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Keywords: Flow regimes, Injection tests, Difference flow logging, Transmissivity, Skin factor.

Preface

The analyses presented in this report were completed in 2008, and the written report has been finalised in 2013. Despite the gap in time, the written report does not reflect any work beyond the effort of 2008. The significant results of the analyses were available to the site descriptive modelling at Forsmark. Hence, we do not believe the results of this investigation affect or alter the conclusions of site assessment activities that support site selection or licensing.

April 2013

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Geosigma AB

Abstract

A large number of constant head injection tests were carried out in the site investigation at Forsmark using the Pipe String System, PSS3. During the original evaluation of the tests the dominating transient flow regimes during both the injection and recovery period were interpreted together with estimation of hydraulic parameters. The flow regimes represent different flow and boundary conditions during the tests. Different boreholes or borehole intervals may display different distributions of flow regimes. In some boreholes good agreement was obtained between the results of the injection tests and difference flow logging with Posiva flow log (PFL) but in other boreholes significant discrepancies were found.

The main objective of this project is to study the correlation between transient flow regimes from the injection tests and other borehole features such as transmissivity, depth, geology, fracturing etc. Another subject studied is whether observed discrepancies between estimated transmissivity from difference flow logging and injection tests can be correlated to interpreted flow regimes. Finally, a detailed comparison between transient and stationary evaluation of transmissivity from the injection tests in relation to estimated transmissivity from PFL tests in corresponding sections is made.

Results from previous injection tests in 5 m sections in boreholes KFM04, KFM08A and KFM10A were used. Only injection tests above the (test-specific) measurement limit regarding flow rate are included in the analyses. For all of these tests transient flow regimes were interpreted. In addition, results from difference flow logging in the corresponding 5 m test sections were used. Finally, geological data of fractures together with rock and fracture zone properties have been used in the correlations. Flow regimes interpreted from the injection period of the tests are generally used in the correlations but deviations between the interpreted flow regimes from the injection and recovery period are also discussed.

The observed discrepancies between the estimated transmissivity from difference flow logging and injection tests can in most cases be correlated to the interpreted flow regimes during the injection tests. In particular, for tests with apparent no-flow boundaries (NFB) during the injection period the estimated transmissivity from the injection tests was frequently much higher than the reported transmissivity of PFL, while tests with pseudo-spherical flow regime (PSF) or pseudo-steady state (PSS) often display rather similar values from injection tests and PFL. This fact is likely to depend on conceptual differences between the two test types.

In KFM04A and KFM10A pseudo-radial (PRF) and pseudo-spherical flow regimes (PSF) were more common than in KFM08A while pseudo-linear flow (PLF) and apparent no-flow boundaries (NFB) were more common in KFM08A than in KFM04A and KFM10A. Tests displaying NFB or PLF are more common in sections with a lower fracture frequency and/or sections in located in fracture domains. PSF is more common to find in sections located in deformation zones and/or sections with an increased fracture frequency.

No clear relationship between interpreted flow regimes and evaluated transmissivity or borehole length (and depth) could be found in the three studied boreholes.

Sammanfattning

Ett stort antal injektionstester med konstant tryck med rörgångssystemet PSS3 utfördes i platsundersökningarna i Forsmark. Vid de ursprungliga tolkningarna av testerna utvärderades de dominerande flödesregimerna under både injektions- och återhämtningsperioden tillsammans med skattning av hydrauliska parametrar. Flödesregimerna representerar olika flödes- och randvillkor under testerna. Olika borrhål eller borrhålsintervall kan uppvisa olika fördelningar av flödesregimer. I vissa borrhål erhölls god överensstämmelse mellan resultaten av injektionstester och differensflödesloggning med Posiva flödeslogg (PFL) men i andra borrhål befanns väsentliga avvikelser.

Huvudsyftet med denna rapport är att studera korrelationen mellan transienta flödesregimer från injektionstesterna och andra borrhålsegenskaper som transmissivitet, djup, geologi, sprickighet etc. Ett annat ämne som studerades är om observerade avvikelse mellan skattad transmissivitet från differensflödesloggning och injektionstester kan korreleras med tolkade flödesregimer. Slutligen gjordes en detaljerad jämförelse mellan transient och stationär tolkning av transmissivitet från injektionstesterna i förhållande till skattad transmissivitet från PFL-tester i motsvarande sektioner.

Resultat från tidigare injektionstester i 5 m sektioner i borrhål KFM04A, KFM08A och KFM10A användes. Bara injektionstester över den (test-specifika) mätgränsen avseende flöde är inkluderade i analyserna. För alla dessa tester tolkades transienta flödesregimer. Dessutom användes resultat från differensflödesloggning i motsvarande 5 m sektioner. Slutligen användes geologiska data för sprickor tillsammans med egenskaper hos bergmassan och sprickzoner i korrelationerna. Flödesregimer tolkade från injektionsperioden av testerna användes vanligen i korrelationerna men avvikelser mellan de tolkade flödesregimerna från injektions- och återhämtningsperioden diskuteras också.

De observerade avvikelserna mellan den tolkade transmissiviteten från differensflödesloggningen och injektionstester kan i de flesta fall korreleras till de tolkade flödesregimerna under injektionstesterna. I synnerhet, för tester med skenbara negativa hydrauliska gränser (NFB) under injektionsperioden var den skattade transmissiviteten från injektionstesterna ofta mycket högre än den rapporterade transmissiviteten för PFL medan tester med pseudo sfärisk flödesregim (PSF) eller pseudo-stationärt flöde (PSS) ofta uppvisar relativt lika T-värden från injektionstester och PFL. Detta beror sannolikt på konceptuella skillnader mellan de två testtyperna.

Pseudo-radiell flödesregim (PRF) och PSF var vanligare i KFM04A och KFM10A än i KFM08A medan pseudo-linjär flödesregim (PLF) och NFB var vanligare i KFM08A än i KFM04A och KFM10A. Test som uppvisar NFB eller PLF var vanligare i sektioner med lägre sprickfrekvens och/eller sektioner befintliga i sprickdomäner. PSF var vanligare i deformationszoner och/eller sektioner med en förhöjd sprickfrekvens.

Inget tydligt samband mellan tolkade flödesregimer och utvärderad transmissivitet eller borrhålslängd (och djup) kunde hittas för det tre borrhål som studerats.

Contents

1 Introduction

A large number of injection tests have been carried out within the site investigation at Forsmark using the Pipe-String System PSS3. By the evaluation of the tests a test-specific interpretation of the dominating flow regimes during both the injection and recovery period is made together with estimation of hydraulic parameters. It was found that different boreholes or sections of them display different flow regimes. In some boreholes good agreement was obtained with the results of previous difference flow logging with Posiva flow log (PFL) but in other boreholes certain discrepancies were found.

These observations raised questions concerning the characteristics of the boreholes and associated flow regimes. For example, why are certain flow regimes more common in some boreholes? Is the difference between the transmissivity from PFL and PSS3 correlated to a specific flow regime? Do steady-state or transient evaluations of the injection tests give different transmissivity in relation to PFL? May the number of fractures in the section affect the results differently for PFL and PSS3? Is there a correlation between interpreted flow regimes and rock and fracture properties?

Comparisons of results from different single-hole hydraulic tests, including e.g. injection tests and difference flow logging, have previously been made in boreholes in the Simpevarp and Laxemar subareas (Rhén et al. 2006a, b). However, these studies did not consider the impact of interpreted transient flow regimes from injection tests on the results. The difference between transmissivity evaluated from PFL and PSS3 and the correlation to flow regimes (dimensions) has previously been studied by Follin et al. (2011) for boreholes KFM02A, KFM03A and KFM06A in Forsmark. The present study may be viewed as a continuation of the study by Follin et al. (2011). However, several aspects of flow regimes such as correlation with fracture frequency and rock domain included in the present study were not analysed by Follin et al. (2011).

Three boreholes were selected for this study; KFM04A, KFM08A and KFM10A. General data of these boreholes are presented in Table 1-1. The boreholes were chosen since they are located in different parts of the site investigation area at Forsmark and since they, at a first comparison, display different relative frequency of the kind of interpreted flow regimes during the injection tests. The studied borehole intervals include rock domains RFM012, RFM029 and RFM032 and fracture domains FFM01, FFM03 and FFM04. The hydrogeological characterisation and modelling of the Forsmark investigation area is described by Follin et al. (2007). The location of the boreholes in the site investigation area in Forsmark is shown in the map in Figure 1-1.

Table 1-1. Technical data for the three boreholes used in the project (from Sicada).

