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Äspö Hard Rock Laboratory

TRUE Block Scale project

Tracer dilution tests during pumping in borehole KI0023B and short-term interference tests in KI0025F02 and KA3510A

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December 1999

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Abstract

This report describes a pressure interference test combined with tracer dilution tests in three selected sections of borehole KI0025F02 and a series of short-term interference tests in the same borehole and in borehole KA3510A. The general objective of the tests is to provide information regarding the connectivity in the borehole array and to verify that the configurations of the installed multi-packer systems are optimal. A specific objective is to demonstrate the feasibility of performing tracer tests within specific test intervals in the new and existing boreholes and to provide data of natural flow and local hydraulic gradients in KI0025F02. The results of the tests generally confirmed the March 99 structural model. This structural model was used instead of the September 98 model due to the late preparation of this report. The tests also showed that it is feasible to perform tracer tests over distances of about 20-35 m in the TRUE Block Scale area.

Sammanfattning

Denna rapport beskriver ett tryckinterferenstest kombinerat med en utspädningsmätning i tre utvalda sektioner av borrhål KI0025F02. Även en serie korta interferenstester i samma borrhål och i borrhål KA3510A beskrivs. Det övergripande syftet med testerna är att skaffa information gällande förbindelsen mellan borrhålen och att verifiera att konfigurationen av det installerade multimanschettsystemet är optimal. Ett specifikt syfte är att demonstrera genomförbarheten av spårämnesförsök inom specifika testintervall i det nya och existerande borrhålen och att ta fram data gällande naturligt flöde och lokala hydrauliska gradienter i KI0025F02. Resultatet av testerna bekräftade generellt strukturmodell Mars ’99. Denna strukturmodell användes istället för modell September ’98 beroende på den sena tidpunkten för skrivandet av denna rapport. Försöken visade också att det är genomförbart att utföra spårämnestester över avstånd på 20-35 m i TRUE Block Scale-området.

Executive Summary

Based on the updated structural model (September 98) of the TRUE Block Scale area and the identified target area for further investigations, an additional borehole, KI0025F02, has been completed, which is located in the ”I-tunnel” at 3500 m tunnel length. Borehole KI0025F02 has been characterised with acoustic flow logging (UCM), borehole radar (Carlsten, 1999), borehole TV (BIPS), POSIVA flow logging (Rouhiainen & Heikkinen, 1998), and hydraulic flow and pressure build-up tests (Adams et al., in prep.). Two interference tests with simultaneous flow measurements with the dilution method were also performed in conjunction with the flow and pressure build-up tests. Based on these measurements a multi-packer system was installed in the borehole (Adams, 1998).

This report includes the results of tracer dilution tests in three selected sections in KI0025F02 (sections P3, P5 and P8) conducted in conjunction with pumping in a selected interval within borehole KI0023B (section P6) in October 1998). Included also are ten short-term interference tests in selected sections of boreholes KI0025F02 and KA3510A.

During the preparation of this report, a further update of the structural model has been done based on the geological interpretation and POSIVA flow log of borehole KI0025F02. This model, the March 99 structural model (Hermanson, in prep.), has been used as a basis for the interpretations in this report.

The general objective of the interference test in KFI0023B:P6 with simultaneous dilution measurements is to provide information regarding the connectivity between the pumped section and three selected sections within KI0025F02. Cross-hole responses in KI0025F02 and KA3510A during the pumping in KI0023B:P6 and the short-term interference tests are of particular interest to verify that the configurations of the installed multi-packer systems are optimal. The specific objectives of the tracer dilution tests are to demonstrate the feasibility of performing tracer tests within specific test intervals in the new and existing boreholes and to provide data of natural flow and local hydraulic gradients in KI0025F02. The reciprocity of flow response in the earlier tested flow path KI0025F02: P5→KI0023B:P6 will also be tested with the aim of optimising future tracer test geometry.

The evaluation of the tracer dilution tests showed that Structure #21 in KI0023B is well connected to sections KI0025F02:P3, P5 and P8. Thus, it is possible to use these flow paths in future tracer tests. A comparison with the tracer dilution tests performed during pumping in KI0025F02:P5 (Adams et al., in prep.) shows a better flow response when KI0023B:P6 is pumped (with approximately the same drawdown). The flow increases with a factor 7 (from 5 to 35 ml/h) compared to a factor of 4 in the opposite direction (from 3 to 11 ml/h).

The evaluation of the cross-hole responses during pumping in KI0023B:P6 (structure #21) shows that the pressure responses in KI0025F02 are significant in sections P5 (#20), P8 (#6), P6 (#22) and P7 (unknown structure) whereas section P3 (#13, 21) gives a weaker and delayed response.

The results of the short-term tests in KI0025F02 generally confirms the structural model (March 99). The only deviation is that section KI0025F:R5 does not seem to be connected to structure #6. The tests also indicate that the multi-packer system in KI0025F02 is well configured. The short-term test in KA3510A confirms the extension of structure #15 to the east. The responses in structures #5, #6 and #7 indicate that structure #15 is connected to this system.

Contents

1 Introduction

During 1996 characterisation work for the TRUE Block Scale Project started at Äspö HRL with drilling of borehole KA2563A from the spiral tunnel. Characterisation data from this borehole and data from boreholes KA2511A, KA3510A, KI0025F, and KI0023B have been used to update the structural model of the south-western part of the Äspö HRL (Hermanson, 1998). Based on this updated model and the identified target area for further investigations, an additional borehole, KI0025F02, has been completed, which is located in the ”I-tunnel” at 3500 m tunnel length.

Borehole KI0025F02 has been characterised with acoustic flow logging (UCM), borehole radar (Carlsten, 1999), borehole TV (BIPS), POSIVA flow logging (Rouhiainen & Heikkinen, 1998), and hydraulic flow and pressure build-up tests (Adams et al., 1999). Two interference tests with simultaneous flow measurements with the dilution method were also performed in conjunction with the flow and pressure build-up tests. Based on these measurements a multi-packer system was installed in the borehole (Adams, 1998).

This report includes the results of tracer dilution tests in three selected sections in KI0025F02 (sections P3, P5 and P8) conducted in conjunction with pumping in a selected interval within borehole KI0023B (section P6). Included also are ten short-term interference tests in selected sections of boreholes KI0025F02 and KA3510A.

The selection of pumping section and sections for tracer dilution measurements were based on the preliminary interpretation of the data obtained from the borehole at the time of onset of the tests (October 1998). In particular, the cross-hole responses obtained during Phase III of the flow and pressure build-up tests in KI0025F02 (Adams et al., 1999) were used to select test sections.

Parallel to the preparation of this report, a further update of the structural model has been done based on the geological interpretation and POSIVA flow log of borehole KI0025F02. This model, the March 99 structural model (Hermanson, in prep.), has been used as a basis for the interpretations in this report. The model and the boreholes involved are presented in Figure 1-1.

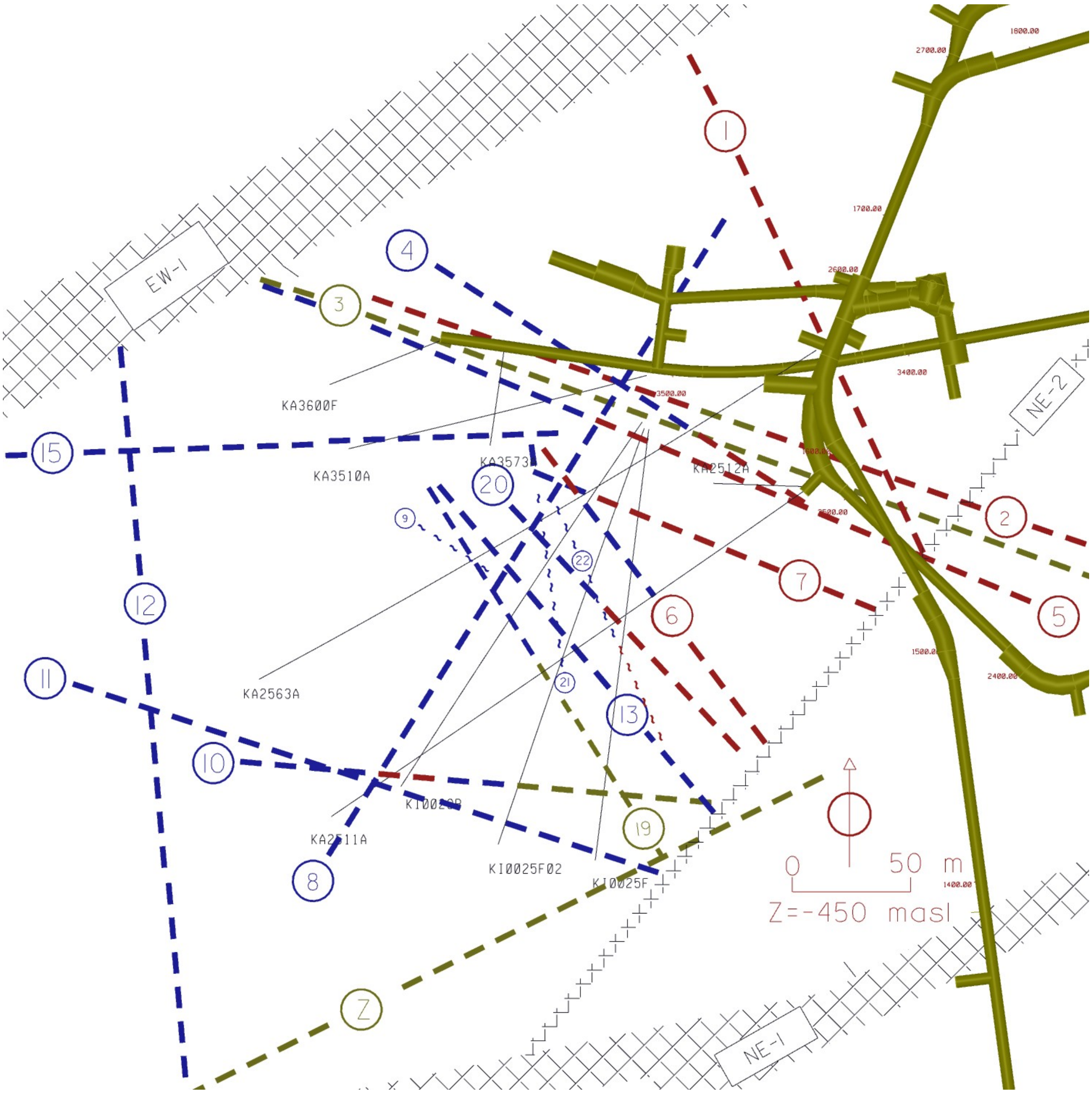

Figure 1-1. *March 99 structural model of the TRUE Block Scale area.*
From Hermanson, (in prep.)

