Distribution
Depth (m)
Log10(T2) (s)
Water Content
Bound
Mobile
WC (%)
K estimates
SDR
SMSE
K (m/day)

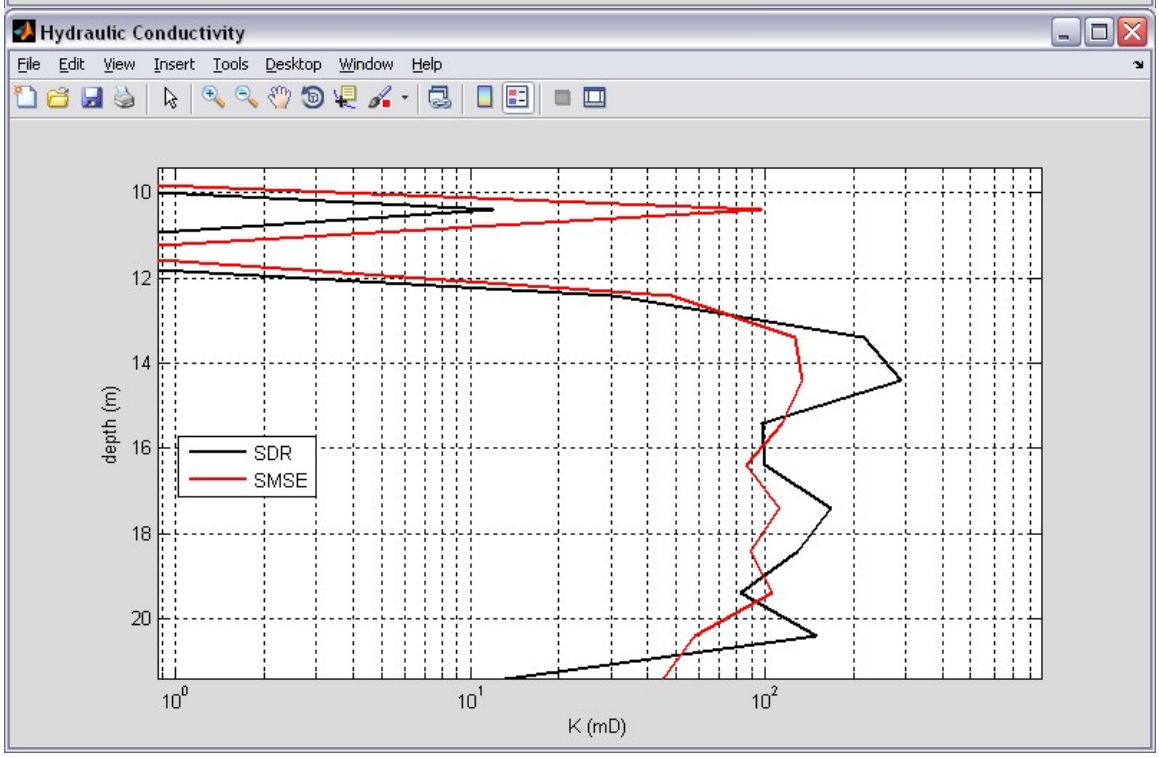

Hydraulic Conductivity
File Edit View Insert Tools Desktop Window Help
depth (m)
SDR
SMSE
K (mD)

Oct 18, 2010 (1.7" NMR log of GEMS Well HT6)



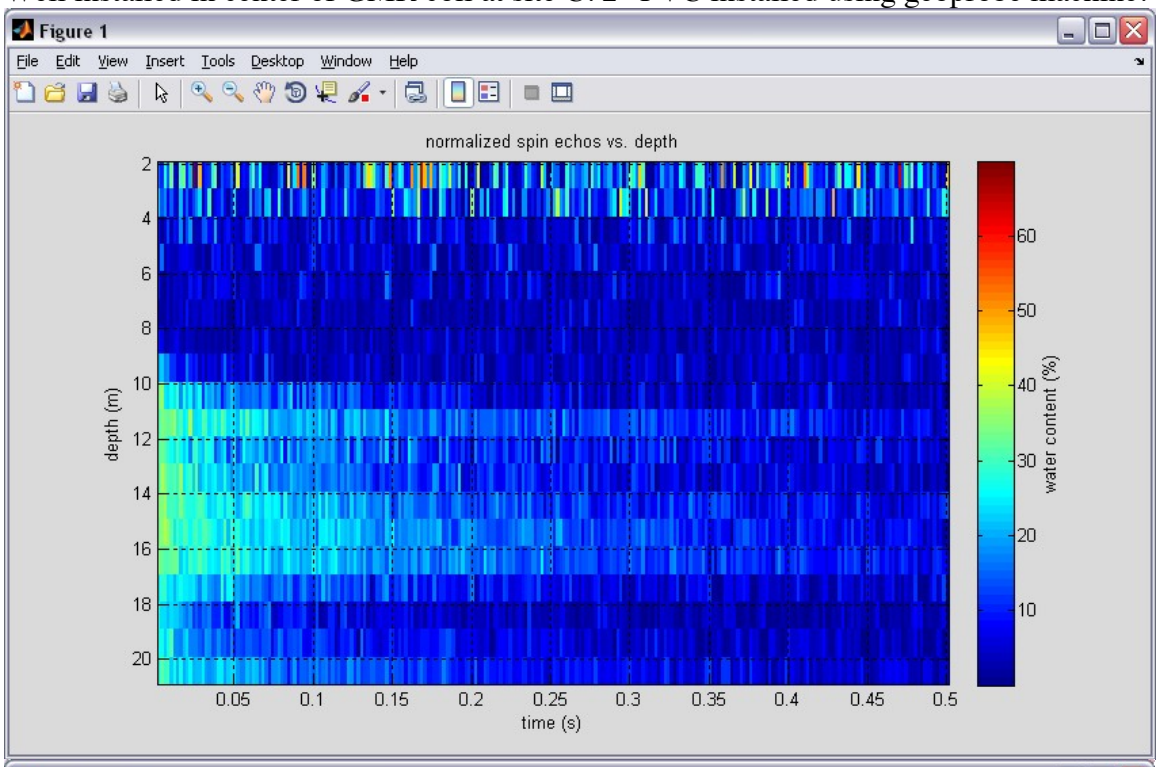


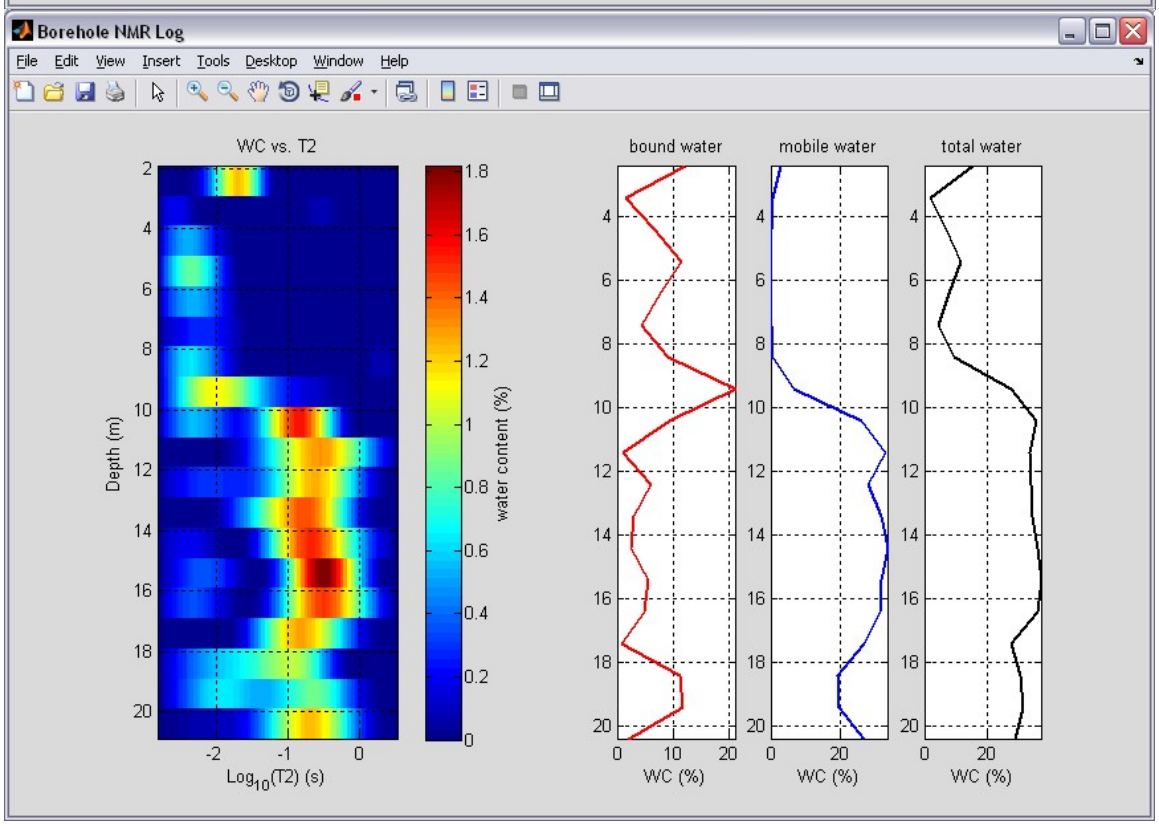

Borehole NMR Log V2
File Edit View Insert Tools Desktop Window Help
T2 Distribution
Water Content
K estimates
Depth (m)
Log10(T2) (s)
WC (%)
K (m/day)
Bound
Mobile
SDR
SMSE