	KFM04A	KFM08A	KFM10A
Borehole length [m]	1,001.42	1,001.19	500.16
Inclination [degrees]	60.08	60.89	50.05
Casing length [m]	106.95	100.20	60.39
Diameter core drilled [mm]	77	77	76

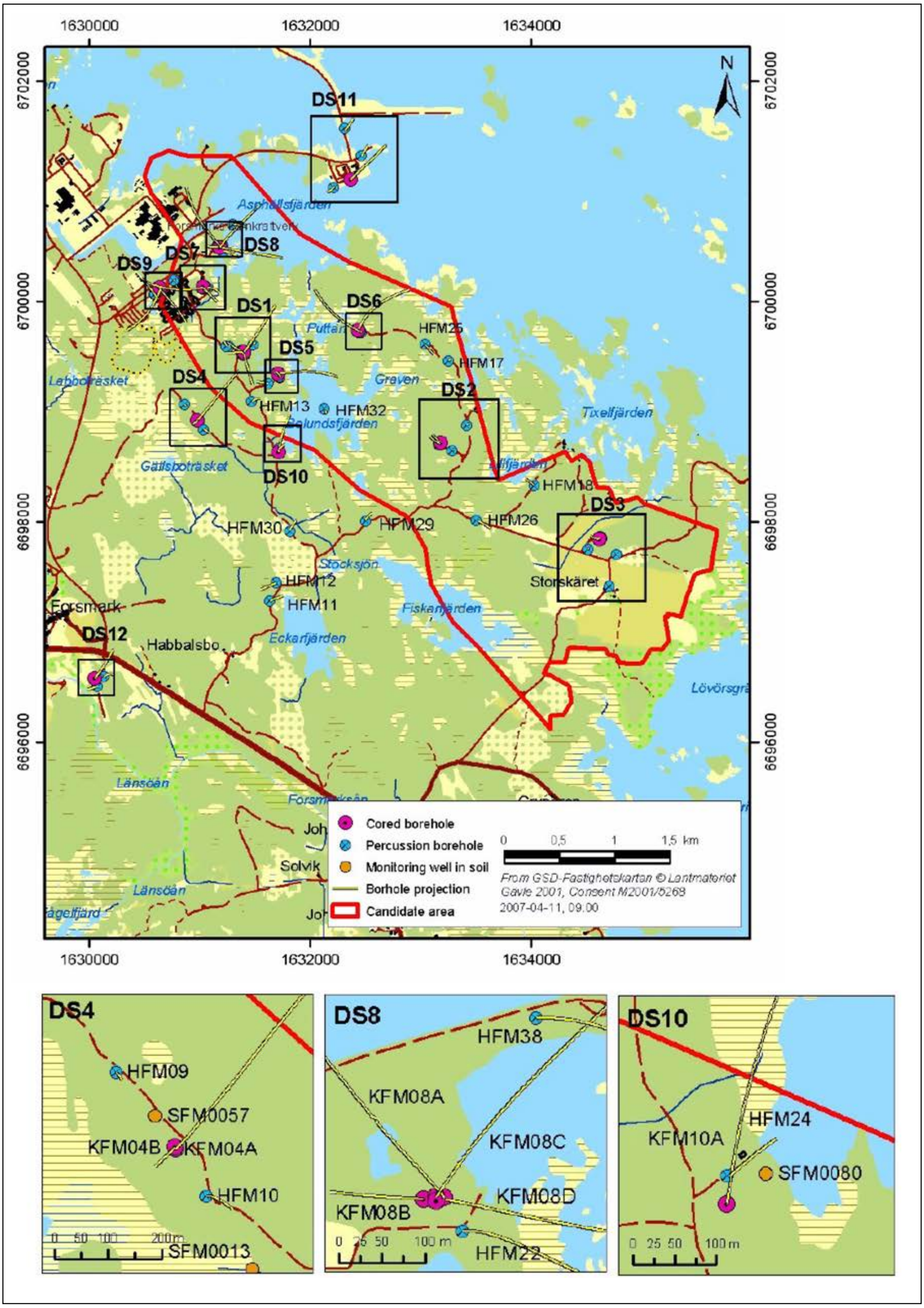

__Figure 1-1.__ Map of the site investigation area at Forsmark. The three drill sites with boreholes KFM04A, KFM08A and KFM10A are shown in separate maps.

2 Objectives and scope

The main objective of this project is to study the correlation between transient flow regimes evaluated from injection tests with PSS3 and other borehole character such as transmissivity, depth, geology etc. The flow regimes represent different flow and boundary conditions during the injection tests. These conditions may possibly be correlated with other borehole characteristics. Another subject studied in this project is whether observed deviations between the estimated transmissivity from difference flow logging (PFL) and injection tests with PSS3 can be correlated to other test data, e.g. flow regimes. Finally, a comparison between the transient and the assumed steady-state evaluation of transmissivity from the injection tests in relation to the estimated transmissivity from the assumed steady-state evaluation of the PFL tests in corresponding sections is also made.

Data of flow rate, pressure and time from injection tests in 5 m sections in boreholes KFM04, KFM08A and KFM10A were used. Only injection tests above the (test-specific) measurement limit regarding flow rate of PSS3 are included in the analyses. For all of these tests transient flow regimes have been interpreted as well as estimates of transient and assumed steady-state evaluation of transmissivity. In KFM08A, pressure pulse tests were performed in several of the tested 5 m sections instead of injection tests. These sections showed signs of a very low transmissivity prior to the test. Results from pressure pulse tests are not included in this study.

In addition, results from difference flow logging in the corresponding 5 m test sections were used. Both the estimated transmissivity in 5 m sections from the sequential logging (TD-5m) as well as the sum of transmissivities of the identified flow anomalies within these sections from the overlapping logging (sum of TDa-5m) are used in this study. Finally, geological data of rock and fracture zone properties have been used in the correlation studies.

Only qualitative analyses of previously reported data have been performed. No statistical analyses are made. The correlations made are presented in cross plots, histograms and tables. Both borehole-specific analyses and analyses of data from all boreholes together are carried out.

3 Evaluation of PSS3 and PFL tests

3.1 General

All data used has been collected and processed during previous investigations in the boreholes It should be noted that the test evaluation is not performed in this study but reported in earlier studies. In the three studied boreholes both difference flow logging (PFL) and injection tests with the pipe-string system (PSS3) have been performed (Hjerne and Ludvigson 2005, Walger et al. 2006, 2007, Rouhiainen and Pöllönen 2004, Sokolnicki and Rouhiainen 2005, Sokolnicki et al. 2006). Relevant data regarding boreholes KFM04A, KFM08A and KFM10A from both PFL and PSS3 measurements are collected from the Sicada database. Interpreted flow regimes from injection tests with PSS3 are collected from the actual P-reports since this information is not stored in the Sicada database. The interpreted flow regimes have not been used in previous studies from the boreholes and have only been presented in P-reports from the injection tests. Other borehole data used in this project, such as geological data on fracture zones, fracture frequency etc. are also derived from the Sicada database.

3.2 Standard evaluation of injection tests

In order to discuss the injection tests in terms of flow regimes and quantitative hydraulic parameters and compare those with other borehole characteristics, a short description of the evaluation procedures for the injection tests is considered necessary. For further information about the performance and evaluation of injection tests see Ludvigson et al. (2007).

3.2.1 Measurement limit for flow rate and transmissivity

The estimated standard lower measurement limit for flow rate for injection tests with PSS3 is c 1 mL/min ($1.7 \cdot 10^{-8}$ m^3/s). However, if the flow rate for a test was close to, or below, the standard lower measurement limit, a test-specific estimate of the actual lower measurement limit of flow rate was made. The test-specific lower limit was based on the measurement noise level of flow rate before and after the injection period, respectively. The decisive factor for the varying test-specific lower measurement limit is not identified, but it might be of both technical and hydraulic character.

The lower measurement limit of (steady-state) transmissivity T_M is based on the specific flow rate, Q/s (Q = flow rate, s = pressure change). The specific flow rate corresponds to the estimated (test-specific) lower measurement limit of flow rate and the actual injection pressure during the test. The steady-state transmissivity is also depending on the radius of the borehole and the section length, see Eqn. (3-2). The intention during the injection tests was to use a standard injection pressure of 200 kPa (20 m water column). However, the injection pressure may be considerably different in some cases. For example, an apparently low injection pressure is often the result of a test section of low transmissivity due to the pressure increase, caused by packer inflation, before the injection start. A highly transmissive section may also result in a low (but real) injection pressure due to limited flow capacity of PSS3.

Whenever the final flow rate (Q_p) was not defined (i.e. not clearly above the measurement noise before and after the injection period), the estimated lower measurement limit for transmissivity was based on the estimated test-specific lower measurement limit for flow rate and a standard injection pressure of 200 kPa. This is done in order to avoid excessively high, apparent estimates of transmissivity for such low-transmissivity sections due to (non-representative) low, apparent injection pressures caused by the pressure increase due to packer inflation. In such cases, no further evaluation of the tests was done, i.e. no transient evaluation or flow regimes were evaluated.

Typically, the test-specific lower measurement limit of flow rate for the injection tests was generally in the range $5 \cdot 10^{-9}$ to $1.5 \cdot 10^{-8}$ m^3/s which corresponds to a steady-state transmissivity T_M of $2 \cdot 10^{-10}$ to $6 \cdot 10^{-10} m^2/s$ according to Moye's formula.

3.2.2 Qualitative analysis of injection tests

Initially, a qualitative evaluation of the dominating flow regimes, e.g. wellbore storage (WBS), pseudo-linear flow (PLF), pseudo-radial flow (PRF), pseudo-spherical (leaky) flow (PSF) and pseudo-steady state (PSS), respectively, was performed. In addition, indications of outer boundary conditions during the tests were identified such as apparent no-flow boundary (NFB) or constant head boundary (CHB). The qualitative evaluation was mainly performed from the log-log plots of flow rate and pressure together with the corresponding derivatives. A schematic illustration of the various flow regimes is presented in Figure 2-4 in Follin et al. (2011). For examples of identified flow regimes in real tests refer to Hjerne and Ludvigson (2005), Walger et al. (2006, 2007) and Ludvigson et al. (2007).