2 Objectives

The general objective of the interference test in KFI0023B:P6 with simultaneous dilution measurements is to provide information regarding the connectivity between the pumped section and three selected sections in KI0025F02. Cross-hole responses in KI0025F02 and KA3510A during the pumping and during the short-term interference tests are of particular interest to verify that the configurations of the installed multi-packer systems are optimal.

The specific objectives of the tracer dilution tests are to demonstrate the feasibility of performing tracer tests within specific test intervals in the new and existing boreholes and to provide data of natural flow and local hydraulic gradients in KI0025F02. The reciprocity of flow response in the earlier tested flow path KI0025F02:P5→KI0023B:P6 will also be checked with the aim of optimising future tracer test geometry.

3 Experimental set-up

3.1 Equipment used

The five boreholes drilled for the TRUE Block Scale Project, KA2511A, KA2563A, KI0023B, KI0025F and KI0025F02 are instrumented with 6-10 inflatable packers such that 5-10 borehole sections are isolated. Each borehole section is connected to a pressure transducer which is connected the Äspö HRL Hydro Monitoring System (HMS). Each of the sections used for tracer dilution tests is equipped with three nylon hoses, two with an inner diameter of 4 mm and one with an inner diameter of 2 mm. The two 4 mm hoses are used for injection, sampling and circulation in the borehole section whereas the 2 mm hose is used for pressure monitoring. The section limits are given in Figure 4-6.

Three additional boreholes located in the main tunnel (KA3548A, KA3573A and KA3600F) were also supplied with pressure transducers and field data loggers.

The tracer dilution tests were performed using three identical equipment set-ups for tracer tests, i.e. allowing three sections to be measured simultaneously. A schematic drawing of the tracer test equipment is shown in Figure 3-1. The basic idea is to have an internal circulation of the borehole section. The circulation makes it possible to obtain a homogeneous tracer concentration in the borehole section and to sample the tracer concentration outside the borehole in order to monitor the injection rate of the tracer with time and the dilution rate.

Circulation is controlled by a pump with variable speed (A) and measured by a flow meter (B). Water and tracer injections are made with two different HPLC plunger pumps (C1 and C2)) and sampling is made by continuously extracting a small volume of water from the system through a flow controller (constant leak) to a fractional sampler (D). The tracer test equipment has earlier been used in the TRUE-1 tracer tests (Andersson, 1996). The tracer used for the dilution tests was the well-known fluorescent dye Uranine (Sodium Fluorescein).

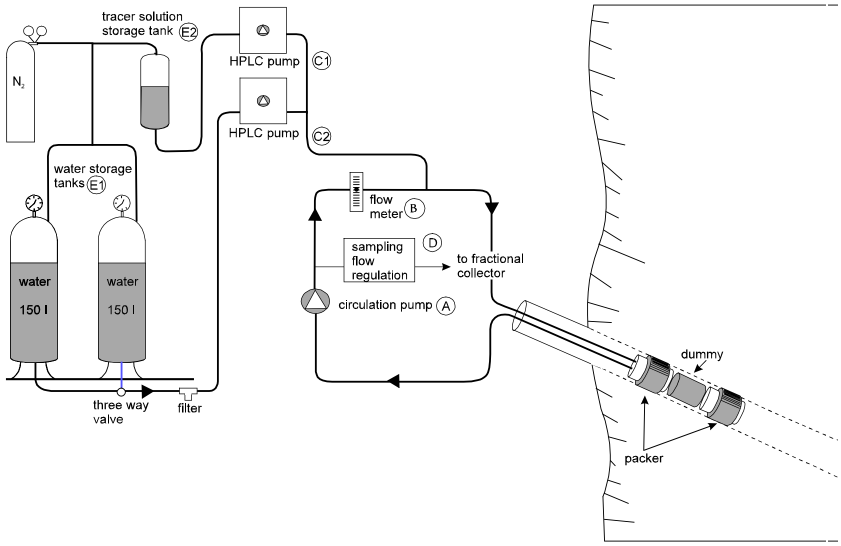

Figure 3-1. *Schematic drawing of the tracer injection/sampling system used in the TRUE Project.*

3.2 Performance of the interference tests and tracer dilution tests

The flow rates in the selected sections were determined by tracer dilution tests in three selected borehole sections during pumping in borehole section KI0023B:P6. The dilution test were performed both under natural gradient (before start of pumping) and under stressed conditions (pumping in KI0023B:P6). Thus, it was possible to simultaneously account both for flow and pressure changes due to the pumping.

The three sections used for tracer dilution tests are listed in Table 3-1. The pumping was performed in section KI0023B:P6 which is interpreted to be associated with structure #21 according to the March´99 structural model (Hermanson, in prep.). The pumping was done by opening the flow lines completely to atmosphere. This means a semi-constant head situation in the test section, due to the change in pressure caused by the frictional losses in the tubing. The test schedule is presented in Table 3-1.

Table 3-1. Test schedule and sections used for the dilution tests performed during pumping of borehole section KI0023B:P6.

Date	Activity	Borehole section(s)
981027	Preparation for dilution tests	KI0025F02:P3, P5, P8
981028	Start dilution tests, no pumping	KI0025F02:P3, P5, P8
981029	Start pumping interference test, Q=2.8 l/min	KI0023B:P6
981030	Stop pumping, demobilisation	

The boreholes used for pumping and monitoring of pressure responses in the interference test are listed in Table 3-2 together with the respective system used for pressure monitoring (HMS system or field logger)

Table 3-2. Boreholes used for pressure registration

Borehole	Monitoring System
KA1751A,	HMS
KA2162B,	HMS
KA2511A,	HMS
KA2563A,	HMS
KA3385A,	HMS
KA3510A,	HMS
KI0023B,	HMS
KI0025F,	HMS
KI0025F02,	HMS
KA3548A,	Field logger
KA3573A,	Field logger
KA3600F,	Field logger

The logging frequency of the HMS system was manually set before start of pumping phase and recovery phase. The logging frequency was set to enable transient evaluation of pressure data according to the following schedule (Table 3-3).

Table 3-3. Logging frequency used during the interference test.

Time (from-to) (min)	Logging frequency (s)
-1 – 10	1
10 – 120	60
120 -	600

The schedule in Table 3-3 refers to the minimum time intervals before changing to a longer logging frequency. Thus, logging with i.e. 1 second intervals may continue longer than 10 minutes but not shorter.

Boreholes KA1751A and KA2162B were both monitored through a hydraulic multiplexer which enables a maximum logging frequency of 5 and 10 minutes, respectively. Field loggers were set to sequential measurement according to the HMS manual (SKB MD 365.021-01).

In addition to the pumping in KI0023B:P6 a number of short-term interference tests were performed by sequential opening of 10 selected borehole sections in KI0025F02 and KA3510A. The tests were performed by opening the flow lines, connected to each section, completely for a period of about 30 minutes. The flow was monitored after 1, 5, 10, 20 and 30 minutes of pumping. A water sample (1 litre) was taken just before closing the sections for subsequent analysis of electrical conductivity (to be used for calculation of hydraulic head). After shut-in, the pressure build-up was monitored for a period of at least 90 minutes. A summary of the pumping in KI0023B:P6 and the short-term interference tests is shown in Table 3-4.

Table 3-4. Summary of performed pumping in KI0023B:P6 and the short-term interference tests during TRUE Block Scale Preliminary Characterisation Stage. Section limits are given in Figure 4-6.

Test #	Sink section	Q_p* (l/min)	s_p ** (m)	Q_p/s_p (m^2/s)	Flow period (min)	Structure in March 99 model
23B:P6	KI0023B:P6	2.9	233	$2.1\cdot10^{-7}$	1440	#21
25F2P1	KI0025F02:P1	2.07	51.5	$6.7\cdot10^{-7}$	36	#10
25F2P2	KI0025F02:P2	1.80	185	$1.6\cdot10^{-7}$	35	#19
25F2P3	KI0025F02:P3	0.90	351	$4.3\cdot10^{-8}$	34	#13, 21
25F2P5	KI0025F02:P5	2.72	34.2	$1.3\cdot10^{-6}$	37	#20
25F2P6	KI0025F02:P6	2.47	131	$3.1\cdot10^{-7}$	34	#22
25F2P7	KI0025F02:P7	0.157	412	$6.4\cdot10^{-9}$	36	#?
25F2P8	KI0025F02:P8	0.317	406	$1.3\cdot10^{-8}$	36	#6
25F2P9	KI0025F02:P9	3.84	13.4	$4.8\cdot10^{-6}$	37	#7
25F2P10	KI0025F02:P10	1.26	359	$5.8\cdot10^{-8}$	37	#5
3510P2	KA3510A:P2	2.19	4.9	$7.4\cdot10^{-6}$	34	#15

* Flow rate at the end of flowing period
** Drawdown at the end of flowing period

4 Results and interpretation

4.1 Tracer dilution tests

The dilution of tracer with time in the injection sections was determined by analysing the samples withdrawn from the sections. Flow rates were calculated from the decay of tracer concentration versus time caused by dilution with natural unlabelled groundwater, c.f. Winberg (ed), (1996). The so-called "dilution curves" were plotted as the natural logarithm of tracer concentration versus time. Theoretically, a straight-line relationship exists between the natural logarithm of the relative tracer concentration (c/c_0) and time (t):

$$Q_{bh} = -V \cdot \Delta \ln (c/c_0) / \Delta t$$

where Q_{bh} (m^3/s) is the groundwater flow rate through the borehole section and V is the volume of the borehole section (m^3).