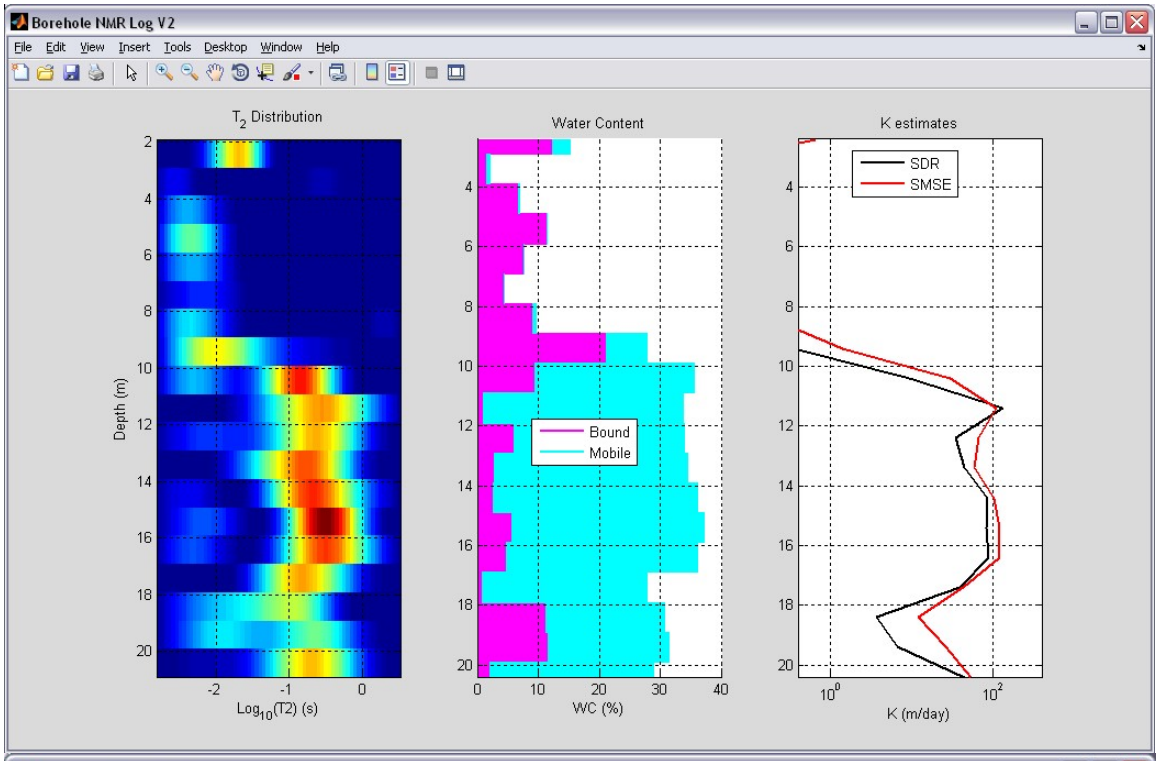

Hydraulic Conductivity
File Edit View Insert Tools Desktop Window Help
depth (m)
K (mD)
SDR
SMSE

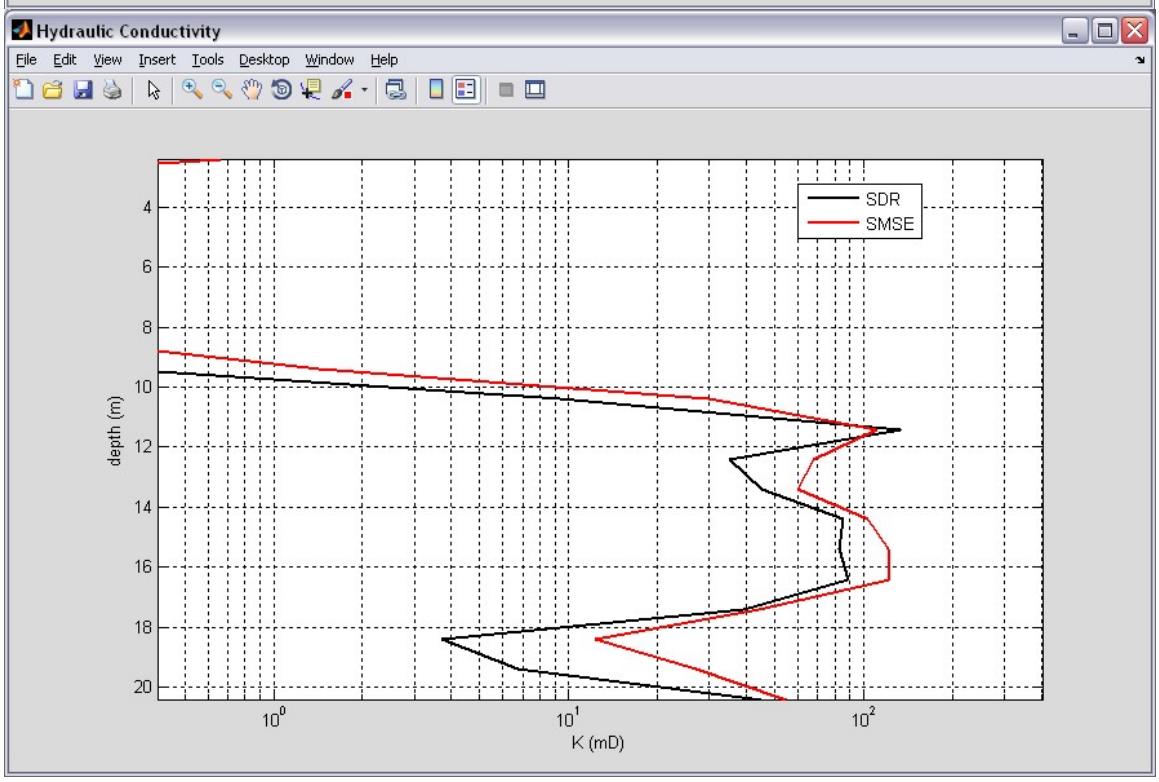
Oct 19, 2010 (1.7" NMR log of GEMS Well C1 before development)

Well installed in center of GMR coil at site C. 2" PVC installed using geoprobe machine.