In particular, time intervals with PRF, reflected by a constant (horizontal) derivative in the test diagrams, were identified. PLF may, at the beginning of the test, be reflected by a straight line of slope 0.5 or less in log-log diagrams, both for the measured variable (flow rate or pressure) and the corresponding derivative. A true spherical flow regime is reflected by a straight line with a slope of –0.5 for the derivative. Other slopes may indicate other types of PSF (e.g. leaky flow), eventually approaching PSS. Due to the limited resolution of the flow meter and pressure sensor, the derivative may sometimes indicate a false horizontal line or exhibit other distortions by the end of periods with apparent pseudo-steady state. Apparent no-flow boundaries (NFB) and constant head boundaries (CHB), or equivalent boundary conditions of fractures, are reflected by a rapid increase/decrease of the derivative, respectively.

3.2.3 Quantitative analysis of injection tests

The quantitative analysis of the injection tests is described in Ludvigson et al. (2007). A preliminary steady-state analysis of transmissivity according to Moye's formula (denoted T_M) was made from the injection period for all tests according to the following equations:

$$T_M = \frac{Q_p \cdot \rho_w \cdot g}{dp_p} \cdot C_M \qquad (3\text{-}1)$$

$$C_M = \frac{1 + \ln\left(\frac{L_w}{2r_w}\right)}{2\pi} \qquad (3\text{-}2)$$

Q_p = flow rate by the end of the flow period (m^3/s)

ρ_w = density of water (kg/m^3)

g = acceleration of gravity (m/s^2)

C_M = geometrical shape factor (–)

dp_p = injection pressure=p_p–p_i (Pa)

r_w = borehole radius (m)

L_w = section length (m)

The equation assumes two-dimensional (radial) flow conditions within a distance of L/2 from the borehole and essentially spherical in three dimensions beyond L/2 (Moye 1967).

From the results of the qualitative evaluation, appropriate interpretation (flow) models for the transient evaluation of the tests were selected. When possible, transient analysis was made on both the injection and recovery period of the tests.

The transient analysis was performed using the test analysis software AQTESOLV (HydroSOLVE, Inc.), which enables both visual and automatic type curve matching. The transient evaluation is generally carried out as an iterative process of manual type curve matching and automatic matching. For the injection period, a model based on the Jacob and Lohman (1952) solution was applied for estimating the transmissivity and skin factor for an assumed value on the storativity when a certain period with pseudo-radial flow could be identified. The storativity has to be assumed since it in principle is impossible to separate the effect of skin and storativity for a single borehole test. The model is based on the effective wellbore radius concept to account for non-zero skin factors according to Hurst et al. (1969).

In borehole KFM10A and KFM08A, the storativity was calculated using an empirical regression relationship between storativity and transmissivity derived from hydraulic interference tests at Äspö Hard Rock Laboratory, see Equation 3-3 (Rhén et al. 1997). In KFM04A, the storativity was assumed to be $1 \cdot 10^{-6}$ in each test since a slightly different evaluation methodology was applied at the time for evaluation of KFM04A.

$$S=0.0007 \cdot T^{0.5} \qquad (3\text{-}3)$$

S = storativity (–)

T = transmissivity (m^2/s)

Firstly, the transmissivity and skin factor were obtained by type curve matching using a fixed storativity value of 10^{-6}. From the transmissivity value obtained, the storativity was then calculated according to Eqn. (3-3) and the type curve matching was repeated. In most cases the change of storativity did not significantly alter the calculated transmissivity by the new type curve matching. Instead, the estimated skin factor, which is strongly correlated to the storativity using the effective borehole radius concept, was altered correspondingly.

For transient analysis of the recovery period, a model presented by Dougherty and Babu (1984) was used when a certain period with pseudo-radial flow could be identified. In this model, a variety of transient solutions for flow in fractured porous media are available, accounting for e.g. wellbore storage and skin effects, double porosity etc. The solution for wellbore storage and skin effects is analogous to the corresponding solution presented in Earlougher (1977) based on the effective wellbore radius concept to account for non-zero skin factors.

For tests characterized by PSF or PSS during the injection period, the model by Hantush (1959) for constant head tests was adopted for the evaluation in KFM08A and KFM10A. The injection tests in KFM04A were performed earlier when this model not yet was in use in the evaluation. In the model by Hantush (1959), the skin factor is not included but can be calculated from the simulated effective borehole radius according to Eqn. (3-4). This model also allows calculation of the wellbore storage coefficient from the recovery period. The corresponding model for constant flow rate tests (Hantush and Jacob 1955) was applied for evaluation of the recovery period for tests showing pseudo-spherical flow or pseudo-steady state during this period.

$$\zeta=\ln(r_w/r_{wf}) \qquad (3\text{-}4)$$

ζ = skin factor

r_w = borehole radius (m)

r_{wf} = effective borehole radius

Some tests showed effects of channelized flow (initial slope of 0.5 or less in a log-log plot). If a certain transition period towards pseudo-radial flow was observed during the test the model described above by Hurst et al. (1969) was used by the transient evaluation of such tests. In addition, a model for an equivalent single fracture intersecting the test section was used for the transient analysis as a complement to standard models for pseudo-radial flow for test showing a fracture response. The model presented in Ozkan and Raghavan (1991a, b) for a uniform-flux vertical fracture embedded in a porous medium was employed. With this model the equivalent hydraulic conductivity of the rock perpendicular (K_x) and parallel (K_y) to the assumed fracture plane may be estimated. In this case, the quotient K_x/K_y was assumed to be 1.0, i.e. isotrpic conditions. Type curve matching provided values of K_x and L_f for an estimated value on the specific storativity S_s based on Eqn. (3-3), where L_f is the apparent length of the assumed fracture. The test section length was then used to convert K_x and S_s to equivalent rock transmissivity $T= K_x \cdot L$ and storativity $S= S_s \cdot L$, respectively. Such estimates of transmissivity from fracture models may be compared with corresponding values from models for pseudo-radial flow in the same test section.

The different transient estimates of transmissivity from the injection and recovery period, respectively, were then compared and examined. One of these values was chosen as the best representative transient transmissivity T_T of the formation adjacent to the test section. At Forsmark, the estimated transmissivity from the injection period was generally chosen as T_T. In cases with more than one PRF during the injection or recovery period, the first one was in most cases assumed as the most representative for the hydraulic conditions in the rock close to the tested section (middle zone).

Finally, a representative value of transmissivity of the test section, T_R, was chosen from T_T and T_M. The latter transmissivity was chosen whenever a transient evaluation of the test data was not possible or not being considered as reliable. If the flow rate by the end of the injection period (Q_p) is too low to be defined, and thus neither T_T nor T_M can be estimated, the representative transmissivity for the test section is considered to be less than T_M based on the estimated lower measurement limit for Q/s (i.e. $T_R < T_M$=Q/s-measl-L$\cdot C_M$).

3.2.4 Differences between transient and steady-state evaluation

The basic difference between transient and steady-state evaluation of the injection tests is that e.g. transmissivity is determined from the shape of the observed data curve during the test in transient evaluation (T_T) whereas the steady-state transmissivity (T_M) is mainly based on the final flow rate and pressure by the end of the injection period. Thus, in the estimate of T_M, neither deviating flow regimes nor boundary effects and skin effects during the test are taken into account. In addition, T_M depends on the length of the test section and the borehole diameter, c.f. Eqn. (3-1 and 3-2). Finally, T_M assumes steady-state flow and pressure conditions by the end. Nevertheless, good correlation is generally obtained between the estimated transient and steady-state transmissivity (Follin et al. 2007, Figure 4-9).

The final flow rate during the injection period may in some cases be affected by both skin effects (positive or negative) and/or (negative) boundary effects (NFB). In such cases, significant discrepancies may arise between the estimated transient and steady-state transmissivity. A discussion of potential differences between transient and steady-state test evaluation is made in Andersson et al. (1993).

Discrepancies may also result between the transient transmissivity estimated from the injection and recovery period, respectively, e.g. due to skin and WBS. In constant head tests the flow period is in general not affected by WBS but the recovery period may be significantly affected by WBS in low-transmissive sections. It has also been observed that the transient data curves during the injection and recovery period are not always consistent as discussed in Ludvigson et al. (2007). For example, some tests show an unexpectedly fast pressure recovery during the recovery period, possibly due to turbulent flow in fractures or other head losses during the injection period. This fact may cause discrepancies between the estimated transmissivity from the injection and recovery period, respectively.

Inconsistent behaviour (and transmissivity) between the injection and recovery period may also result when apparent NFB:s are present, c.f. Figure 3-3 below. This effect is also discussed by Follin et al. (2007, 2011). In such cases the injection period may be dominated by an apparent NFB whereas the pressure recovery may be slow and incomplete, even in relatively high-transmissivity sections. Such effects may be due to flow restrictions of fracture(s) penetrating the test section, e.g. fractures with limited extent or decreasing aperture away from the borehole. In such cases, it may not be possible to determine a representative transmissivity from transient evaluation of the injection period (c.f. Figure 3-3) or alternatively, a much lower transient transmissivity than T_M may be estimated. However, the estimated transient transmissivity from the recovery period may, in some cases, be in the same order as the steady-state transmissivity T_M from the injection period. The estimated transmissivity from the recovery period was generally selected as representative in such cases. This item is discussed in Section 5.2.1.