The tracer dilution tests were performed between October 28th to October 30th 1998 in three selected sections within borehole KI0025F02 (sections P3, P5 and P8). The measurements were done both during “undisturbed” pressure conditions and during pumping in borehole section KI0023B:P6. The pumping was performed by opening the flow lines completely to the atmosphere. The flow rate was 2900 ml/min at the start (after one minute) and decreased gradually to 2650 ml/min just before the pumping was stopped after 24 hours (Figure 4-1).

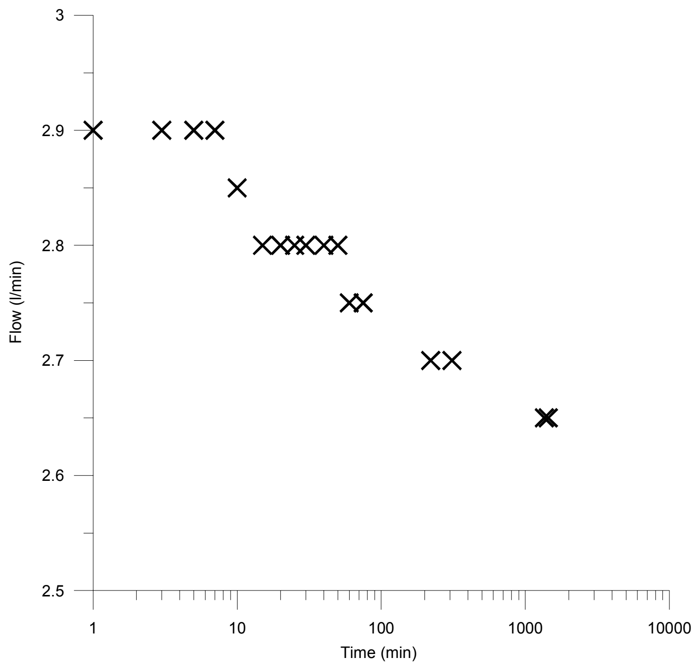

Figure 4-1. *Flow versus time (log) during pumping in section KI0023B:P6.*

All three borehole sections show a very significant influence of the pumping on the flow through the test sections. Borehole section KI0025F02:P3 shows an increase in flow from about 14 ml/h to 94 ml/h, i.e. a factor of 7, cf. Figure 4-2. The flow in section P5 increased from about 5 ml/h to 35 ml/h, i.e. also a factor of 7, due to the pumping in borehole section KI0023B:P6 (Figure 4-3). The measurement in section P5 was somewhat disturbed by malfunctions in the equipment for sample withdrawal. The malfunctions have resulted in very small or even zero volumes of sample in some of the test tubes. However, enough samples were collected for a reliable interpretation to be done and a clear effect on the flow due to the pumping can be seen.

Borehole section KI0025F02:P8 (Figure 4-4) responded somewhat different from the other sections to the pumping with a decrease in flow from about 30 ml/h to 3.5 ml/h, i.e. a factor of 9. This suggests that the direction of the hydraulic gradient has been reversed, or at least significantly altered. All results are summarised in Table 4-1.

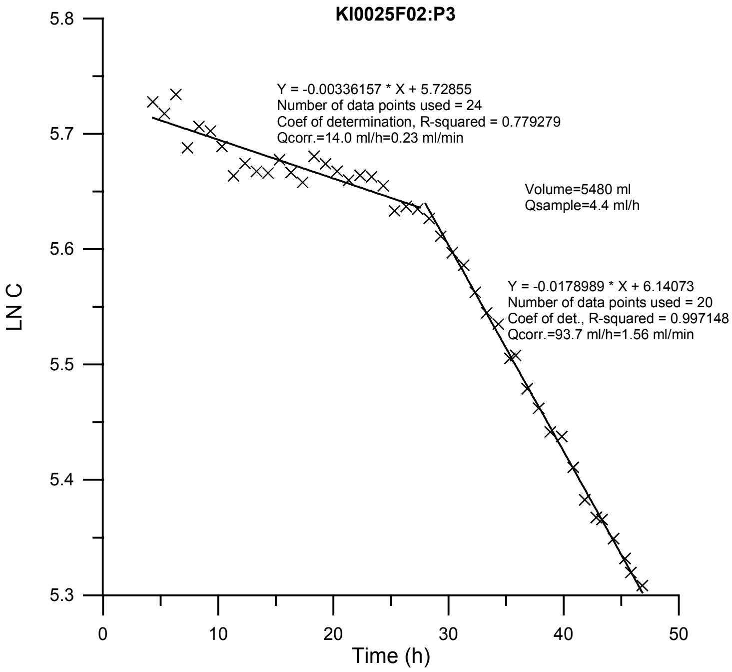

Figure 4-2. *Tracer dilution curve including straight-line fit for borehole section KI0025F02:P3 before and during pumping in borehole section KI0023B:P6.*

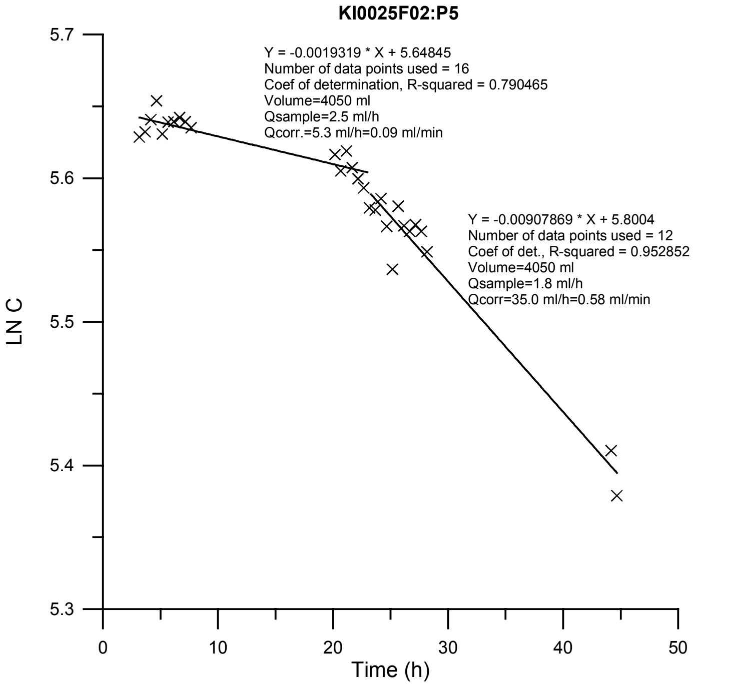

Figure 4-3. *Tracer dilution curve including straight-line fit for borehole section KI0025F02:P5 before and during pumping in borehole section KI0023B:P6.*

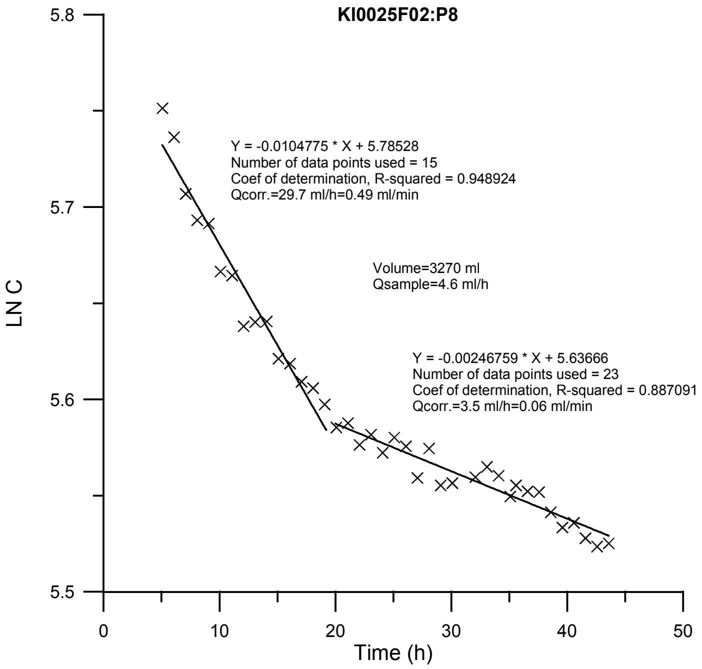

Figure 4-4. *Tracer dilution curve including straight-line fit for borehole section KI0025F02:P8 before and during pumping in borehole section KI0023B:P6.*

Table 4-1. Summary of flow measurements using the tracer dilution method before and during pumping of KI0023B:P6. Structures refer to the March 99 structural model Hermanson (in prep.).

Borehole section	Structure #	Flow at natural conditions (ml/h)	Flow at pumped conditions (ml/h)
KI0025F02:P3	13, 21	14	98
KI0025F02:P5	20	5.3	35
KI0025F02:P8	6	30	3.5

4.2 Interference test responses from KI0023B:P6

4.2.1 Qualitative evaluation

The hydraulic responses have been evaluated in different steps at which parts of the data has been sorted out for further (quantitative) evaluation. This test is a repetition of a test performed in April 1998, ESV-1c (Andersson et al., 1998) which already has been quantitatively evaluated with the exception of responses in borehole KI0025F02.

Firstly, time-drawdown- and time-recovery plots were prepared for sections showing a drawdown (or recovery) of more than s_p=0.1 m (1 kPa) by the end of the tests. This threshold value was selected with consideration of the amplitude of the tidal effects which are in the order of 1 kPa. These types of plots were used to estimate the response times (t_R) for each section. The response time is here defined as the time after start of pumping when a drawdown (or recovery) of 1 kPa (0.1 m) is observed **(**in the logarithmic plots**)** for the actual observation section. The qualitative evaluation was made on the drawdown phase. Data from the recovery phase were used as supporting data.

To account for the different flow rates used in the tests and to make the response plots comparable between tests, the final drawdown by stop of pumping (s_p) is normalised with respect to the flow rate (Q). The ratio s_p/Q is plotted on the Y-axis. On the X-axis, the ratio of the response time and the squared straight-line distance R in space between the (midpoint of the) source section and (the midpoint of) each observation section (t_R/R^2) is plotted. The latter ratio is inversely related to the hydraulic diffusivity of the rock, which indicates the speed of propagation in the rock of the drawdown created in the pumping section.