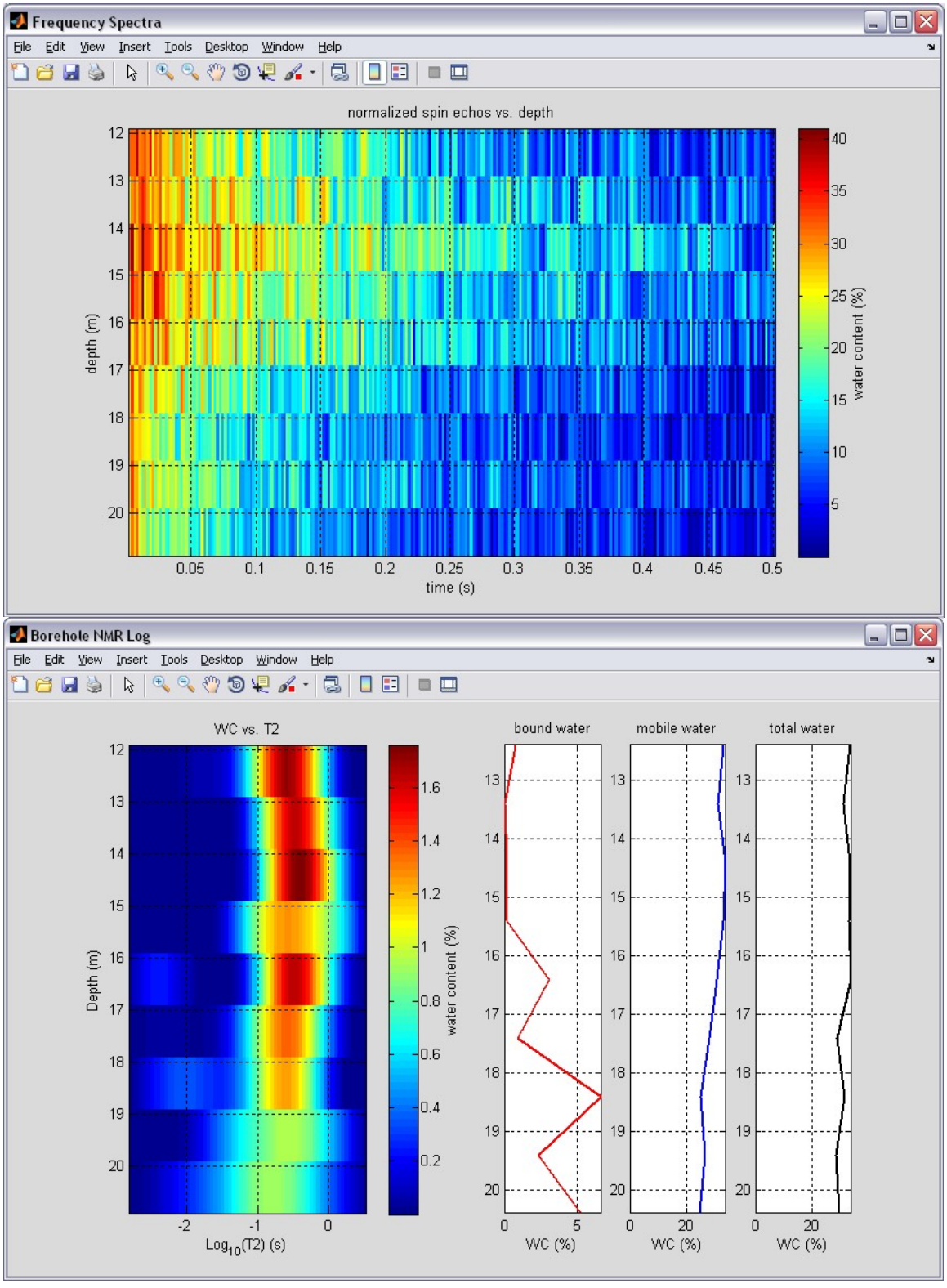


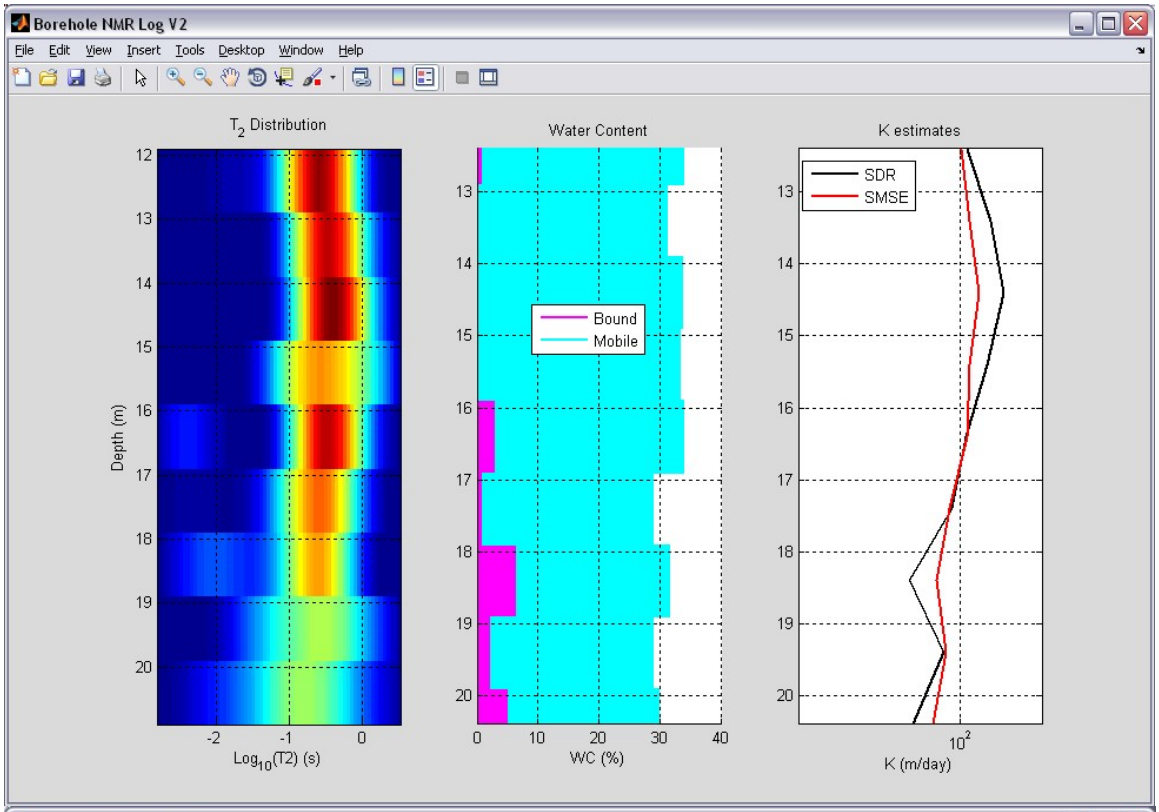


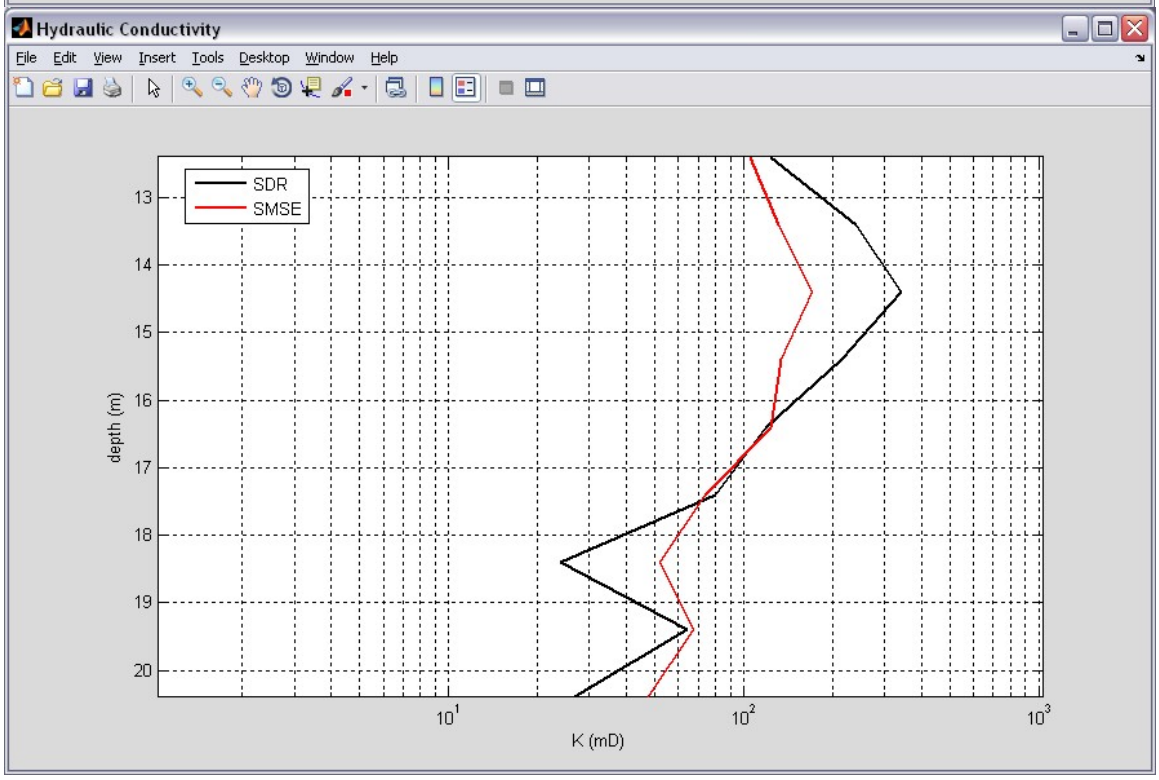

Borehole NMR Log V2
File Edit View Insert Tools Desktop Window Help
T2 Distribution
Water Content
K estimates
Depth (m)
Log10(T2) (s)
WC (%)
K (m/day)
Bound
Mobile
SDR
SMSE


Hydraulic Conductivity
File Edit View Insert Tools Desktop Window Help
depth (m)
K (mD)
SDR
SMSE

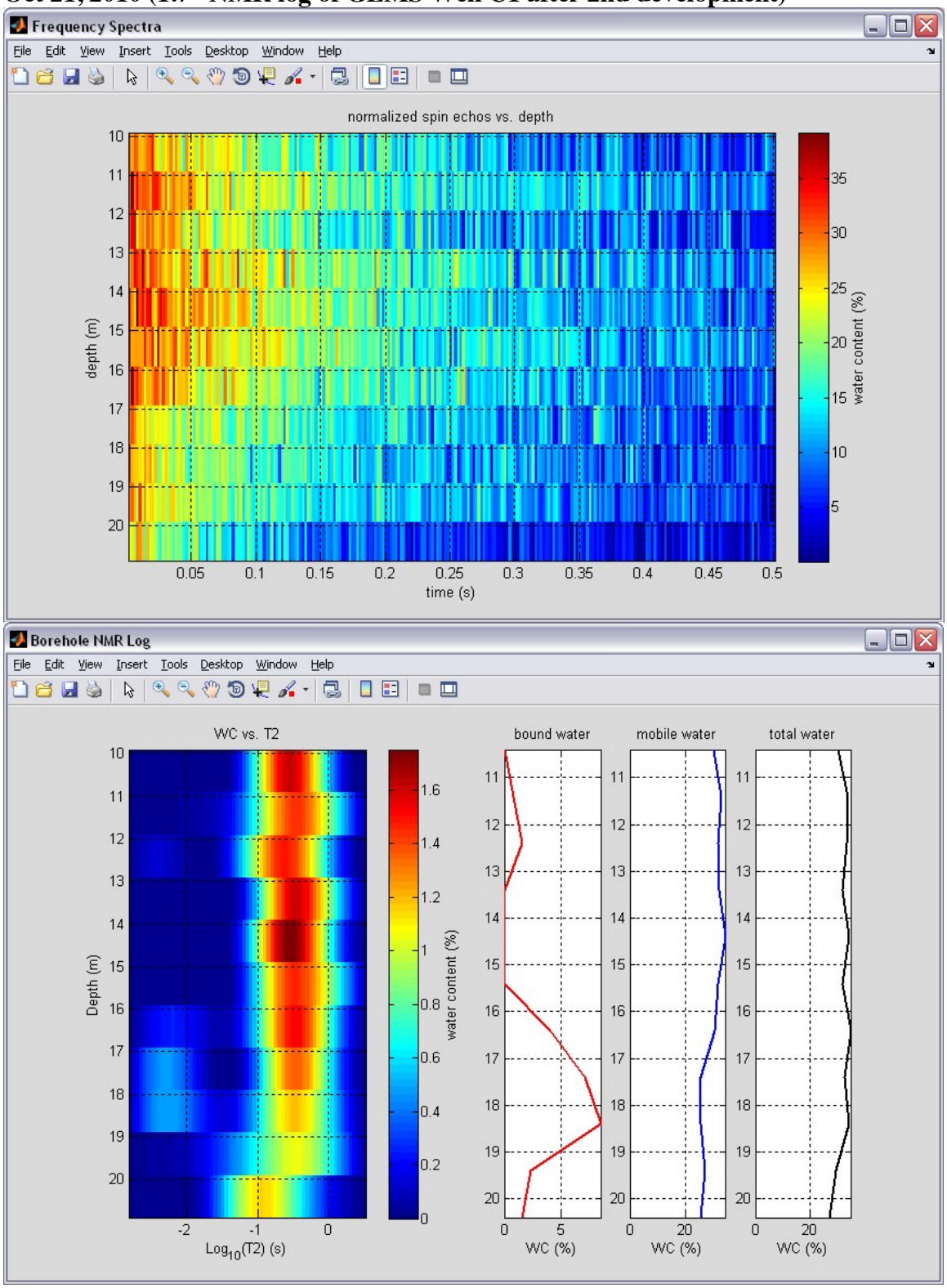
Oct 21, 2010 (1.7" NMR log of GEMS Well C1 after 1st development)