A comparison between the estimated transient and steady-state transmissivity from the injection tests in relation to the transmissivity estimated from difference flow logging in the corresponding 5 m sections is made in this study. The results are discussed in terms of interpreted flow regimes, skin factors and degree of pressure recovery in these sections during the injection tests.

3.2.5 Examples of flow regimes during the injection period

Examples of transient flow regimes during the injection period of the tests are presented in Figures 3-1 to 3-5. All of the figures show the ratio Head/Flow rate versus time on log-log scales. The blue squares indicate the actual data curve while the black crosses indicate the time derivative of the data. The red lines show the model fit to the data according to the type of model and the actual parameters shown on the right hand side of the figures.

A typical PRF can be seen in Figure 3-1 from an injection test in section 352.0–357.0 m in KFM04A. The PRF is lasting from c. 30 until 1,200 seconds which is the total length of the injection period.

A typical PSF (leaky flow) is reflected by a negative slope on the derivative, as seen in Figure 3-2. This test in section 77.9–82.9 m in KFM10A was evaluated with the Hantush model for leaky flow described in section 3.2.3. The initial c. 60 s of the test shows an unstable injection pressure. Hence, the first c. 60 s may not be used for qualitative or quantitative evaluation in this case.

Figure 3-3 displays an apparent NFB during the injection period in section 144.0–149.0 m in KFM08A. The NFB is interpreted due to the rapid increase of the derivative (head/flow rate) in log-log scale. A NFB may occur at any time during the period but in this case it is dominating the entire injection period. When the test period only shows an apparent NFB no unambiguous transient evaluation is possible. If the NFB is preceded by another type of flow regime (e.g. a short PRF) it may be possible to perform a transient evaluation of this period. In such cases, the latter flow regime may possibly represent a fracture of limited extent or with a decreasing aperture with distance from the borehole.

Often more than one flow regime is interpreted during the test. In Figure 3-4 the injection period from section 477.9–482.9 m in KFM10A is displayed where a PRF may be seen from c 30 s to about 150 s. After this time, the derivative decreases significantly which is interpreted as a transition to a PSF (leaky flow).

Another type of transition may be seen in Figure 3-5 where the flow regime initially is interpreted as PLF and after c 80 s transitions to a PRF where the derivative flattens out.

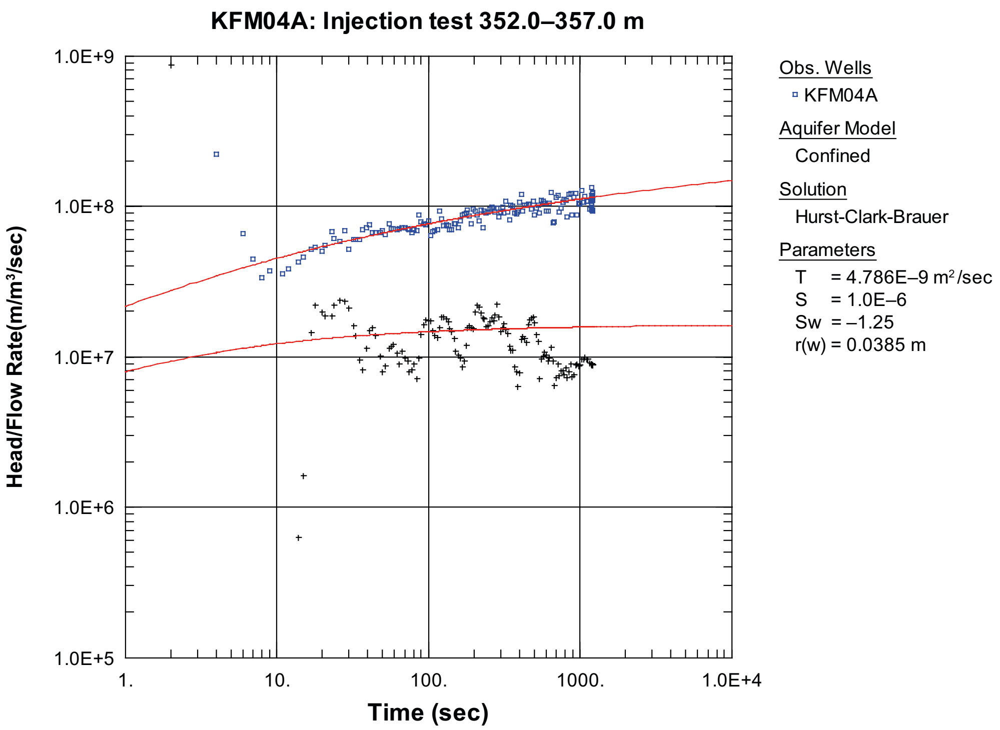

Figure 3-1. Injection period of the test at 352.0–357.0 m in KFM04A showing a typical PRF.

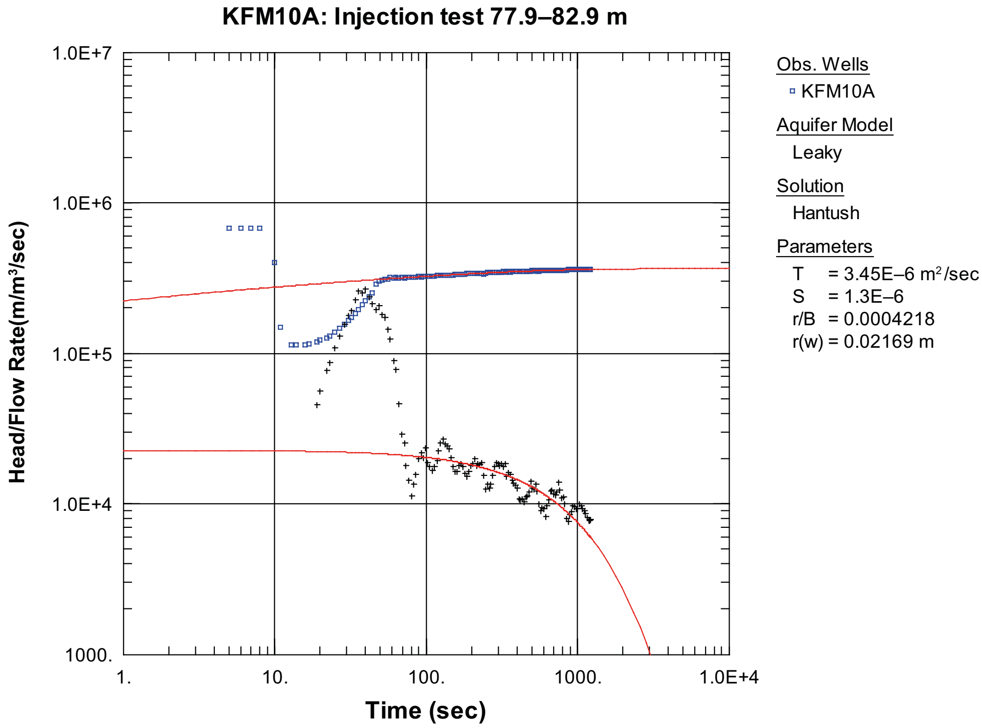

Figure 3-2. *Injection period of the test at 77.9–82.9 m in KFM10A showing a typical PSF.*

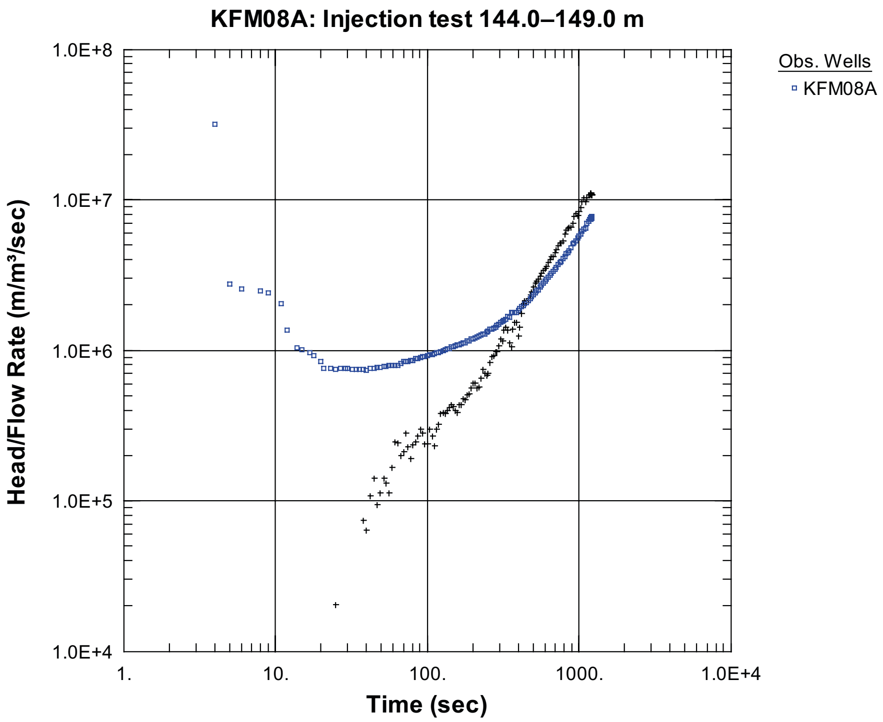

Figure 3-3. *Injection period of the test at 144.0–149.0 m in KFM08A showing an apparent NFB.*