From the response plots of s_p/Q versus t_R/R^2 for each test, sections with anomalous fast response times (high hydraulic diffusivity) and large (normalised) drawdowns can be identified. Such sections showing primary responses can be assumed to have a distinct hydraulic connection to the pumping section and may be intersected by fracture zones or other conductive structures in the rock. On the other hand, sections with delayed and weak responses may correspond to sections in the rock mass between such structures.

The response diagram for the test in KI0023B:P6, presented in Figure 4-5, shows that pressure responses are monitored in 14 sections of the TRUE Block Scale array. The response in section KA2563A:R1 was later found to be uncertain and is therefore omitted in the response diagram. Very good responses were found in all sections intersected by structure #20 while somewhat slower responses were found in sections intersected by structures #6, #22 and #13.

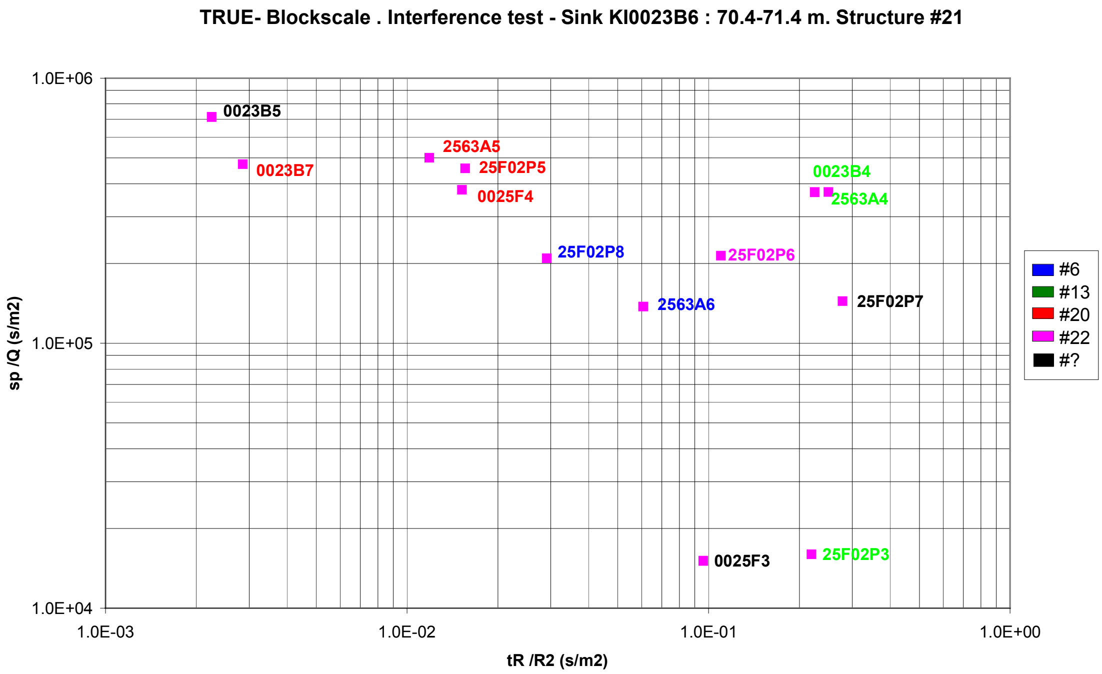

Figure 4-5. *Diagnostic plot for determination of the most significant responses during the interference test in KI0023B:P6. Red labels represent structure #20, green labels structure #13, blue labels structure #6, and lilac labels structure #22. Sections with black labels represent structures of unknown extent.*

From the calculated values of s_p/Q (index 1) and t_R/R^2 (index 2) for each observation section during each test a response matrix, showing the response patterns for all tests, was prepared by classifying the responses by means of the above index 1 and -2. For index 1 the following class limits and drawdown characteristics were used:

Index 1 (s_p/Q) (coded by colour in Figure 4-6)

$s_p/Q > 1\cdot10^5$ s/m^2	Excellent
$3\cdot10^4 < s_p/Q \leq 1\cdot10^5$ s /m^2	High
$1\cdot10^4 < s_p/Q \leq 3\cdot10^4$ s /m^2	Medium
$s_p/Q \leq 1\cdot10^4$ s /m^2	Low

For index 2 the following class limits and response characteristics were used:

Index 2 (t_R/R^2) (coded by letter notation in Figure 4-6)

$t_R/R^2 < 0.01$ s/m^2	Excellent (E)
$0.01 \le t_R/R^2 < 0.1$ s/m^2	Good (G)
$0.1 \le t_R/R^2 < 0.3$ s/m^2	Medium (M)
$t_R/R^2 \ge 0.3$ s/m^2	Bad (B)

The results from the qualitative analysis were compared with the structural (March´99) model and checked for consistency and possible need of revision. It should be pointed out that the response diagrams of s_p/Q versus t_R/R^2 described above were only used as a diagnostic tool to identify the most significant responses during each test and to construct the response matrix. The diagrams should be used with some care since the true distances (along pathways in the fracture network) between the source and observation sections are uncertain which may affect the position of a certain section in the x-wise direction in the diagrams. However, in most cases, the shortest distance between the sink and observation section, as used here, is considered as a sufficiently robust approximation for the above purpose.

Another potential source of error in the response diagrams may occur if (internal) hydraulic interaction exists between sections along a borehole. For example, such interaction could either be due to packer leakage (insufficient packer sealing) or leakage through interconnecting fractures around the packers. This fact may give a false impression that good hydraulic communication exists between such observation sections and the actual source section. However, any analysis method will suffer from this potential source of error.

The response matrix, presented in Figure 4-6, is almost identical to that produced from the ESV-1c test (Andersson et al., 1998). The only difference is that the sink is stronger (Q_p= 2.6 l/min compared to Q_p= 1.0 l/min during ESV-1c) gives somewhat shorter response times, $t_{R.}$. Four sections in the new borehole, KI0025F02, respond significantly during the test in KI0023B:P6. These sections are associated with structures 6, 20 and 22. The response in KI0025F02:P3 is somewhat weaker although this section is interpreted to include structure #21, i.e. the pumped structure. The straight-line distances from the receiver sections to the sink for the interference test in KI0023B:P6 are given in Appendix 3.

	Structure #	#20	#20	#21	#21	
Borehole	**Interval (m)**	ESV-1a	ESV-1b	ESV-1c	23B:P6	Structural model March 99
KA2563A:R1	262-363	E	E	E	E	#9, 10
KA2563A:R2	225-228					#19
KA2563A:R3	220-225					?
KA2563A:R4	191-219	B	M	B	M	#13
KA2563A:R5	187-190	S	G	G	G	#20
KA2563A:R6	146-186	G	G	G	G	#6, 7
KA2563A:R7	75-145					#4, 5, 17
KI0025F:R1	169-194					Z
KI0025F:R2	164-168					#19
KI0025F:R3	89-163	G	E	M	G	?
KI0025F:R4	86-88	G	S	G	G	#20
KI0025F:R5	41-85					#6, 7
KI0025F:R6	3.5-40					#5
KI0023B:P1	113.7-200.7					#10
KI0023B:P2	111.25-112.7					#19
KI0023B:P3	87.2-110.25					?
KI0023B:P4	84.75-86.20	M	B	B	M	#13
KI0023B:P5	72.95-83.75	G	G	G	E	?
KI0023B:P6	70.95-71.95	G	G	S	S	#21
KI0023B:P7	43.45-69.95	G	G	G	E	#6, 20
KI0023B:P8	41.45-42.45					#7
KI0023B:P9	4.6-40.45					#5
KI0025F02:P1	135.15-204	NR	NR	NR		?
KI0025F02:P2	100.25-134.15	NR	NR	NR		#19
KI0025F02:P3	93.40-99.25	NR	NR	NR	M	#13, 21
KI0025F02:P4	78.25-92.4	NR	NR	NR		?
KI0025F02:P5	73.3-77.25	NR	NR	NR	G	#20
KI0025F02:P6	64.0-72.3	NR	NR	NR	M	#22
KI0025F02:P7	56.1-63.0	NR	NR	NR	M	?
KI0025F02:P8	51.7-55.1	NR	NR	NR	G	#6
KI0025F02:P9	38.5-50.7	NR	NR	NR		#7
KI0025F02:P10	3.4-37.5	NR	NR	NR		#5
KA3510A:P1	122.02-150		NR			?
KA3510A:P2	114.02-121.02	NR	NR	NR		#15
KA3510A:P3	4.52-113.02	NR	NR	NR		#3,4,5,6,8
KA3573A:P1	18-40		NR			#15
KA3573A:P2	4.5-17		NR			#5
KA3600F:P1	22-50.1		NR			#15?
KA3600F:P2	4.5-21		NR			#5 #7?
KA3548A:P1	15-30	NR	NR	NR		
KA3548A:P2	10-14	NR	NR	NR		

INDEX 1=sp/Q
EXCELLENT
HIGH
MEDIUM
LOW
NO RESPONSE

INDEX 2=tr/R2
E=EXCELLENT
G=GOOD
M=MEDIUM
B=BAD

S=SOURCE
NR=No registration

Figure 4-6. *Pressure response matrix for interference test in KI0023B:P6 including a comparison with the corresponding matrices for tests ESV-1a –c (Andersson et al., 1998).*

4.2.2 Quantitative evaluation

The main purpose of the quantitative interpretation of the interference tests performed in this study is to estimate the hydraulic parameters and the hydraulic characteristics of the most significant responses as identified from the qualitative interpretation. The estimated hydraulic parameters represent the hydraulic properties of some of the structures tested. In addition, time-drawdown analysis may also provide some (soft) information on the flow geometry during the test, including effects of outer hydraulic boundaries. The quantitative evaluation also involved plotting of the most significant responses in a drawdown versus time/distance squared (t/R^2)-diagram. The transmissivity and storativity of the limiting Theis' curve was estimated using Theis' model.