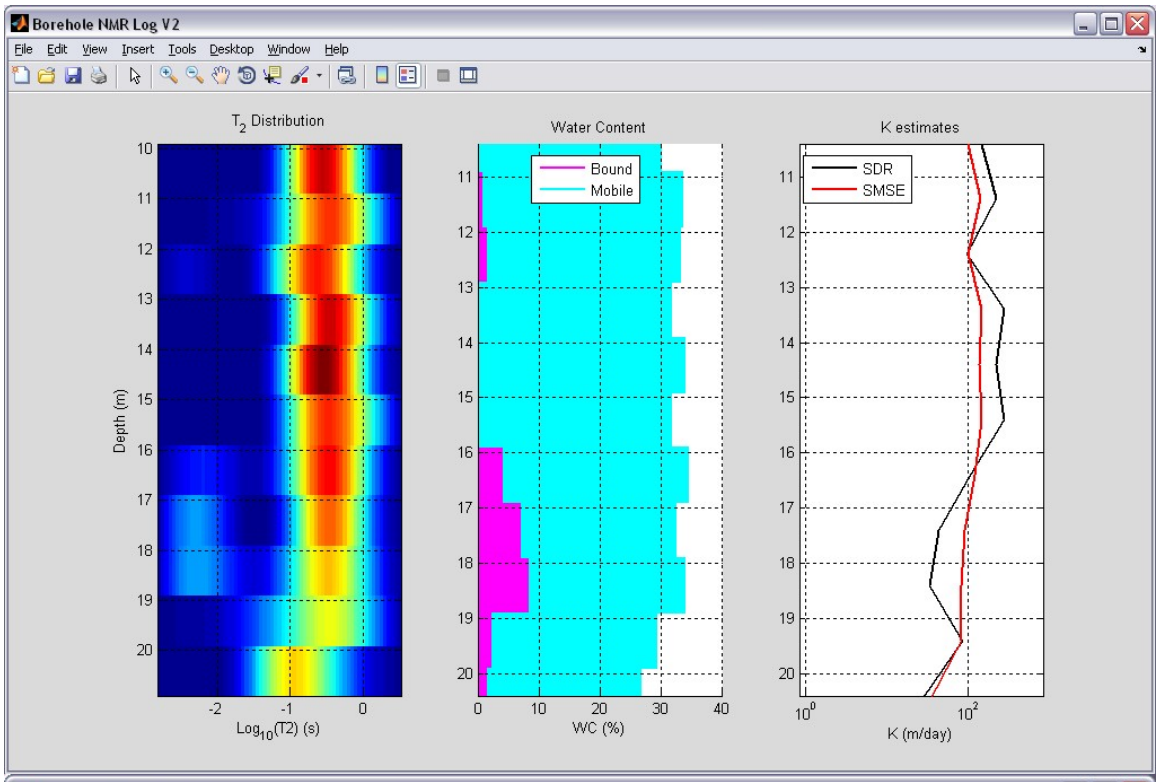


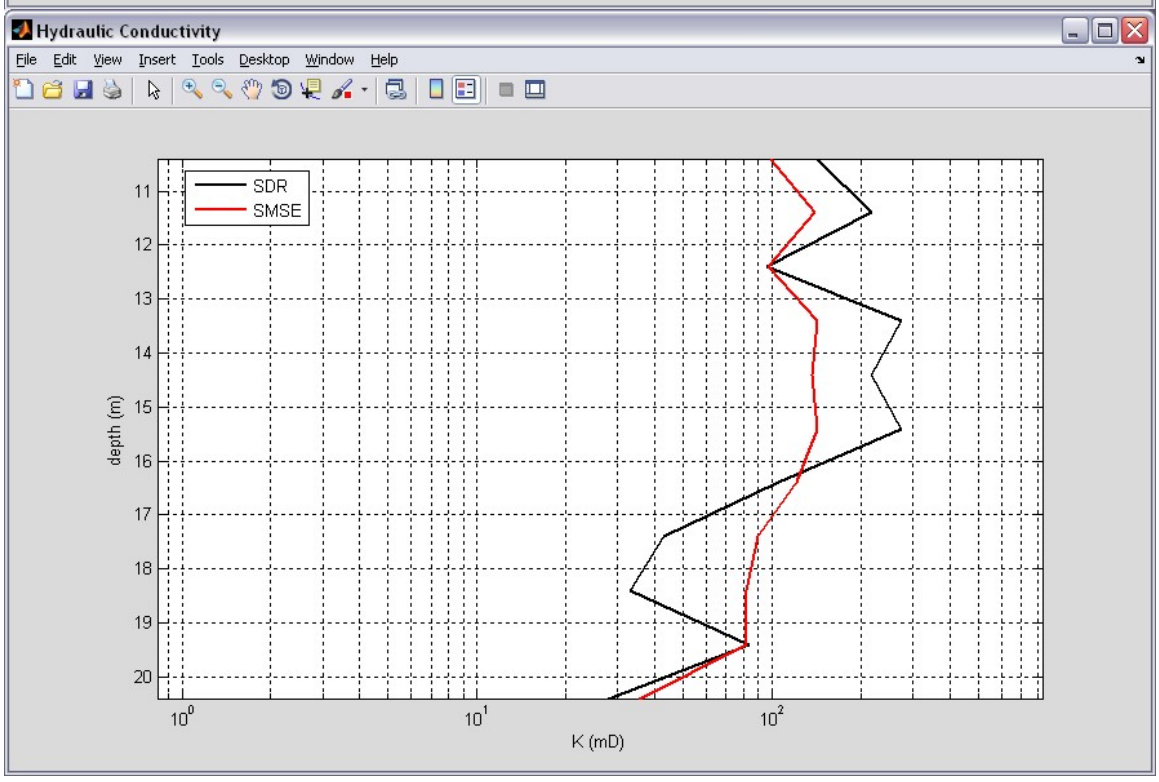

Borehole NMR Log V2
File Edit View Insert Tools Desktop Window Help
T2 Distribution
Water Content
K estimates
Depth (m)
Log10(T2) (s)
WC (%)
K (m/day)
Bound
Mobile
SDR
SMSE


Hydraulic Conductivity
File Edit View Insert Tools Desktop Window Help
SDR
SMSE
depth (m)
K (mD)

Oct 21, 2010 (1.7" NMR log of GEMS Well C1 after 2nd development)




Borehole NMR Log V2
File Edit View Insert Tools Desktop Window Help
T2 Distribution
Water Content
K estimates
Depth (m)
Log10(T2) (s)
Bound
Mobile
WC (%)
SDR
SMSE
K (m/day)


Hydraulic Conductivity
File Edit View Insert Tools Desktop Window Help
SDR
SMSE
depth (m)
K (mD)

Compare WellC1 NMR logs, before and after development

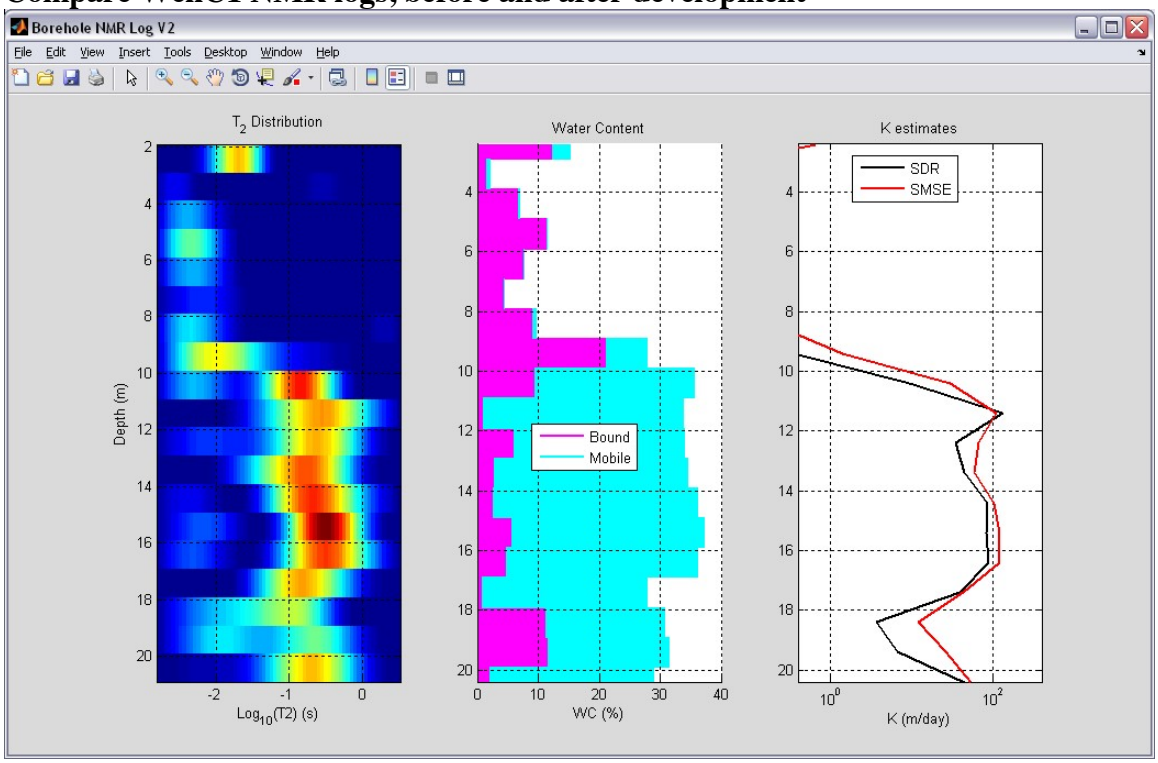


Figure 7: well C1 before development.

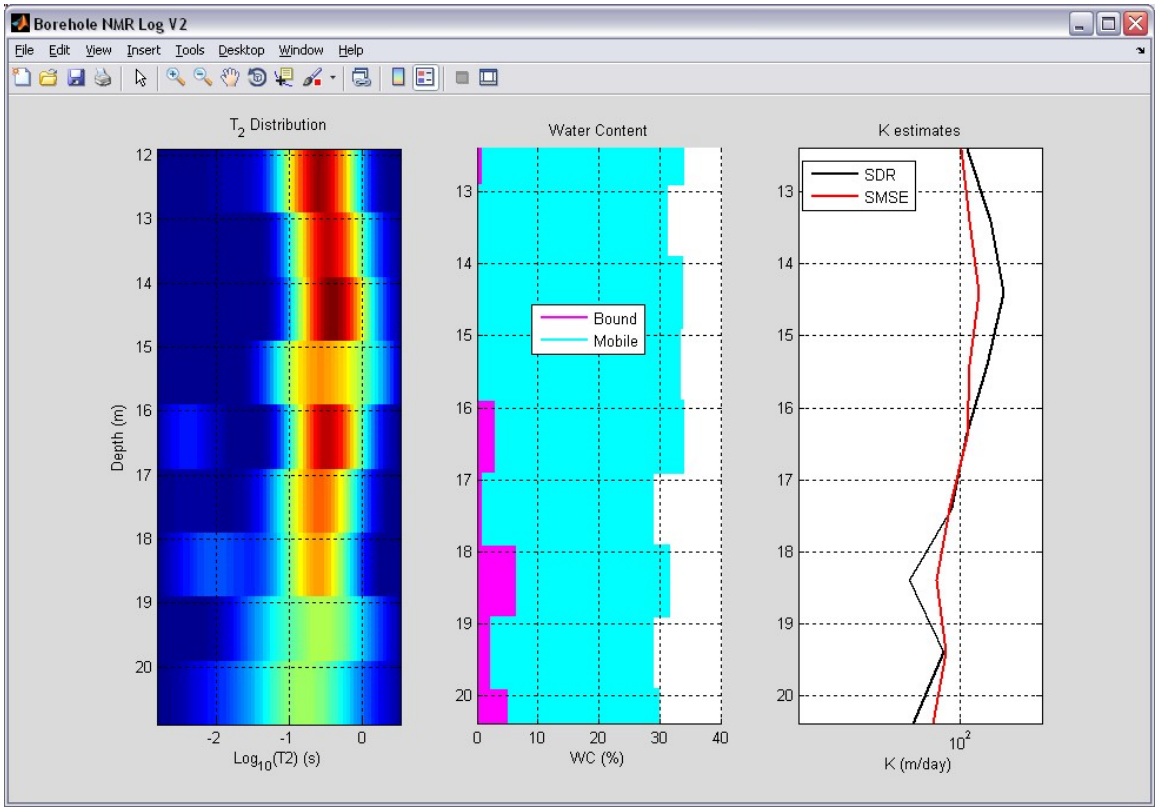


Figure 8: Well C1 after 1st development.