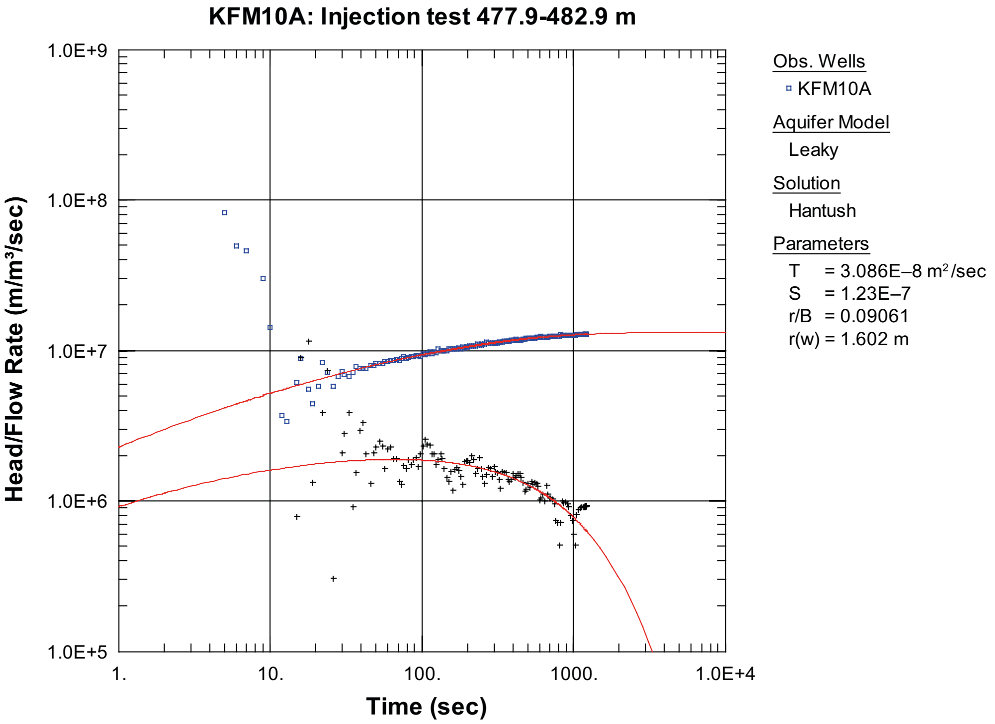

Figure 3-4. *Injection period of the test at 477.9–482.9 m in KFM010A showing an early PRF transitioning to a PSF after c 150 s.*

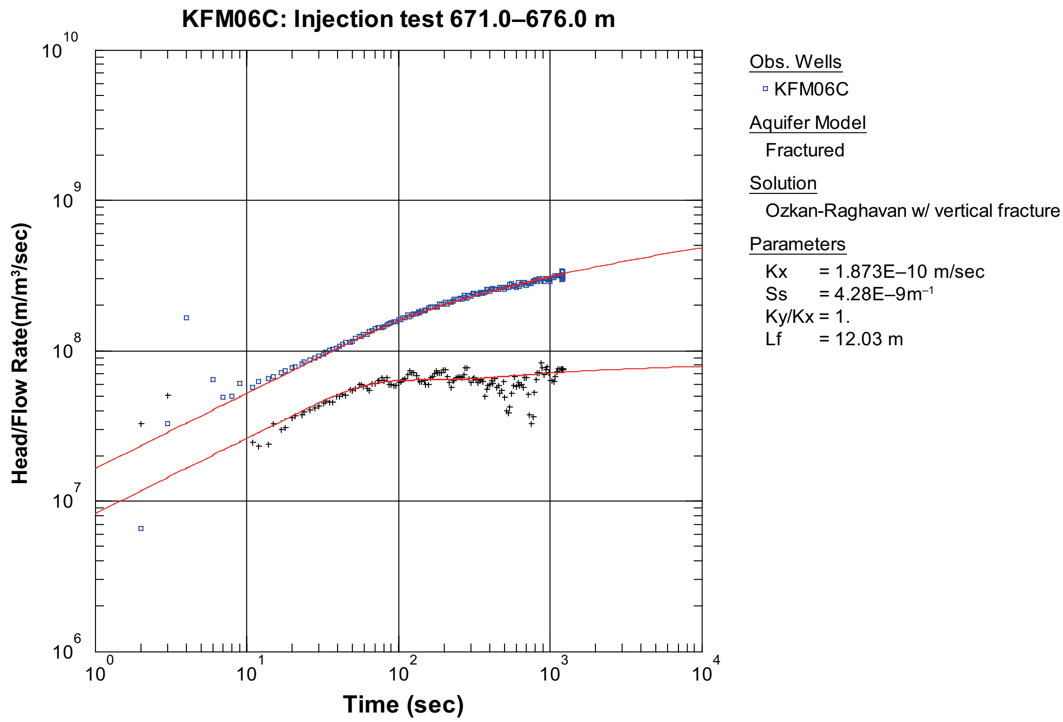

Figure 3-5. *Injection period of the test at 671.0–676.0 m in KFM06C showing an early PLF transitioning to a PRF after c 100 s. This plot shows the test evaluated with the Ozkan-Raghavan model for flow in a single vertical fracture imbedded in a porous medium. The values Kx and S_S should be multiplied by the section length (5 m) to get the equivalent transmissivity and storativity, respectively for the section.*

3.3 Basic evaluation of difference flow logging

The difference flow logging in the selected boreholes has been made with the Posiva Flow Log/difference flowmeter. When measuring with the PFL the open borehole has been pumped for about a week (5–7 days) until a nearly stationary flow and pressure is reached before the test probe is lowered in the borehole. The flow to the borehole can be measured in two ways; sequential and an overlapping mode. In sequential mode the measurement increment is as long as the test section length. This mode is used to determine the transmissivity and the hydraulic head in 5 m sections along the borehole. In overlapping mode the test section is moved in small increments, e.g. 0.1 m along the borehole. This method is used to locate the position of conductive fractures and its transmissivity. Two different data sets, called TD-5m and TD_a, respectively are produced from these measurements and reported to Sicada. TD-5m represents the estimated transmissivity for 5-m sections while TD_a shows the transmissivity for each detected fracture in the borehole. The positions of the identified conductive fractures are also stored in Sicada. The methodology of PFL is presented in test reports from SKB site investigations, e.g. Sokolnicki et al. (2006).

3.4 Important differences between injection tests and difference flow logging

One of the major conceptual differences between PFL and PSS3 is the disturbance time in the borehole/section before and during the tests. The normal time of injection in PSS3 test is 20 minutes making the radius of influence rather limited, especially in low-transmissive sections. On the other hand, in difference flow logging the borehole has been pumped during several days which imply that a nearly steady-state flow prevails and thus information about the interconnected, transmissive network of fractures far away from the borehole is obtained.

Further, as discussed by Follin et al. (2007, 2011), in injection tests the investigated transient flow field is smaller and may thus also sample isolated fractures close to the borehole. For example, sections showing apparent NFB (isolated fractures or fractures with decreasing aperture) during injection tests often have lower transmissivities from the PFL method, more representative of the long-term conditions of the interconnected fracture network. This fact is assumed to be due to the longer pumping time and radius of influence for the latter period making flow boundaries dominant. This effect is further studied in this report.

The transmissivity of 5 m sections and identified fractures in PFL is estimated from the measured flows and the applied drawdown in the borehole during difference flow logging by steady-state methods (Thiem's or Dupuit's formula) assuming cylindrical (radial) flow (PRF) to the borehole. Thus, neither deviating flow regimes nor skin effects are considered by the calculation of transmissivity. Furthermore, the ratio R/r_0, i.e. the radius of influence divided by the borehole radius was assumed to 500 in difference flow logging in SKB site investigations.

Thus, at least some of the observed discrepancies in estimated transmissivity from difference flow logging and injection tests respectively may depend on the above assumptions and test conditions. A discussion of potential uncertainties in the estimation of transmissivity in difference flow logging is presented in Ludvigson et al. (2002).

4 Methodology

4.1 Data used

4.1.1 Injection tests and difference flow logging

Results from injection tests in 5 m sections in boreholes KFM04, KFM08A and KFM10A were used in this study. The number of injection tests in 5 m sections in a borehole is dependent on several considerations. Firstly, the boreholes are tested with longer test sections (100 m and 20 m). If a test with a longer section resulted in a final flow rate very close to or below the test-specific flow rate this section was not tested with 5 m section length. Secondly, in some cases a certain part of a borehole was not tested in 5 m sections for other reasons, c.f. KFM04A.

Only injection tests with a final (test-specific) flow rate above the measurement limit are included in this study since no interpretation of flow regimes was made for test below this limit. In KFM08A, in 22 of the tested 5 m sections pressure pulse tests were performed instead of injection tests. These sections showed signs of a very low transmissivity prior to the test. Results from pressure pulse tests are not included in this study since flow regimes were not identified from these tests. The pressure pulse tests are therefore not included in Table 4-1.

In addition, results from difference flow logging in the corresponding 5 m sections were used. Both the estimated transmissivity in 5 m sections from the sequential logging (TD-5m) as well as the sum of transmissivities of the identified flow anomalies within these sections from the overlapping logging (sum of TDa-5m) are used in this study.