The quantitative evaluation was made using the software AquiferTest (Waterloo Hydrologic). As a standard interpretation model for the time-drawdown analysis, the Hantush model for constant flow rate tests in a leaky (or non-leaky) aquifer with no aquitard storage was used. This model was used because of its generality and its ability to analyse pure radial flow (Theis' type curve) as well as leaky (pseudo-spherical) flow. The type curve for r/L=0 in the Hantush' model (no leakage) corresponds to the classical Theis' type curve for pure radial flow. In addition, tests showing periods with (pseudo-) radial flow were analysed using Cooper-Jacob's method in semi-logarithmic graphs. In the analysis of constant head tests, a varying (declining) flow rate was applied at the sink.

The time derivative of drawdown was used as a diagnostic tool in the interpretation of the flow geometry and identification of hydraulic boundaries in the time-drawdown analysis. The derivative was generated by the SKB-code PUMPKONV and plotted together with the drawdown curves versus time.

The observation sections with most significant pressure responses during the interference test in KI0023B:P6 are shown in a drawdown versus time/distance squared (t/R^2)-diagram in Appendix 1. In a homogenous and isotropic medium all response curves should merge to a common curve. The figure clearly shows that the tested rock is heterogeneous. In particular, the responses in sections KI0025F:R3 and KI0025F02:P3 are diverging. The estimated transmissivity and storativity corresponding to the limiting (fast-responding) Theis´-curve are indicated in the figure.

Time-drawdown evaluation was only made for the responding sections of the new borehole KI0025F02 together with the sink section (Table 4-2). In this table, the transmissivity (T), storativity (S), the hydraulic diffusivity (T/S) and the leakage coefficient (K'/b') are estimated. In addition, the dominating flow geometry during the test and (apparent) hydraulic boundaries are deduced. The time-drawdown curves (including the drawdown derivative) at the sink as well as in the receiver sections indicate a dominating leaky (pseudo-spherical) flow approaching a constant-head boundary.

The estimated values on the hydraulic parameters represent parameters of an equivalent fractured porous medium. Accordingly, the interpretations of flow geometry and hydraulic boundaries also represent such a medium.

It should be observed that the results from receiver sections with small drawdowns, e.g sections located at a long distance from the sink section or, alternatively , sections with decreased hydraulic connection to the sink section, are associated with uncertainty. In particular, the transmissivity may be over-estimated in such cases. Uncertain results due to any of the above reasons are marked with an asterix in Table 4-2.

Table 4-2. Results of quantitative evaluation of responding sections in KI0025F02 together with the sink during the interference test in KI0023B:P6. S=Sink, Leaky=pseudospherical, CHB=Apparent Constant head boundary,

Borehole Section	Structure #	T (m^2/s)	Storativity (-)	T/S (m^2/s)	K'/b' (s^{-1})	Dom. Flow Geometry
KI0023B:P6 (S)	21	$1.3 \cdot 10^{-6}$	-	-	-	Leaky→CHB
KI0025F02:P3	13, 21	$1.3 \cdot 10^{-5}$ *	$4.9 \cdot 10^{-6}$ *	2.6 *	$2.1 \cdot 10^{-10}$ *	Leaky→CHB
KI0025F02:P5	20	$7.9 \cdot 10^{-7}$	$2.6 \cdot 10^{-7}$	3.1	$2.4 \cdot 10^{-10}$	Leaky→CHB
KI0025F02:P6	22	$1.3 \cdot 10^{-6}$	$1.1 \cdot 10^{-6}$	1.2	$1.8 \cdot 10^{-10}$	Leaky→CHB
KI0025F02:P7	?	$1.4 \cdot 10^{-6}$ *	$4.3 \cdot 10^{-6}$ *	0.32 *	$4.1 \cdot 10^{-10}$ *	Leaky→CHB
KI0025F02:P8	6	$1.2 \cdot 10^{-6}$	$5.3 \cdot 10^{-7}$	2.3	$1.5 \cdot 10^{-10}$	Leaky→CHB

* = uncertain value, see discussion above.

4.3 Short-term interference tests

Only a qualitative evaluation was made of the short-term interference tests. The response diagrams are shown in Appendix 2. The pressure response matrix for these tests is shown in Figure 4-7. The responses in section KA2563A:R1 are uncertain and have been omitted, both in the response diagrams and in the response matrix. Figure 4-7 shows that the test responses generally are consistent with the March´99 structural model (Hermanson, in prep.). However, the tests in KI0025F02:P8 and :P9 may indicate that section KI0025F:R5 is located in #7 rather than in #6. The straight-line distances from the receiver sections to the sink for the short-term interference tests are shown in Appendix 3.

Borehole	Interval (m)	25F2P1	25F2P2	25F2P3	25F2P5	25F2P6	25F2P7	25F2P8	25F2P9	25F2P10	3510P2	Structural model March 99
	Structure #	#?	#19	#13	#20	#22	#?	#6	#7	#5	#15	
KA2511A:S1	242-244											#18
KA2511A:S2	217-241	G										#10
KA2511A:S3	110-216											#17,19,20
KA2511A:S4	92-109											#6,16
KA2511A:S5	52-54								E			#7
KA2563A:R1	262-363	u	n	c	e	r	t	a	i	n		#9, 10
KA2563A:R2	225-228		B		M	B						#19
KA2563A:R3	220-224				M	M						?
KA2563A:R4	191-219			B	M	M		B				#13
KA2563A:R5	187-190			M	E	G	B	G	B			#20
KA2563A:R6	146-186				G	G	B	B	M			#6, 7
KA2563A:R7	75-145								M			#4, 5, 17
KI0025F:R1	169-194		M									Z
KI0025F:R2	164-168		G									#19
KI0025F:R3	89-163		B		G	M						?
KI0025F:R4	86-88			B	G	G	B	M	B			#20
KI0025F:R5	41-85				B				E	B	G	#6, 7
KI0025F:R6	3.5-40								B	B	G	#5
KI0023B:P1	113.7-200.7	G										#10
KI0023B:P2	111.25-112.7		G									#19
KI0023B:P3	87.2-110.25		G		G	G						?
KI0023B:P4	84.75-86.20			B	M	M		B				#13
KI0023B:P5	72.95-83.75			B	G	M	B	M	B			?
KI0023B:P6	70.95-71.95			B	G	M	B	M	B			#21
KI0023B:P7	43.45-69.95			M	E	G	B	G	B			#6, 20
KI0023B:P8	41.45-42.45				B	B			E	B	G	#7
KI0023B:P9	4.6-40.45								B	G	M	#5
KI0025F02:P1	135.15-204.0	S										?
KI0025F02:P2	100.25-134.15		S									#19
KI0025F02:P3	93.40-99.25			S	B	M						#13, 21
KI0025F02:P4	78.25-92.40				B	B						?
KI0025F02:P5	73.3-77.25			B	S	M	B	M	B			#20
KI0025F02:P6	64.0-72.3			B	M	S	B	B	B			#22
KI0025F02:P7	56.1-63.0			B	B	G	S	B	B			?
KI0025F02:P8	51.7-55.1			B	G	B	B	S	B		M	#6
KI0025F02:P9	38.5-50.7				B	B			S	B	G	#7
KI0025F02:P1(	3.4-37.5								B	S	M	#5
KA3510A:P1	122.02-150											tight
KA3510A:P2	114.02-121.02								G	G	S	#15
KA3510A:P3	4.52-113.02								B	E		#3,4,5,6,8
KA3573A:P1	18-40								G	G	B	#15
KA3573A:P2	4.5-17								M	G		#5
KA3600F:P1	22-50.1								G		B	#15?
KA3600F:P2	4.5-21								E	M		#5 #7?
KA3548A:P1	15-30								B	G		#5
KA3548A:P2	10-14								M	G		#5

INDEX 1=sp/Q
- EXCELLENT
- HIGH
- MEDIUM
- LOW
- NO RESPONSE

INDEX 2=tr/R2
- E=EXCELLENT
- G=GOOD
- M=MEDIUM
- B=BAD

S=SOURCE
NR=No registration

Figure 4-7. *Pressure response matrix for the short-term interference tests in KI0025F02.*

5 Conclusions

The following conclusions can be drawn from the tests described in this report:

- Structure #21 in KI0023B is well connected to sections KI0025F02:P3, :P5 and :P8 based on the tracer dilution responses. Thus, it is possible to use these injection sections and associated flow paths in future tracer tests.

- A comparison with the reversed tracer dilution tests performed during pumping in KI0025F02:P5 (Adams et al., 1999) shows a better flow response when KI0023B:P6 is pumped (with approximately the same drawdown). The flow increases with a factor 7 (from 5 to 35 ml/h) compared to a factor of 4 in the reversed direction (from 3 to 11 ml/h).

- The pressure responses in KI0025F02 during pumping in KI0023B:P6 (#21) are good in sections P5 (#20), P8 (#6), P6 (#22) and P7 (unknown structure) whereas section P3 (#13, 21) shows a weaker and delayed response. The latter was not expected based on the structural interpretation and the tracer dilution response reported above.

- The short-term pressure interference tests in KI0025F02 generally confirm the structural model (March 99). The only deviation is that section KI0025F:R5 does not seem to be connected to structure #6.

- The results of the pumping test in KI0023B:P6 and the short-term interference tests in KI0025F02 indicate that the multi-packer system in KI0025F02 is well configured in relation to the structural model.

- The short-term test in KA3510A confirms the extension of structure #15 to the east as far as presented in the March´99 structural model (Figure 1-1). The responses in structures #5, #6 and #7 indicate that structure #15 is connected to this system.