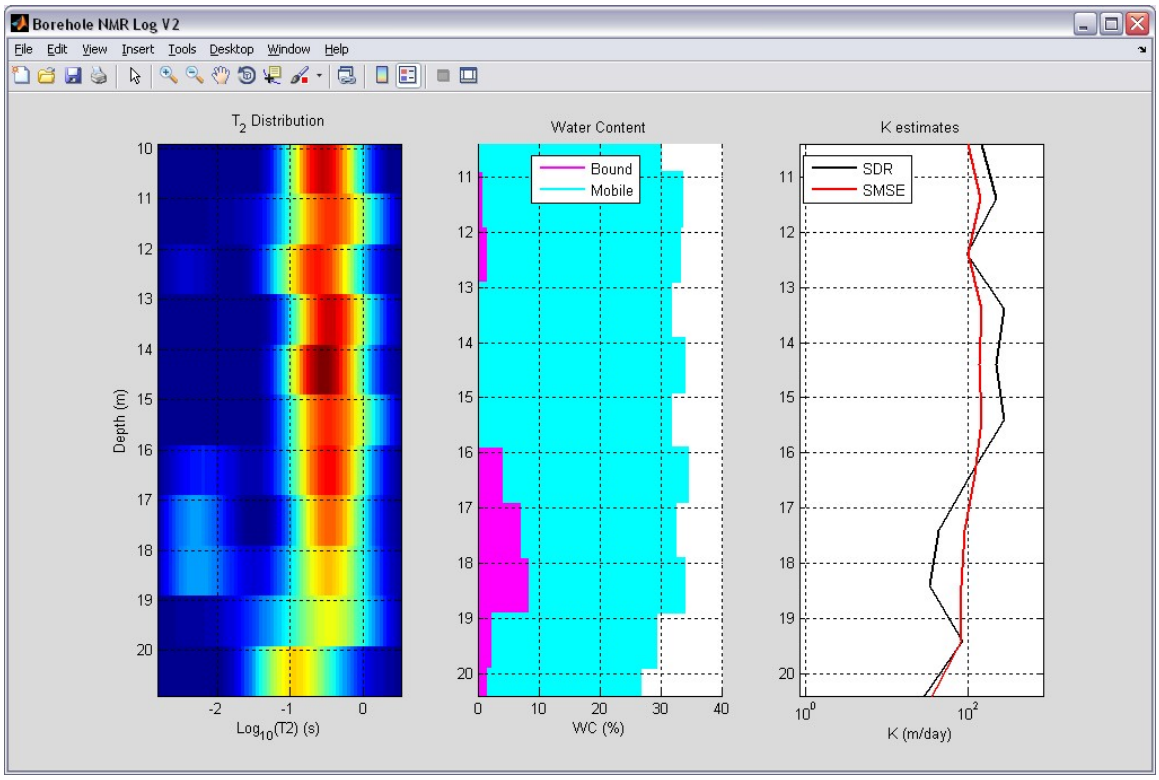
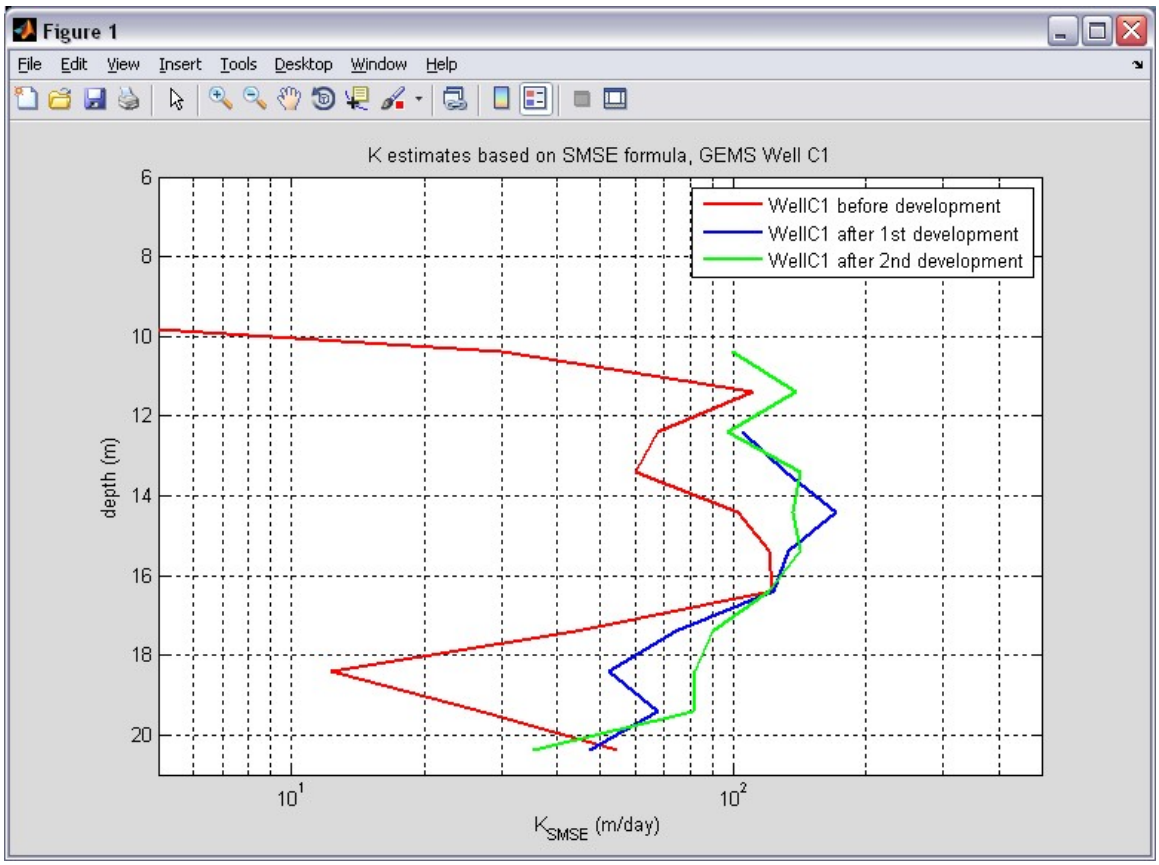


Figure 9: Well C1 after 2nd development.



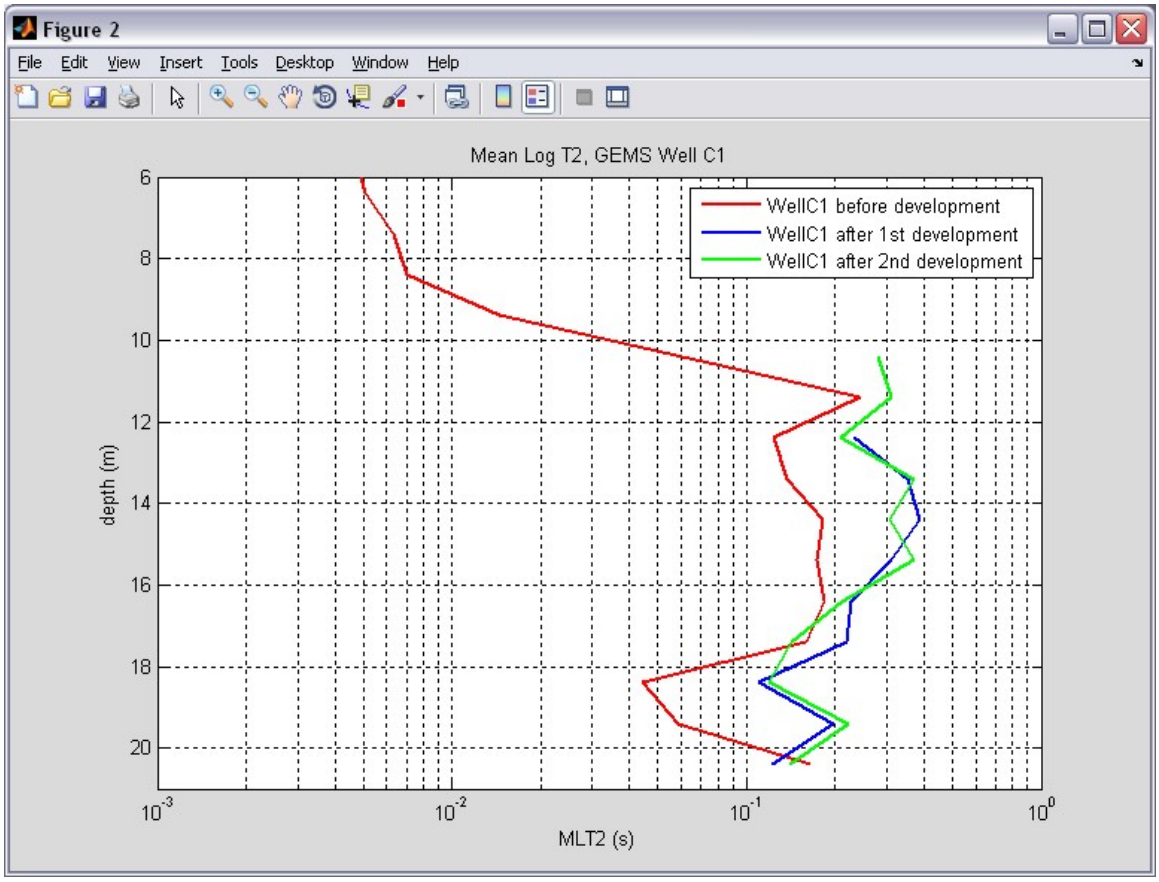


Figure 2
File Edit View Insert Tools Desktop Window Help
Mean Log T2, GEMS Well C1
WellC1 before development
WellC1 after 1st development
WellC1 after 2nd development
depth (m)
6
8
10
12
14
16
18
20
10^{-3}
10^{-2}
10^{-1}
10^{0}
MLT2 (s)