Table 4-1 displays the number of injection tests in 5 m sections, corresponding TD-5m sections and injection test sections including at least one flow anomaly in the sum of TDa-5m. In addition, the number of corresponding sections with a transmissivity with Value type=0 (i.e. value within the measurement range) is shown for the injection tests and TD-5m, respectively. Finally, the last two columns in Table 4-1 show the number of injection tests with a Value type of 0 and the number of corresponding sections from difference flow logging (TD-5m and sum of TDa-5m) with a transmissivity above the practical measurement limit. In the lower part of Table 4-1 the measured intervals with 5 m sections in the selected boreholes are shown.

Table 4-1. Number of injection tests in 5 m sections in KFM04A, KFM08A and KFM10A and corresponding sections measured with TD-5m and sum of TDa-5m sections. Value type 0 indicates number of tests above the test-specific lower measurement limit for each method. In the lower part of the table the measured intervals with 5 m sections in the selected boreholes are shown.

Borehole	Injection tests (5 m)		Corresponding TD-5m sections		Injection sections including at least one TDa	Sections with Value type=0 for both injection test and:	
	Total	Value type=0	Total[1)]	Value type=0[2)]		TD-5m	Sum of TDa-5m
KFM04A	32	19	31	8	8	8	8
KFM08A	38	36	36	18	24	18	24
KFM10A	64	47	63	27	28	26	27
Total	**134**	**102**	**130**	**53**	**60**	**52**	**59**

Borehole	KFM04A	KFM08A	KFM10A
Measured intervals with PSS3 in 5-m sections	297–437 517–537	104–304 404–429 449–484 684–704 784–804	62.9–182.9 262.9–382.9 422.9–492.9

[1)] When correlating the PSS3- and TD-sections, two TD-sections were summed up into the same Injection test-section as described further in Section 4.2.

[2)] Includes a few sections with TD-5m values below the practical measurement limit, classified as uncertain.

Table 4-1 indicates that more test sections are above the test-specific measurement limit for injection tests than for TD-5m. For example, of 32 injection tests in KFM04A, 19 tests were above the measurement limit. The corresponding number for the TD-5m sections was only 8 out of 31. This fact can be expected since the test-specific lower measurement limit for injection tests generally is in the range of $1–3 \cdot 10^{-10}$ m^2/s while the lower practical measurement limit for TD-5m in most cases is in the order of $1–3 \cdot 10^{-9}$ m^2/s. Nevertheless, this fact is important to keep in mind in this study since comparisons of injection tests and difference flow logging tests in e.g. cross plots are best suited when both tests show transmissivity values above the lower measurement limit. Hence, the population of tests that can be included in the analyses is often restricted by the difference flow logging results when correlating injection and PFL-tests. For example, when correlating flow regimes to the transmissivity from both injection tests and the sum of TDa-5m from PFL-tests, totally 59 tests are available for analysis while a total of 102 tests are available for analysis when correlating flow regimes only to the transmissivity of injection tests.

4.1.2 Rock and fracture properties

Information in Sicada about the cores in the boreholes was used. The number and aperture of open and sealed fractures together with different rock and fracture domains and deformation zones are used for correlations in this study. These data, which were plotted and correlated to transmissivity and flow regimes, are presented in the overview plots for each borehole, c.f. Section 5.1.

One item studied in this project is if the amount and type of fractures affect the type of flow regime evaluated for the section from the injection tests. In Sicada, information about position of each fracture is stored and if it is open or sealed. There is also a third group called partly open fractures. In this study the latter fractures have been included in the open fracture category. The centre position of every fracture has been compared with the 5 m sections used by the injection tests with PSS3 and summed up into each section, sealed and open separated. The amount of fractures in a certain section was plotted in a histogram (see Figures 5-14 to 5-19). If a tested section displayed a certain flow regime this was plotted in the same diagram to see if the number of fractures affected the type of flow regime.

The rock domains, deformation zones and fracture domains in each borehole are categorized in Sicada. These domains and zones have been plotted in the overview plots (Figures 5-1 to 5-3) to be able to see if these features affect the type of flow regime evaluated, estimated transmissivity or other results.

4.2 Data structuring

The representative data regarding transmissivity, rock properties etc. were gathered from the Sicada data base and copied into an Excel-sheet. Information about flow regimes is not included in Sicada and therefore gathered from earlier P-reports. The information was then structured in Excel so that comparisons of different types of properties for a certain borehole section were possible.

Since the flow regimes derived from the injection tests are the key component in this study, other characteristics such as results from PFL measurements and geologic information were structured in order to fit the section limits of the PSS3 injection tests. Some information such as the number of fractures was rather straight forward to structure since it only required a simple summation of the observed fractures within each PSS3 test section. Other information such as transmissivity from PFL requires more attention when structuring it to fit the PSS3 section limits.

As mentioned earlier in this report, two types of transmissivity values are produced with the PFL difference flow logging (TD-5m and TD_a). TD_a is reported as the transmissivity of a flow anomaly in 0.1 m intervals. Hence, it is straight forward to fit TD_a to the PSS3 section limits with a simple summation of existing TD_a within each PSS3 test section (sum of TDa-5m). The centre of each TD_a was used to fit the PSS3 section limits.

Fitting TD-5m correctly to the PSS3 section limits is somewhat more complicated since the section limits of TD-5m and PSS3-5m often differs slightly. In most cases the TD-5m sections were assigned in the comparision to the closest PSS3 test section. For example, if a TD-5m section is 150–155 m and the closest two PSS3 test sections were 148–153 m and 153–158 m, TD-5m was correlated to the first PSS3 test section. However, if a flow anomaly (TD_a) exists within the TD-5m section this anomaly will control the correlation of TD-5m to the actual PSS3 test section. Using the same example as above but adding a flow anomaly TD_a at 154.0 m will result in a correlation of the TD-5m section at 150–155 m to the PSS3 test section at 153–158 m instead. If two or more flow anomalies were found in the same TD-5m section, the position of the dominating anomaly (in terms of transmissivity) was used in the correlation of TD-5m to the actual PSS3 test section.

4.3 Analyses and interpretations

Within this study a number of parameters were analysed and related to each other in order to examine and detect possible correlations between the flow regimes and other characteristics of the test sections.

The following relationships and correlations were examined and analysed in this study:

- flow regimes and borehole, i.e., differences of the flow regime distribution between boreholes,
- flow regimes and borehole length,
- flow regimes and transmissivity,
- flow regimes and difference between transmissivity from PSS3 and PFL,
- transient and stationary PSS3-transmissivity correlated to PFL-transmissivity,
- flow regimes and fracture frequency,
- flow regimes and deformation zones,
- flow regimes and rock domains.

The analyses were performed by extraction and presentation of relevant data in figures and tables. The type of figures and/or tables used was depending on the type of data presented. The program used for preparation of figures in this study was Grapher, which works with data files compatible with sheets in Excel format. Thereby plotting of large amount of data is simplified.

It is important to keep in mind that most of the injection tests display several flow regimes, for example an early PLF transitioning to a later PRF. In these cases all reported flow regimes are used in the analyses. Hence, the test in this example is accounted for both as a PLF and as a PRF.

A detailed study focused on the difference between steady-state and transient transmissivity from PSS3 are PFL transmissity is presented in Appendix 1.

5 Results

5.1 Overview plots

To give a concise picture of all the data used for each of the three selected boreholes, overview plots are displayed in Figure 5-1 for KFM04A, Figure 5-2 for KFM08A and Figure 5-3 for KFM10A. The plots contain interpreted data of flow regimes, transmissivities from PSS3 and PFL tests, rock domains, fracture domains, deformation zones and open or closed fractures. On the Y-axis the borehole length is plotted. Firstly, the evaluated flow regimes for each 5-m injection test with PSS3 are shown, each colour representing one type of flow regime. Flow regimes are displayed for both the injection and recovery period. The flow regimes are organized according to the normal chronological order during a test, i.e. starting with PLF (WBS in the case of recovery), followed by PRF, PSF, PSS and finally NFB and CHB.

The next part of the figures shows representative transmissivity values from both the injection tests (T_R) and difference flow logging (sum of TD_a in 5 m sections). The last part of the overview plots displays fracture domains (FD) and deformation zones (DZ) as well as rock domains and finally the number of fractures within each PSS3 section.