6 References

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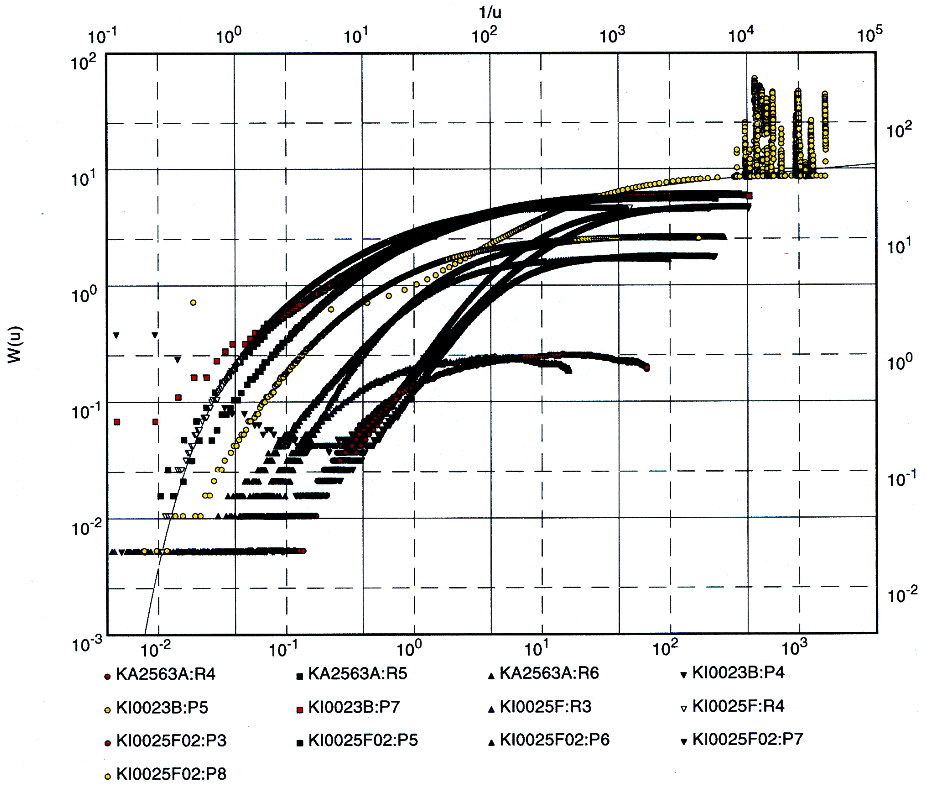
Winberg A (ed), 1996: First TRUE Stage - Tracer Retention Understanding Experiments. Descriptive structural-hydraulic models on block and detailed scales of the TRUE-1 site. Swedish Nuclear Fuel and Waste Management Company. Äspö Hard Rock Laboratory International Cooperation Report ICR 96-04.

APPENDIX 1: Drawdown-time/distance plot for test in KI0023B:P6.

GEOSIGMA AB P.O. Box 894 S-751 08 Uppsala Sweden	Pumping test analysis Theis analysis method Confined aquifer	Page 1 Project: TRUE Block Scale Evaluated by: JEL Date: 24.09.1999
Pumping Test No. Interference test in KI0023B:P6	Test conducted on: 29.10.1998	
Drawdown vs t/R2 for receiver sections		

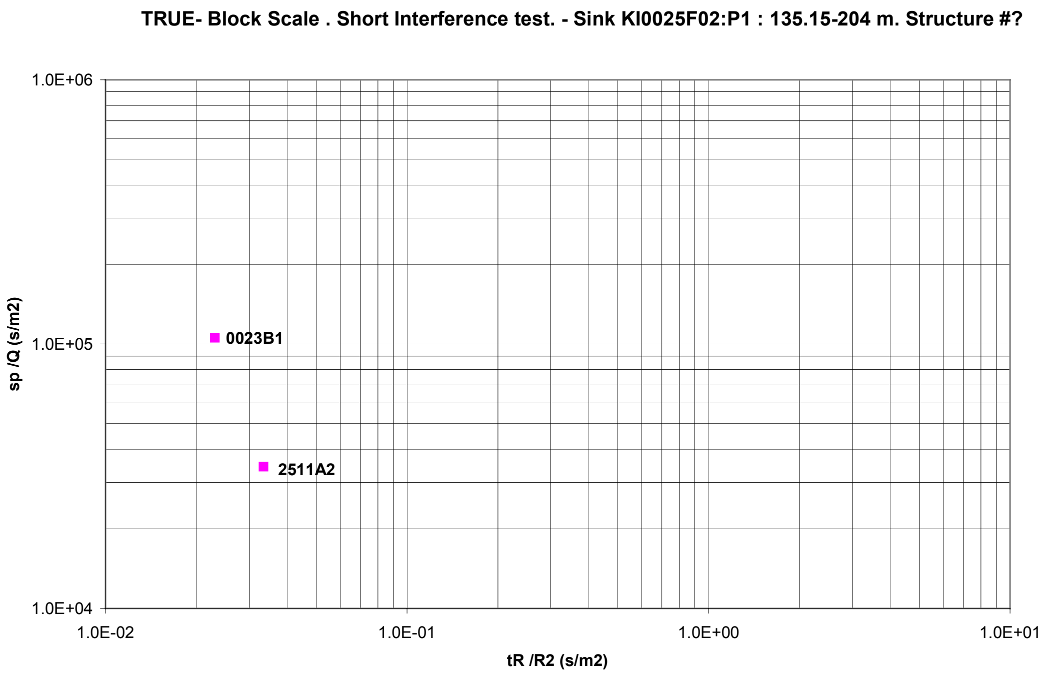


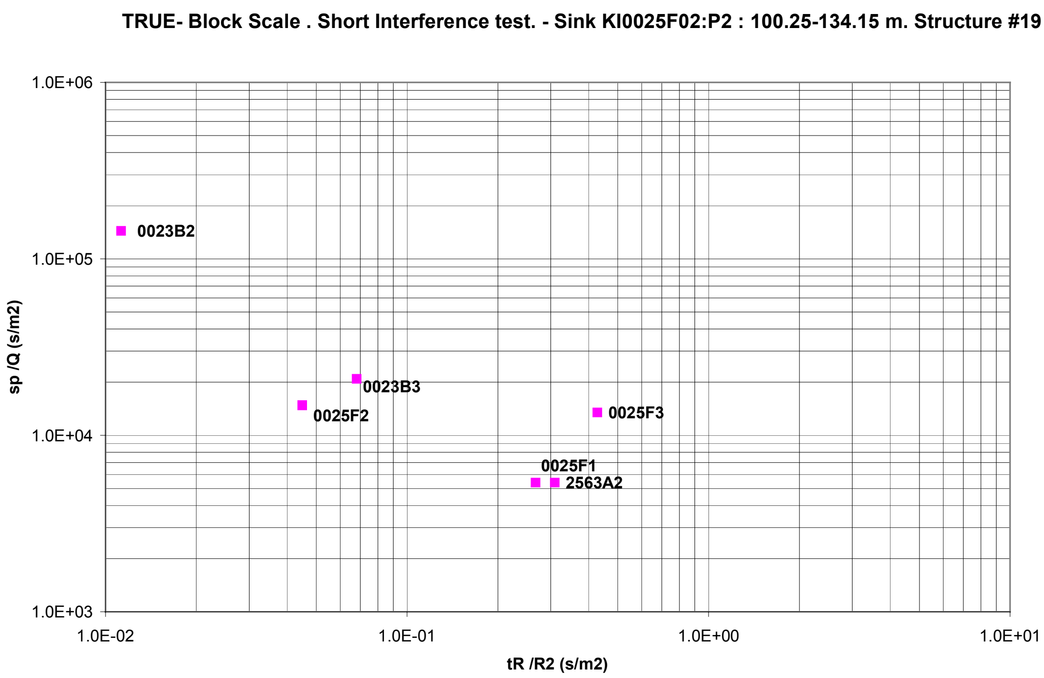
Data curves: X-axis:time/distance squared (s/m2)
Y-axis:drawdown (m)

tp=1440 mins (24 hours)

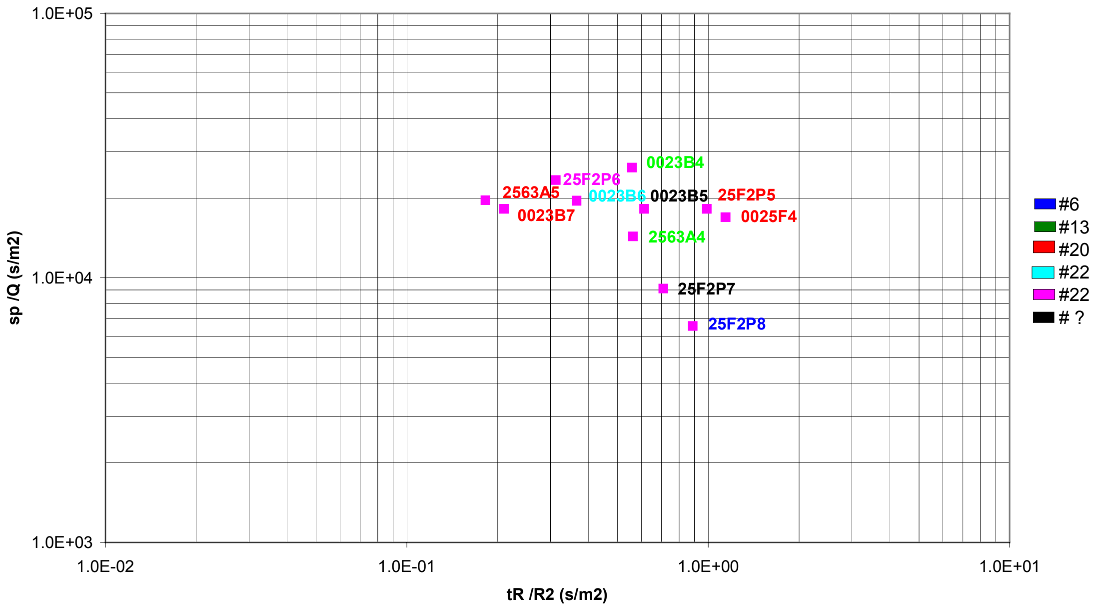
T=8.95E-7 m2/s (represents limiting Theis' curve)
S=1.42E-7

APPENDIX 2: Pressure response plots for short-term interference tests in KI0025F02.