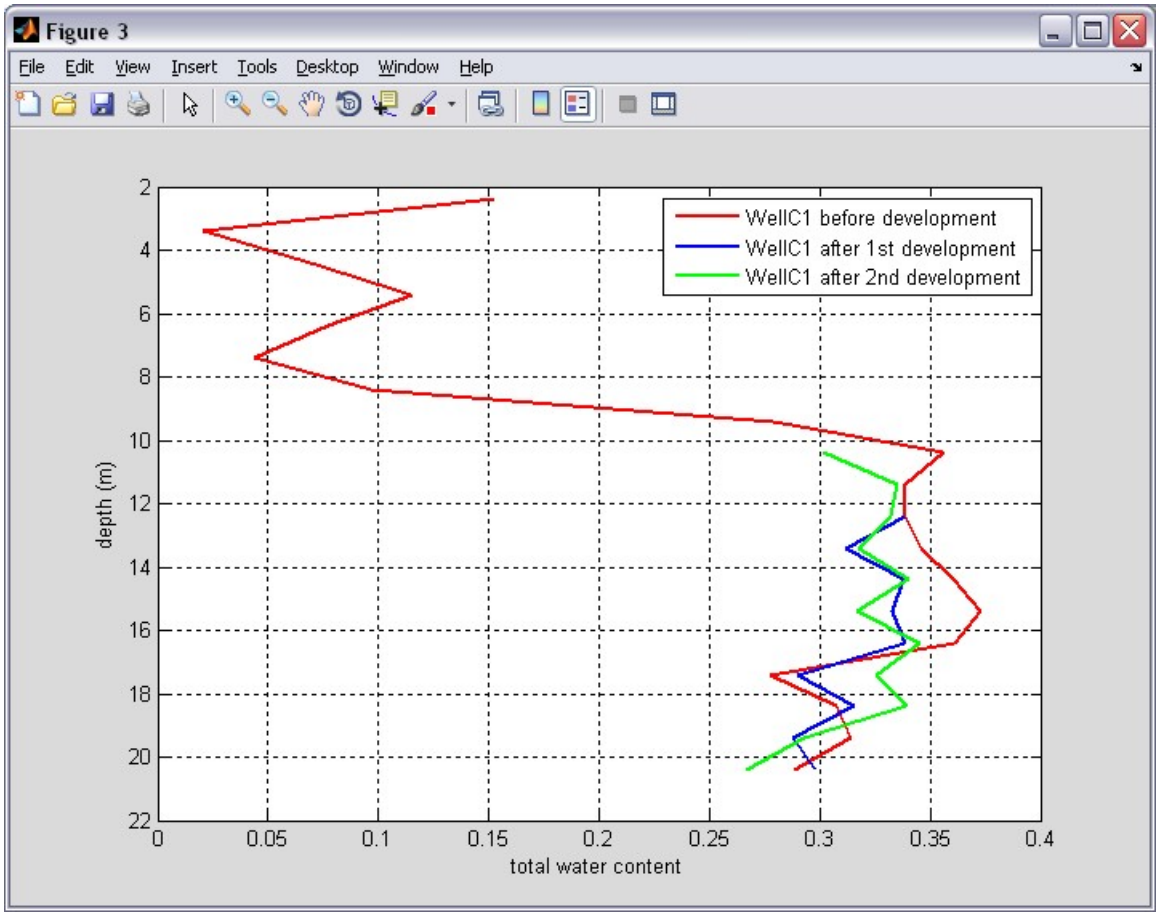
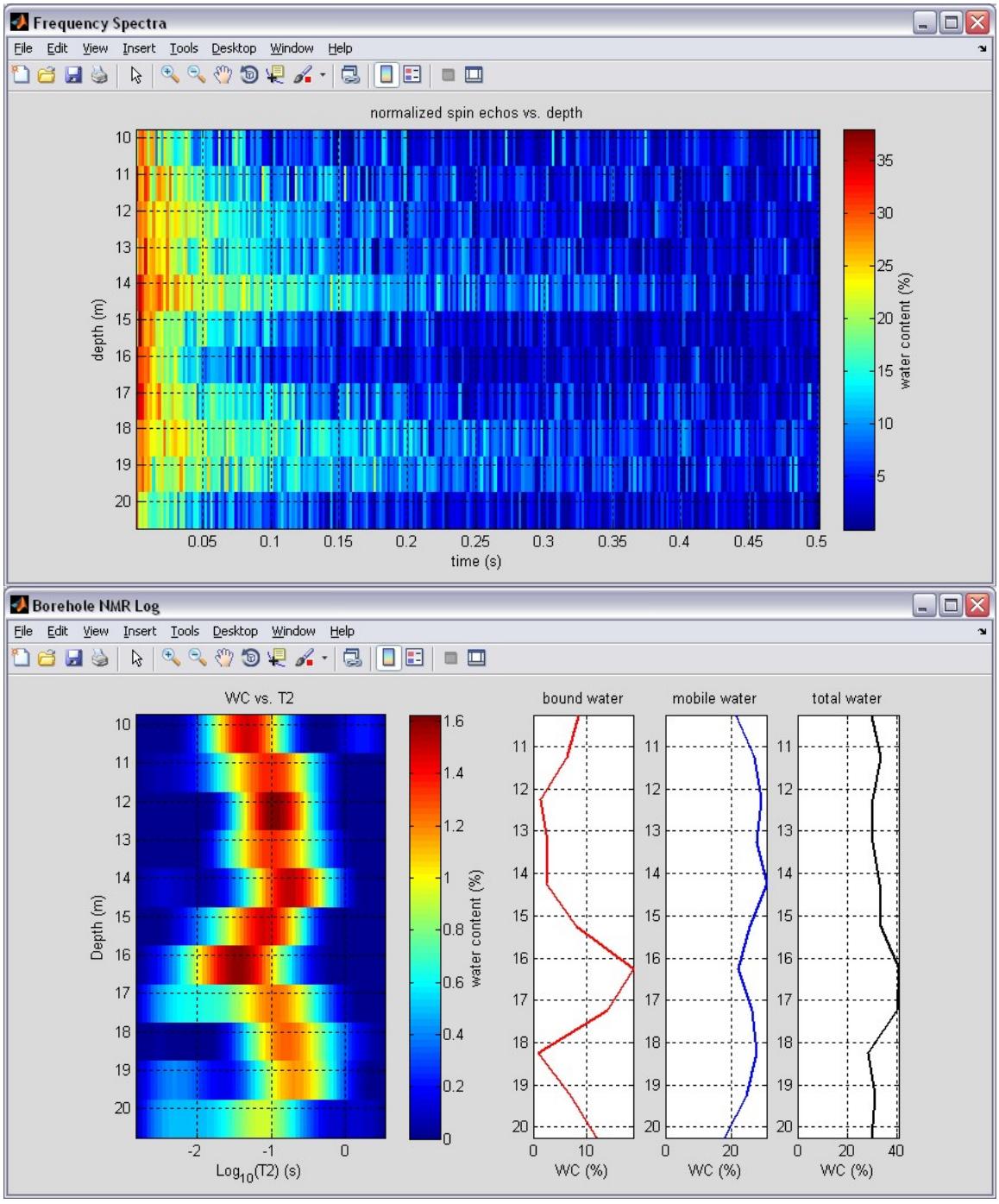
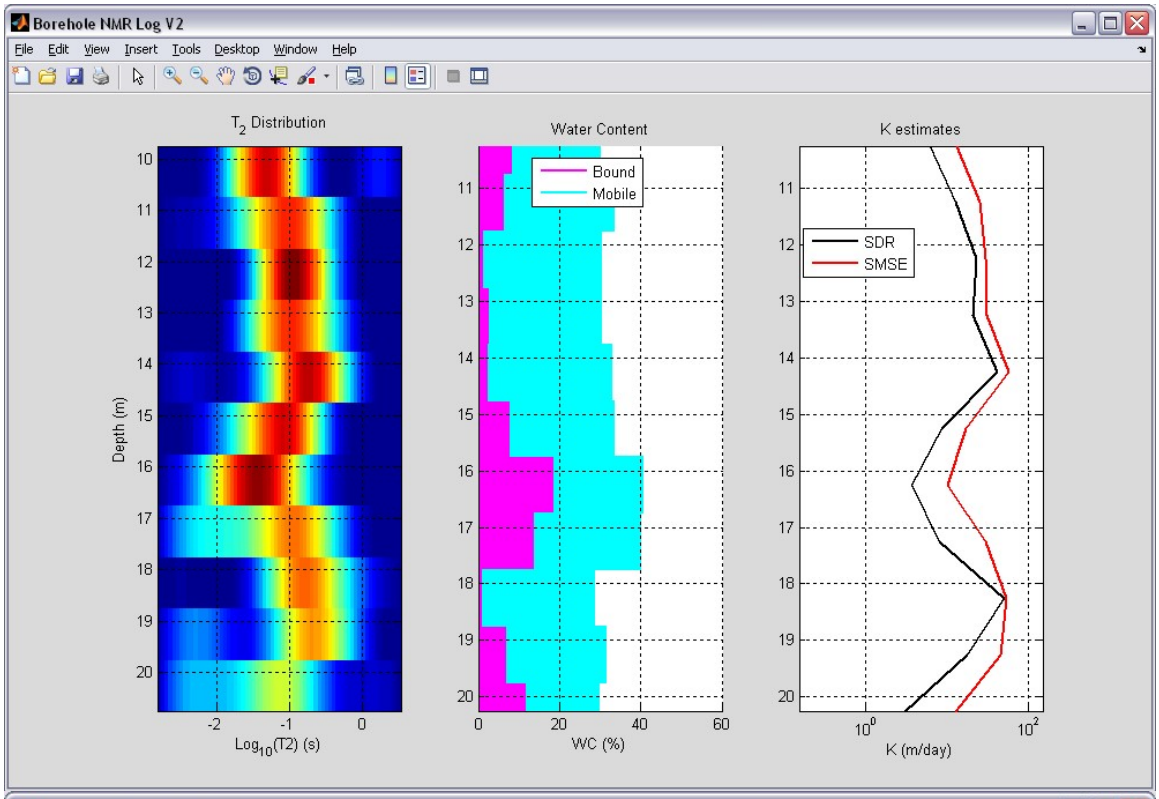
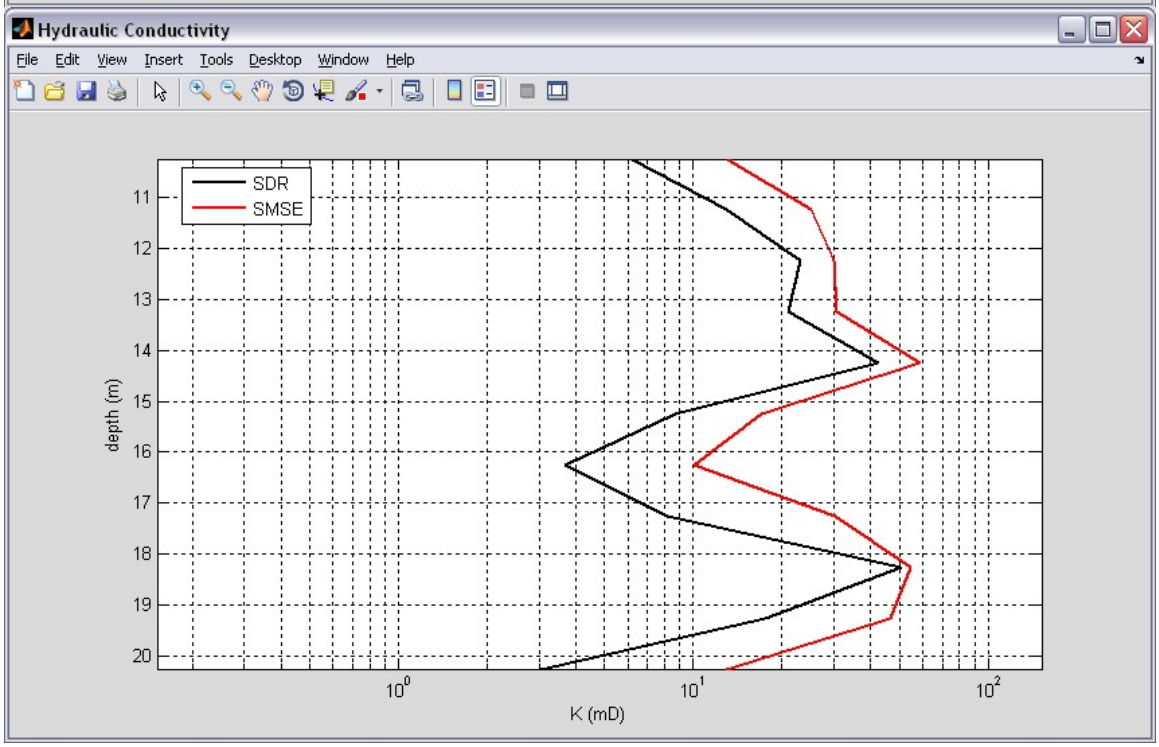