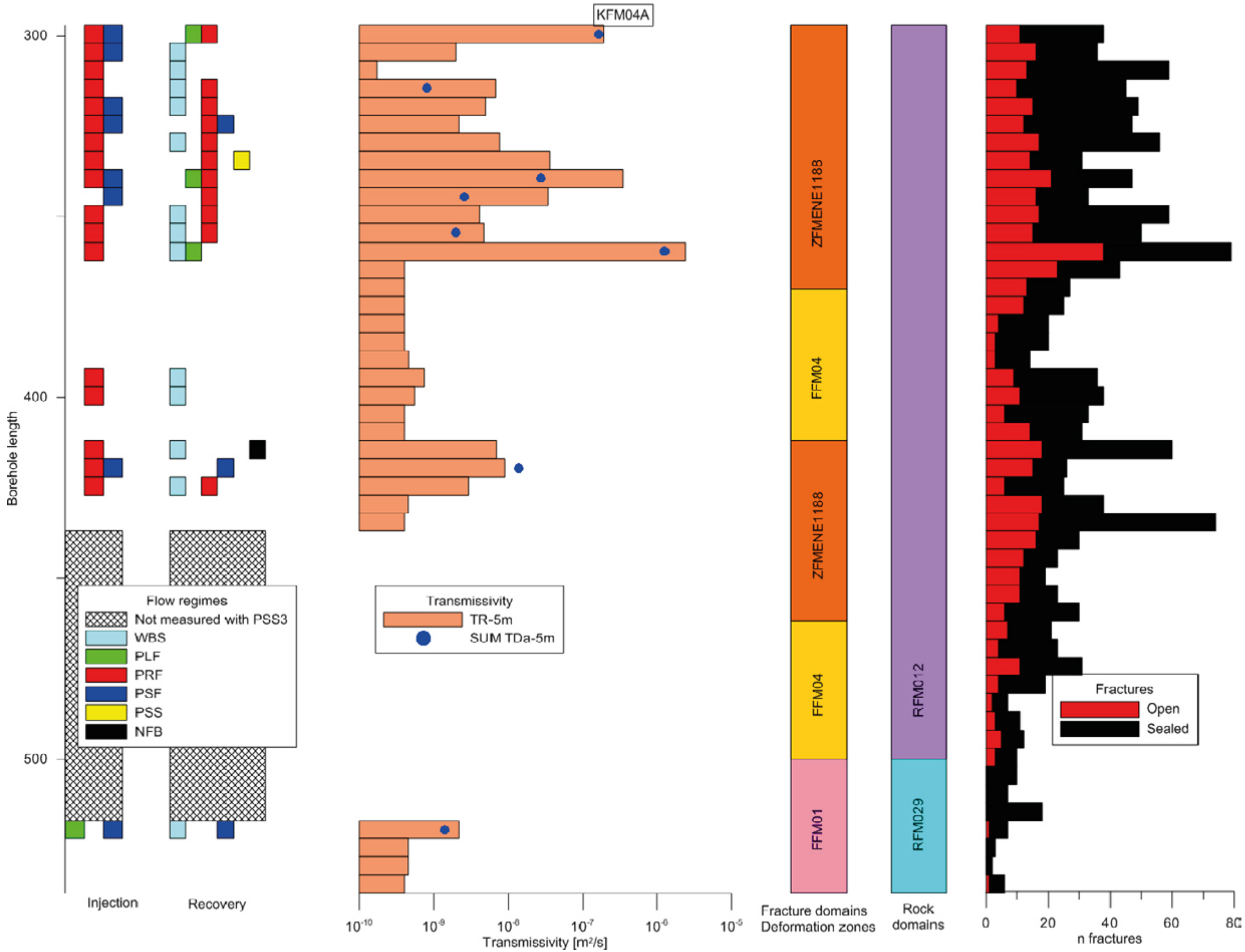

***Figure 5-1**. Overview plot for KFM04A showing interpreted flow regimes for the injection and recovery period, transmissivities, fracture domains and deformation zones, rock domains and number of fractures. These data are compared in the 5-m sections used during injection tests with the PSS3 equipment.*

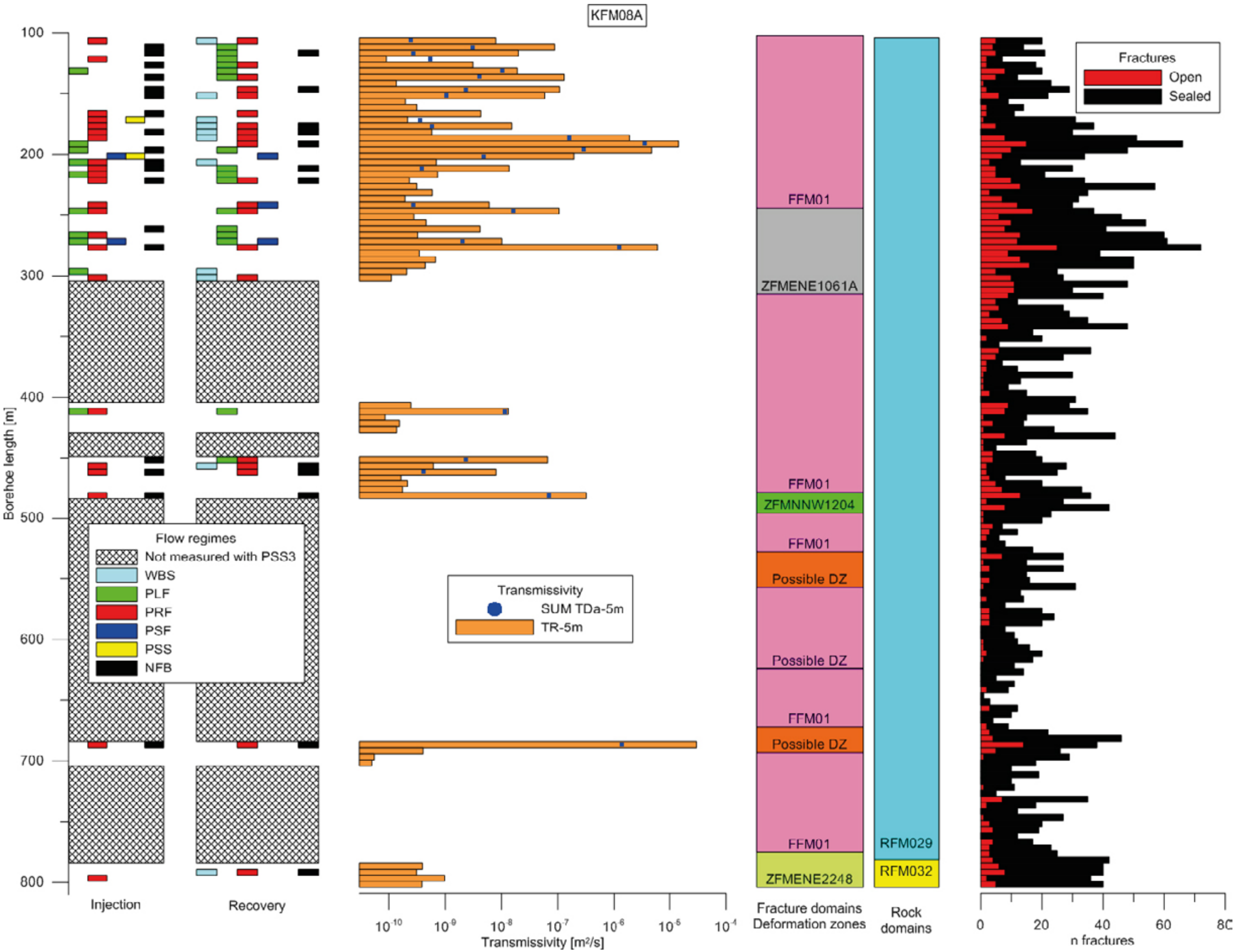

Figure 5-2. *Overview plot for KFM08A showing interpreted flow regimes for the injection and recovery period, transmissivities, fracture domains and deformation zones, rock domains and number of fractures. These data are compared in the 5-m sections used during injection tests with the PSS3 equipment.*