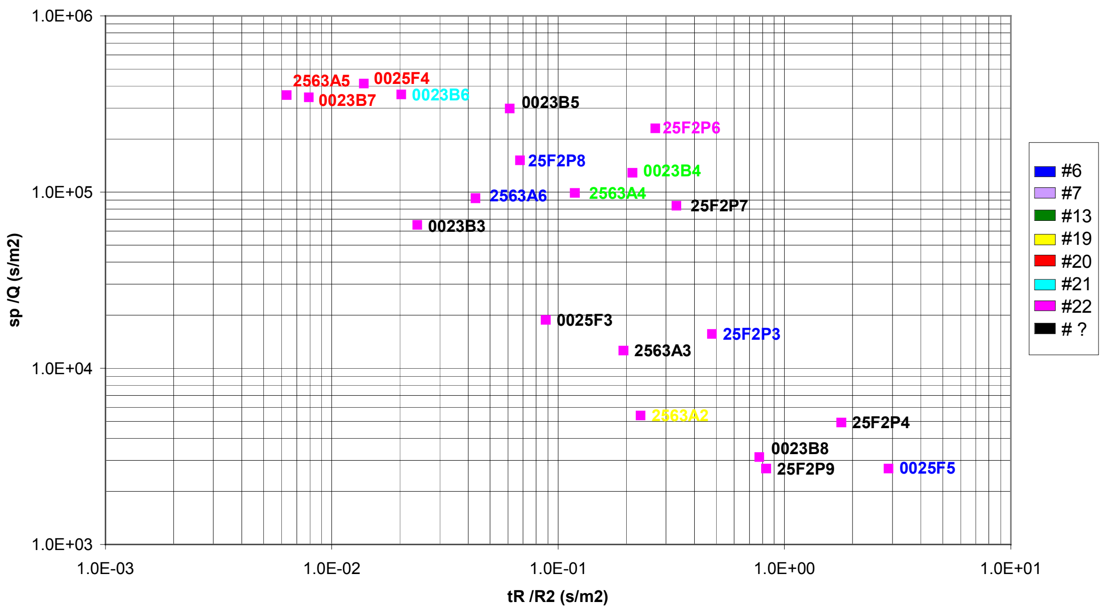




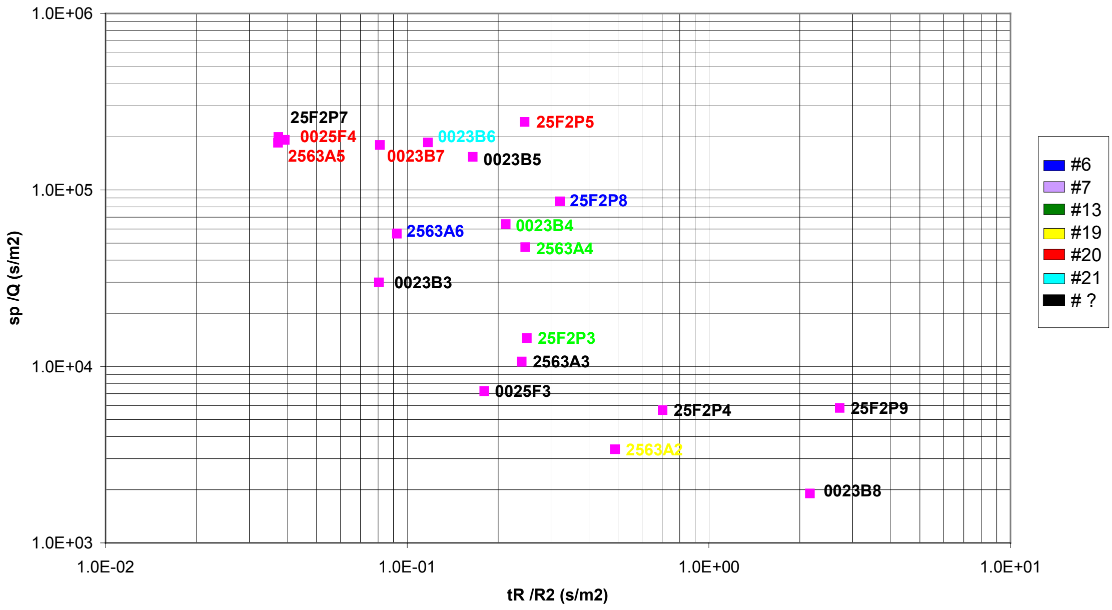
TRUE- Block Scale . Short Interference test. - Sink KI0025F02:P3 : 93.40-99.25 m. Structure #13, 21



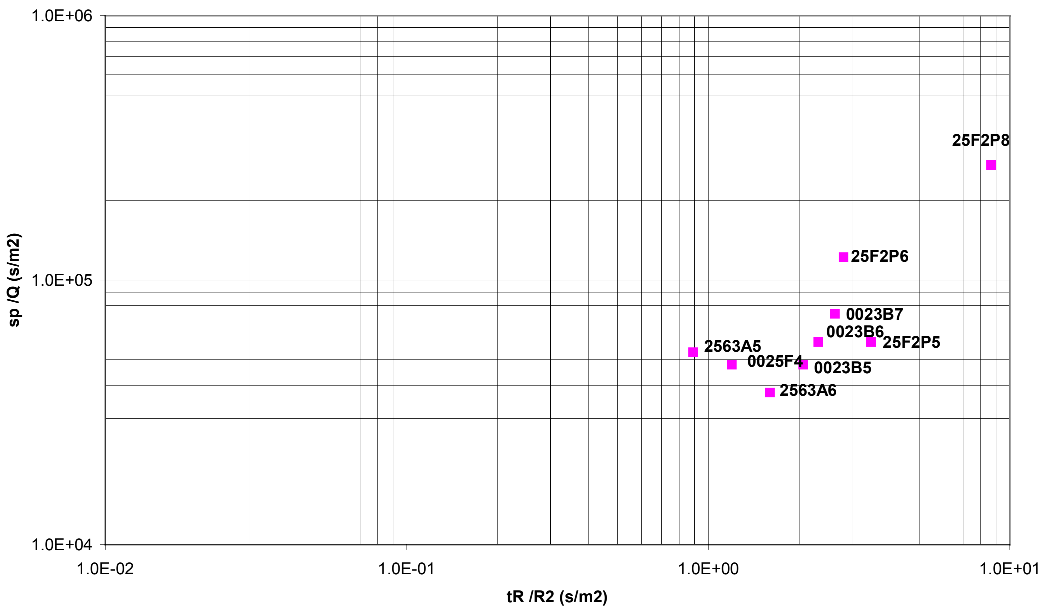
TRUE- Block Scale . Short Interference test. - Sink KI0025F02:P5 : 73.30-77.25 m. Structure #20

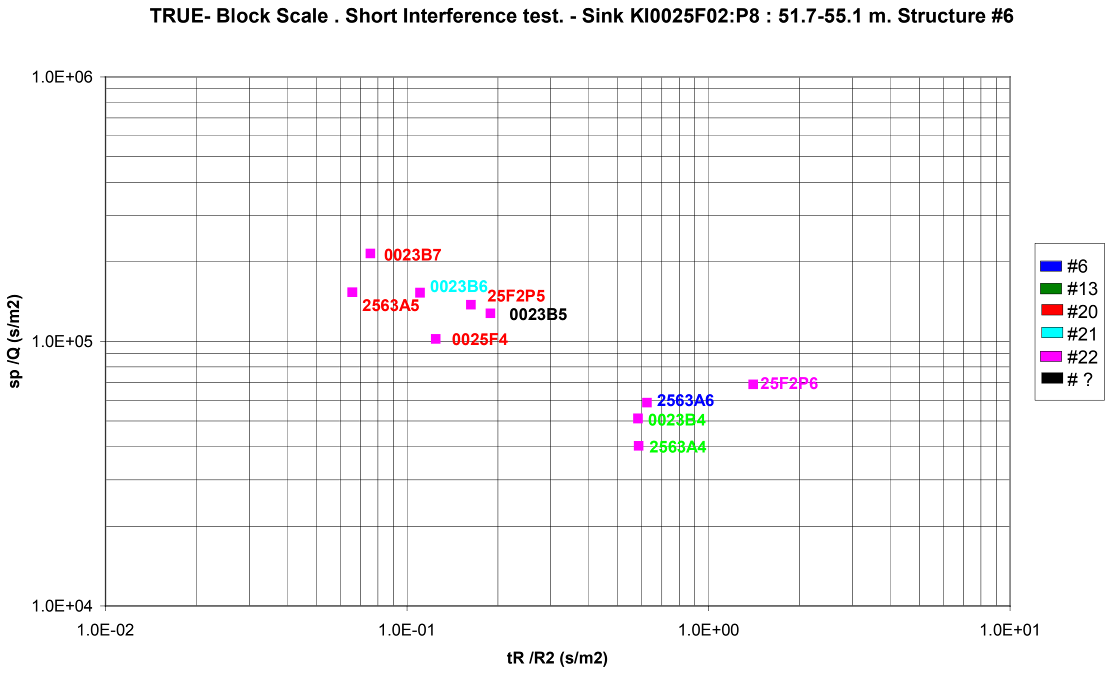


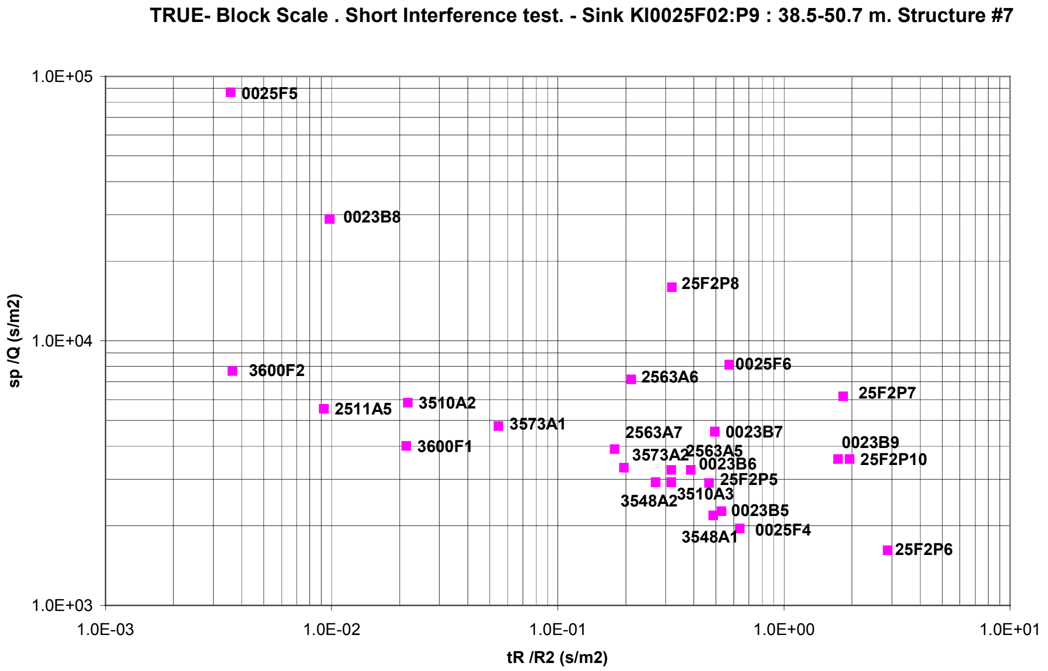
TRUE- Block Scale . Short Interference test. - Sink KI0025F02:P6 : 64.0-72.3 m. Structure #22