Figure 3
File Edit View Insert Tools Desktop Window Help
WellC1 before development
WellC1 after 1st development
WellC1 after 2nd development
depth (m)
total water content
2
4
6
8
10
12
14
16
18
20
22
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4

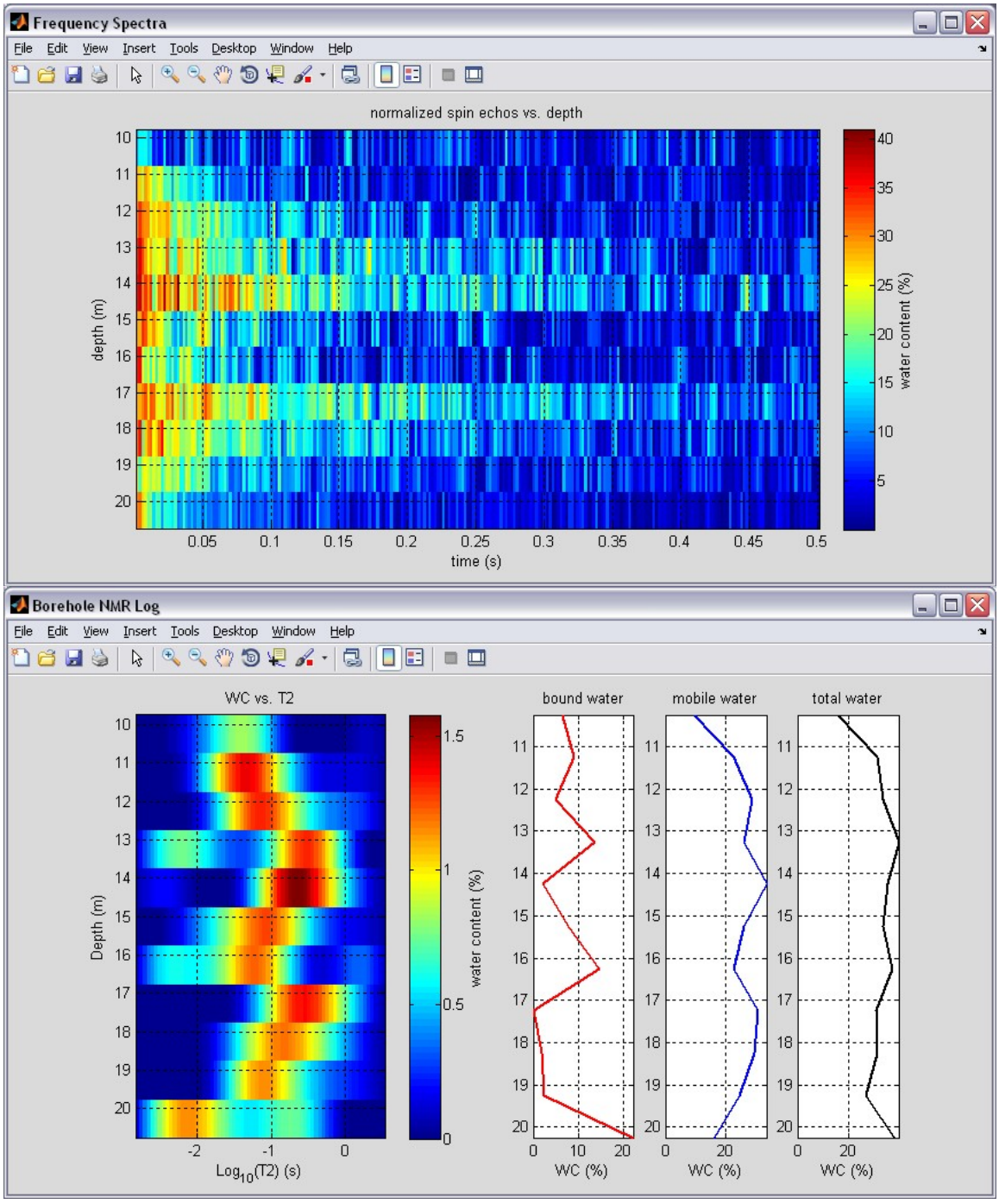
Oct 20, 2010 (1.7" NMR log of GEMS Well A1 before development)

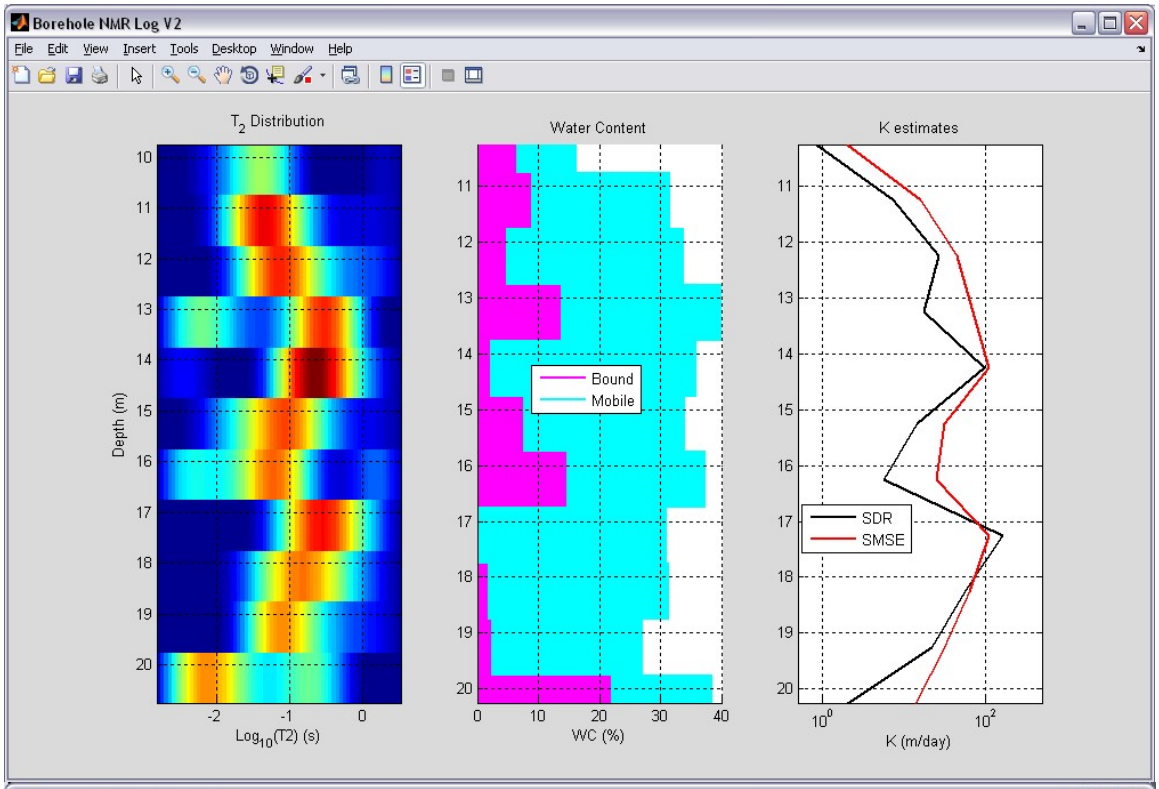


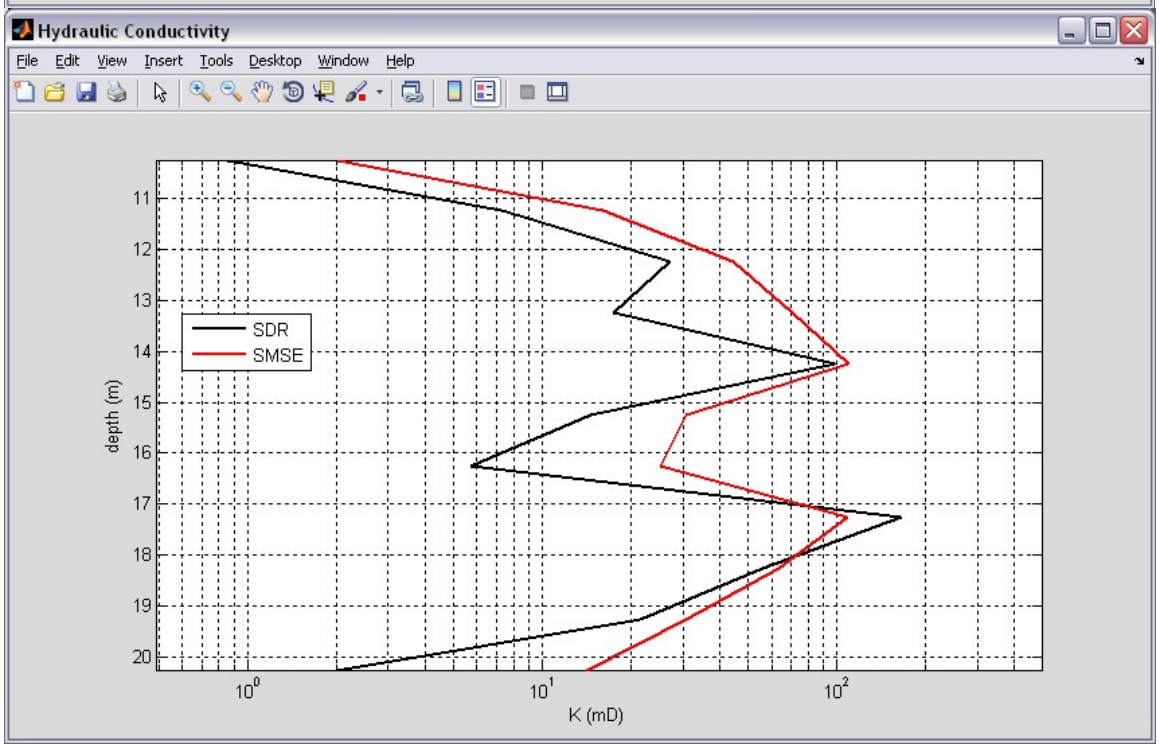

Borehole NMR Log V2
File Edit View Insert Tools Desktop Window Help
T2 Distribution
Depth (m)
Log10(T2) (s)
Water Content
Bound
Mobile
WC (%)
K estimates
SDR
SMSE
K (m/day)