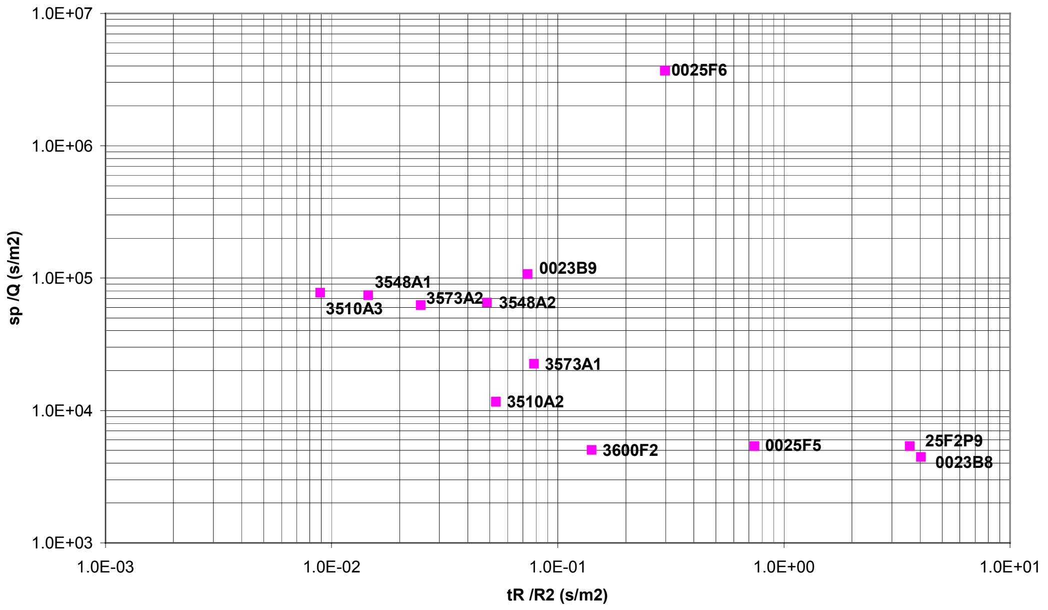
TRUE- Block Scale . Short Interference test. - Sink KI0025F02:P7 : 56.1-63.0 m. Structure #?



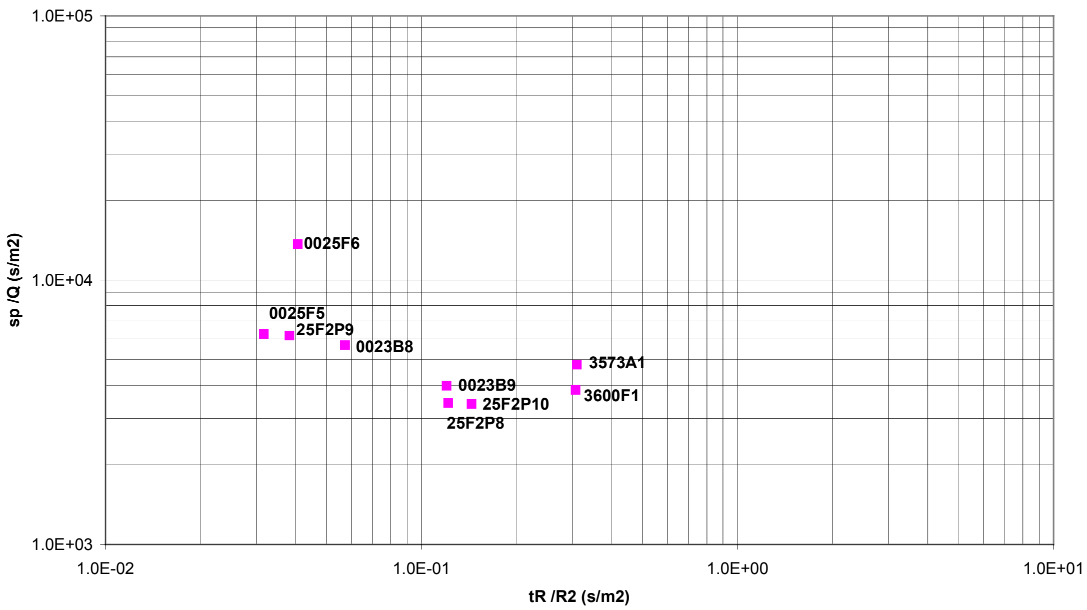

TRUE- Block Scale . Short Interference test. - Sink KI0025F02:P8 : 51.7-55.1 m. Structure #6
sp /Q (s/m2)
1.0E+06
1.0E+05
1.0E+04
1.0E-02
1.0E-01
1.0E+00
1.0E+01
tR /R2 (s/m2)
0023B7
0023B6
2563A5
25F2P5
0023B5
0025F4
25F2P6
2563A6
0023B4
2563A4
#6
#13
#20
#21
#22
?


TRUE- Block Scale . Short Interference test. - Sink KI0025F02:P9 : 38.5-50.7 m. Structure #7
sp /Q (s/m2)
1.0E+05
1.0E+04
1.0E+03
1.0E-03
1.0E-02
1.0E-01
1.0E+00
1.0E+01
tR /R2 (s/m2)
0025F5
0023B8
25F2P8
3600F2
0025F6
2563A6
25F2P7
2511A5
3510A2
3573A1
3600F1
2563A7
0023B7
0023B9
3573A2
2563A5
0023B6
25F2P10
25F2P5
3548A2
3510A3
0023B5
0025F4
3548A1
25F2P6

TRUE- Block Scale . Short Interference test. - Sink KI0025F02:P10 : 3.4-37.5 m. Structure #5



TRUE- Block Scale . Short Interference test. - Sink KA3510A:P2 : 114.02-121.02 m. Structure #15



APPENDIX 3: Straight-line distances between sink sections and receiver sections.

Borehole	23B:P6	25F2P1	25F2P2	25F2P3	25F2P5	25F2P6	25F2P7	25F2P8	25F2P9	25F2P10	3510P2
KA2511A:S1	109	66	73	92	110	116	123	128	139	157	146
KA2511A:S2	99	67	67	83	100	105	112	117	128	145	142
KA2511A:S3	71	100	77	68	71	73	76	79	87	100	142
KA2511A:S4	92	153	124	102	91	89	87	86	85	88	168
KA2511A:S5	128	197	166	142	127	123	119	116	111	105	199
KA2563A:R1	122	101	102	114	128	133	138	142	152	168	99
KA2563A:R2	39	97	67	50	51	53	57	60	68	83	61
KA2563A:R3	35	99	68	49	48	50	53	56	64	79	62
KA2563A:R4	21	107	73	47	38	38	40	42	49	63	67
KA2563A:R5	16	117	81	51	35	32	31	31	35	48	76
KA2563A:R6	30	133	96	64	43	37	31	28	24	30	91
KA2563A:R7	83	179	142	110	87	81	74	69	58	44	138
KI0025F:R1	125	43	62	90	111	118	125	131	143	162	186
KI0025F:R2	110	40	49	75	96	102	110	115	128	147	174
KI0025F:R3	73	56	31	39	57	63	70	76	88	107	145
KI0025F:R4	42	88	52	25	24	28	33	38	49	68	124
KI0025F:R5	33	110	73	40	20	17	16	18	27	44	115
KI0025F:R6	52	149	111	77	53	46	39	33	20	7	112
KI0023B:P1	91	41	45	69	90	96	104	109	122	141	122
KI0023B:P2	41	69	37	29	43	48	55	60	72	91	93
KI0023B:P3	28	80	45	25	32	37	43	48	60	78	89
KI0023B:P4	15	92	56	27	23	26	31	35	46	65	86
KI0023B:P5	7.3	98	62	31	20	21	25	29	39	57	85
KI0023B:P6	S	105	68	36	20	18	20	23	32	50	85
KI0023B:P7	15	118	81	48	26	21	16	15	19	36	87
KI0023B:P8	29	132	94	61	37	31	24	19	12	22	92
KI0023B:P9	48	151	113	79	55	48	40	34	22	7	100
KI0025F02:P1	105	S	38	72	96	103	111	117	130	150	152
KI0025F02:P2	68	38	S	34	58	65	73	79	98	112	125
KI0025F02:P3	36	72	34	S	24	31	39	45	58	78	108
KI0025F02:P4	26	85	47	13	11	18	26	32	45	65	103
KI0025F02:P5	20	96	58	24	S	7	15	21	34	54	101
KI0025F02:P6	18	103	65	31	7	S	8	14	27	47	100
KI0025F02:P7	20	111	73	39	15	8	S	6	19	39	99
KI0025F02:P8	23	117	79	45	21	14	6	S	13	33	99
KI0025F02:P9	32	130	92	58	34	27	19	13	S	20	101
KI0025F02:P10	50	150	112	78	54	47	39	33	20	S	106
KA3510A:P1	99	153	131	117	114	114	114	114	117	123	19
KA3510A:P2	85	152	125	108	101	100	99	99	101	106	S
KA3510A:P3	63	161	126	96	78	73	68	64	58	54	59
KA3573A:P1	67	166	131	103	85	80	75	72	66	62	70
KA3573A:P2	82	182	147	118	99	93	88	84	76	68	75
KA3600F:P1	115	196	168	146	135	132	129	127	124	121	70
KA3600F:P2	108	198	166	141	126	122	118	116	111	105	70
KA3548A:P1									57	43	
KA3548A:P2									63	47	