Hydraulic Conductivity
File Edit View Insert Tools Desktop Window Help
SDR
SMSE
depth (m)
K (mD)

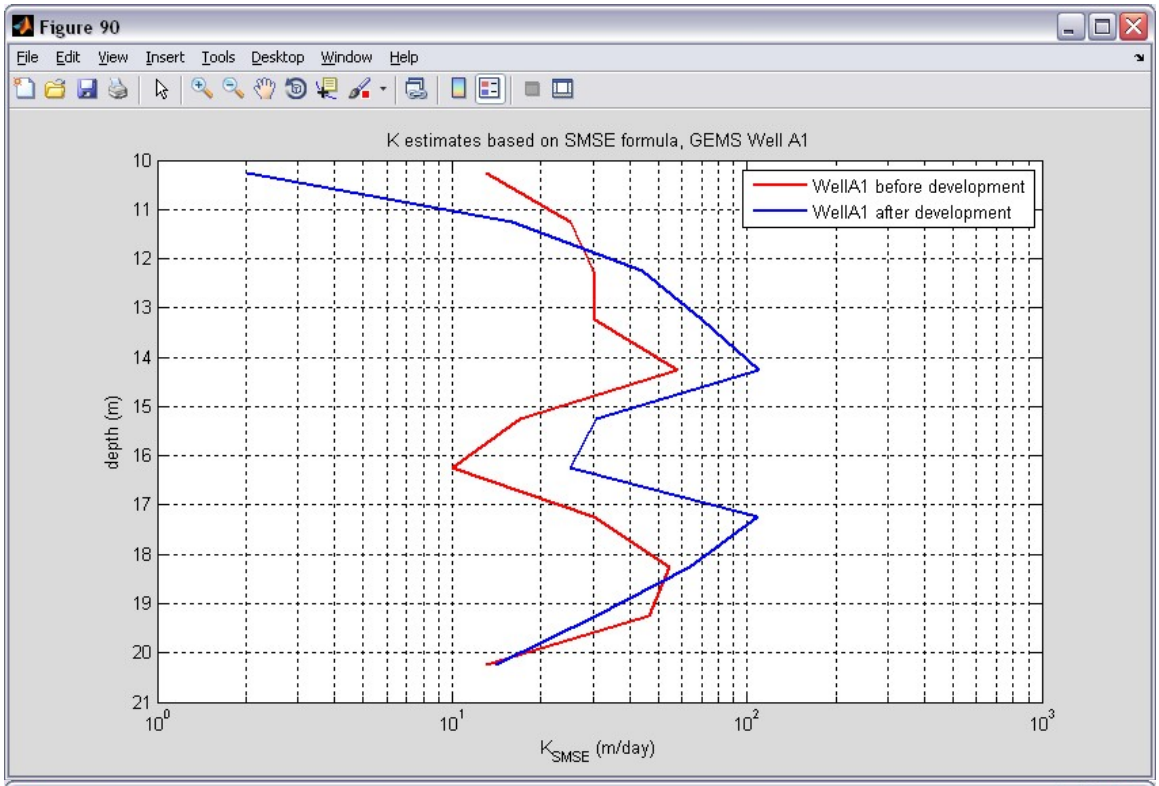
Oct 20, 2010 (1.7" NMR log of GEMS Well A1 after development)

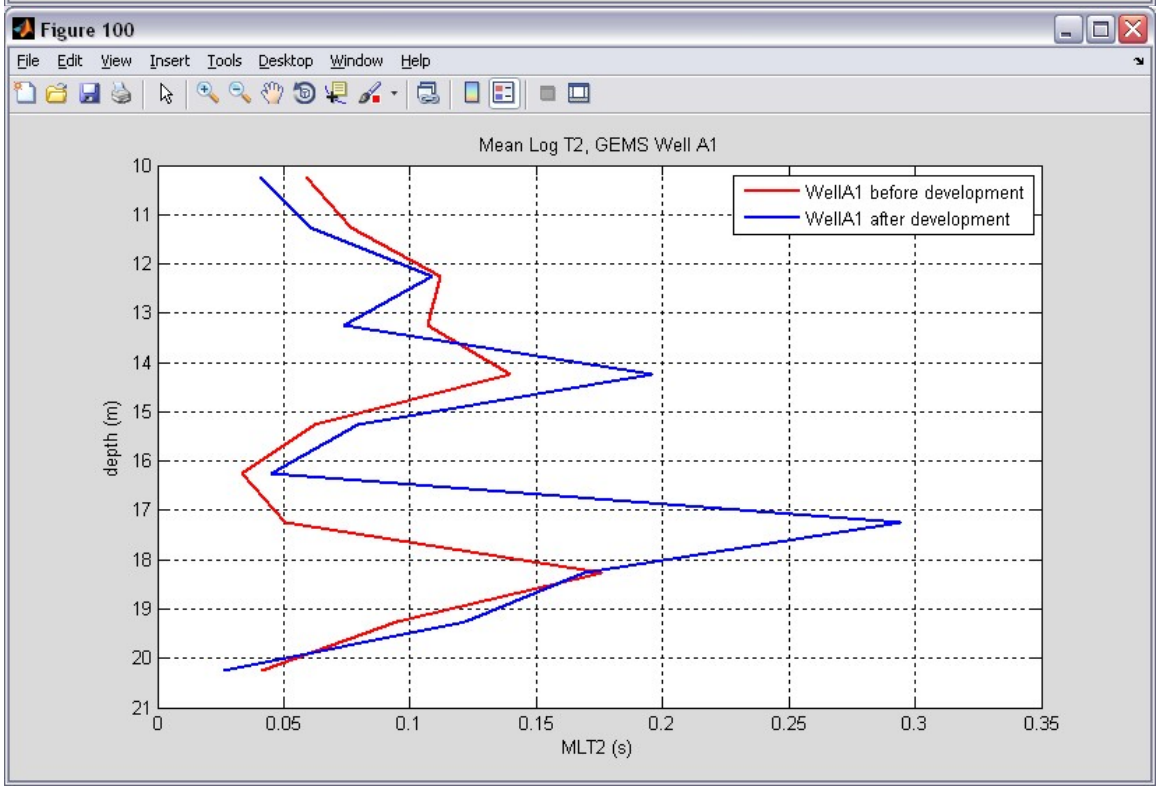



Borehole NMR Log V2
File Edit View Insert Tools Desktop Window Help
T2 Distribution
Water Content
K estimates
Depth (m)
Log10(T2) (s)
Bound
Mobile
WC (%)
SDR
SMSE
K (m/day)


Hydraulic Conductivity
File Edit View Insert Tools Desktop Window Help
depth (m)
SDR
SMSE
K (mD)

Compare WellA1 NMR logs, before and after development





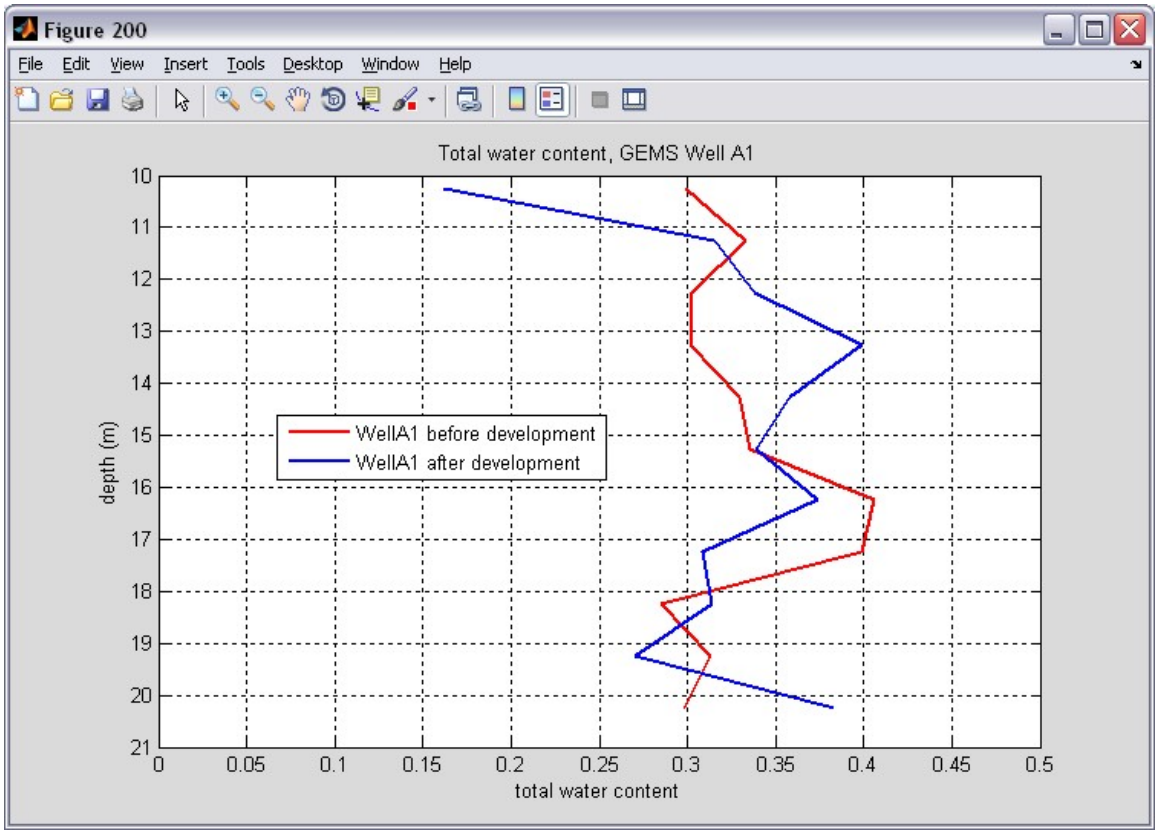


Figure 200
File Edit View Insert Tools Desktop Window Help
Total water content, GEMS Well A1
depth (m)
total water content
WellA1 before development
WellA1 after development
10
11
12
13
14
15
16
17
18
19
20
21
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5