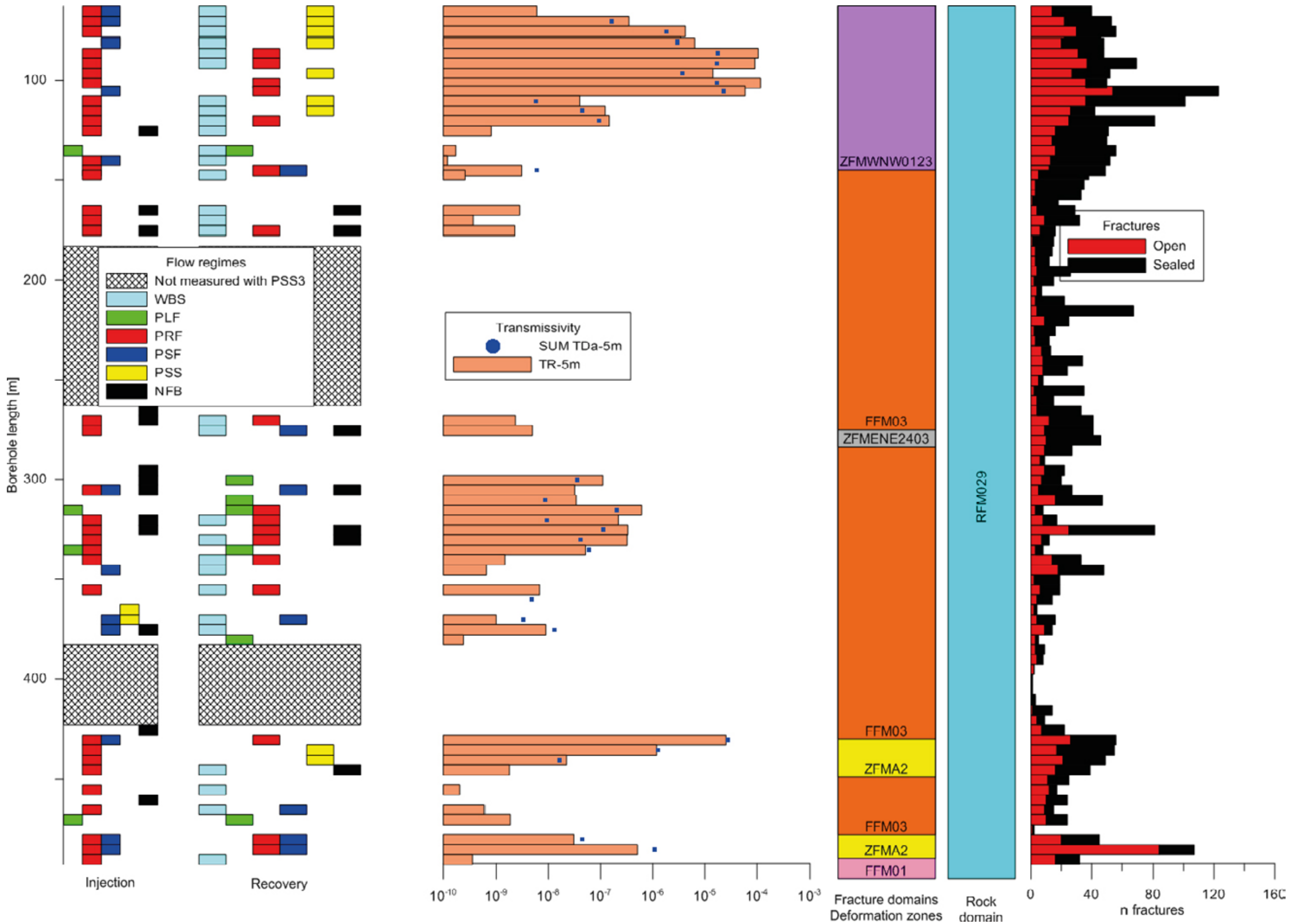

Figure 5-3. *Overview plot for KFM10A showing interpreted flow regimes for the injection and recovery period, transmissivities, fracture domains and deformation zones, rock domains and number of fractures. These data are plotted and compared in the 5-m sections used during injection tests with the PSS3 equipment.*

5.2 Interpreted flow regimes in the boreholes

In this section the interpreted flow regimes in the different boreholes are presented and discussed. Firstly, a comparison of the flow regimes interpreted during the injection and recovery period, respectively of the tests is made. Secondly, the frequency of interpreted flow regimes of certain types in the different boreholes is discussed. Finally, the distribution of flow regimes along the boreholes is studied.

5.2.1 Comparision of injection and recovery flow regimes

For all of the injection tests with a definable flow rate at least one flow regime is interpreted. In Table 5-1 the number of interpreted flow regimes from the injection tests in KFM04A, KFM08A and KFM10A is shown. All interpreted flow regimes are included in this table. For example, an injection period showing a PLF transitioning to a PRF contributes to both PLF and PRF. The first two columns display the number of each flow regime interpreted during the injection and recovery period, respectively. The last two columns show the number of test that display the actual flow regime during only the injection and recovery period, respectively. For example, 15 of the tests displayed a PLF during the injection period, but 3 of these tests did not display a PLF during the recovery.

In an ideal constant head injection test it is expected that the injection and recovery period would display the same flow regimes (except WBS). If this were the case for all tests in this study, the last two columns in Table 5-1 would only show zeros, but as seen in the table, this is clearly not the case. Several reasons may be found that may explain the observed inconsistency of flow regimes between the injection and recovery periods. Firstly, at the start of the injection period a certain time is required to achieve an approximately constant injection pressure. No flow regimes are possible to interpret from the injection period before a constant injection pressure prevails. Hence, early and short flow regimes (e.g. PLF) may therefore be masked by an unstable injection pressure leading to inconsistent responses during injection and recovery.

Early flow regimes may also be masked during the recovery period due to WBS. As visible in Table 5-1, 54 of the 101 tests display WBS during the recovery period. Hence, WBS may play an important part in explaining inconsistencies in early flow regimes between the injection and recovery period. These early disturbances in interpretation of flow regimes have the largest effect on the flow regimes that often develops early, i.e. PLF and PRF. Another possible reason for inconsistencies is the relatively short duration (c 20 min for each period) of the injection tests. Sometimes the flow regimes are developing at different times during the injection and recovery periods. For example, it is possible that a pseudo-steady state (PSS) is reached during the injection period but not during the recovery period. This effect mainly influences flow regimes which often develop at later times during the tests, i.e. PSF, PSS and NFB. Other reasons to inconsistent flow regimes during the injection and recovery period are discussed below.

Table 5-1 shows that the most common type of flow regime is PRF during both the injection and recovery period (WBS excluded). Then follows NFB, PSF, PLF and PSS in decreasing order during the injection period. During the recovery period PRF is followed by PLF, PSF, NFB and PSS in order. The lower number of PLF during the injection period may possibly be due to that this flow regime is sometimes masked by the pressure regulation to a constant injection pressure as discussed above. The lower number of PRF during recovery may sometimes depend on initial WBS which may result in that other flow regimes (e.g. PRF) are masked and not present during the duration of the recovery period. The number of PSF regimes is similar during the injection and recovery period whereas PSS is more common during recovery including tests with fast recovery, see below. Finally, the number of NFB is higher during the injection period. Possible reasons to this fact are discussed below.

Table 5-1. Number of interpreted flow regimes during injection and recovery periods in KFM04A, KFM08A and KFM10A. Total number of tests with interpreted flow regimes = 102.

	Inj	Rec	Only during Inj	Only during Rec
PLF	15	26	3	14
PRF	74	40	42	8
PSF	23	21	12	10
PSS	4	11	4	11
NFB	31	20	17	6
WBS	–	54	–	–
Total (except WBS)	**147**	**118**	**78**	**49**

As seen in Table 5-1, more flow regimes are interpreted for the injection period than for the recovery period (excluding WBS). This may point to that the recovery period in general is more affected by flow regime masking effects, such as WBS and limited test time than the injection period. Besides, the flow regimes during the injection period are in general considered as more representative for the hydraulic conditions of the rock near the tested borehole section whereas the flow regimes during the recovery period are assumed to be more representative of the conditions further away from the borehole. For these reasons, the flow regimes during the injection period are in general considered as more representative for the specific characteristics of the tested borehole section than the flow regimes during the recovery period. Consequently, the flow regimes from the injection period are the main focus in this study. In addition, in previous test reports from Forsmark the injection period was generally considered to provide the most representative value of transmissivity (Hjerne and Ludvigson 2005, Walger et al. 2006, 2007) which also supports the choice of the injection period as the main focus in this report.

A special case which may cause inconsistent behaviour between the injection and recovery period is when a fracture of limited extent (or with decreasing aperture) intersects the test section. As discussed in Ludvigson et al. (2007, Section 6.2) the transient response during the injection period may only show an apparent no-flow boundary (NFB) in such cases. During the recovery period a limited pressure recovery may occur in such tests, even in relatively high-transmissive sections. No unambiguous transient evaluation can in most cases be obtained from the injection period in such cases. However, the transient evaluation of the recovery period may sometimes provide a transmissivity in the same order as the steady-state transmissivity from the injection period (T_M). This fact will be more discussed in Section 5.4.

Furthermore, some tests display an unexpectedly fast pressure recovery. As discussed in Ludvigson et al. (2007) other factors may be assumed to influence these tests, e.g. turbulent flow in fractures intersecting the test section. Such factors may also cause inconsistent responses during injection and recovery.

5.2.2 Distribution of flow regimes in the boreholes

The measured intervals with injection tests in 5 m sections in the boreholes are shown in Table 4-1. In Figure 5-4 the percentages of interpreted flow regimes are shown for each borehole separately. For example, in c. 60% of the injection tests in KFM08A in 5 m sections a PRF were interpreted at some time during the injection period. Again, it should be noted that all interpreted flow regimes are included in Figure 5-4. For example, an injection period showing a PLF and a transition to a PRF contributes to both PLF and PRF in the figure. Hence, the sum of the different stacks in Figure 5-4 will be more than 100% for an individual borehole and test period.

Even though a larger test population would be desirable when making decisive conclusions, some significant differences are obvious when comparing the boreholes. Examples of observations which can be made from Figure 5-4 regarding interpreted flow regimes in the different boreholes include:

- **PLF:** KFM08A has a significantly higher frequency of PLF than the other boreholes during both injection and recovery.
- **PRF:** Rather high frequency of PRF during the injection period for all boreholes. Notably is that KFM04A has close to 90% of PRF during the injection period but only c 10% during the recovery period. This fact may possibly depend on the relatively high frequency of WBS in KFM04A which may have masked a PRF during the recovery. For comparison, KFM08A has around 60% of PRF during both periods.
- **PSF:** PSF is more common in KFM04A than in the other two boreholes, especially during the recovery period.
- **PSS:** Very few tests display PSS so any conclusions are rather uncertain.
- **NFB:** Large differences between boreholes since no NFB is interpreted for the injection period of KFM04A while c 30% and 50% of the tests in KFM10A and KFM08A, respectively, display NFB for the same period.
- **WBS:** WBS is more than twice as common in KFM04A and KFM10A as in KFM08A.

Considering the list above, it is clear that differences regarding flow regimes exist between the studied boreholes. However, the comparison between the boreholes does not reveal why these differences exist. Instead, the differences have to be correlated to other features of the boreholes to get such explanations as done later in this report.

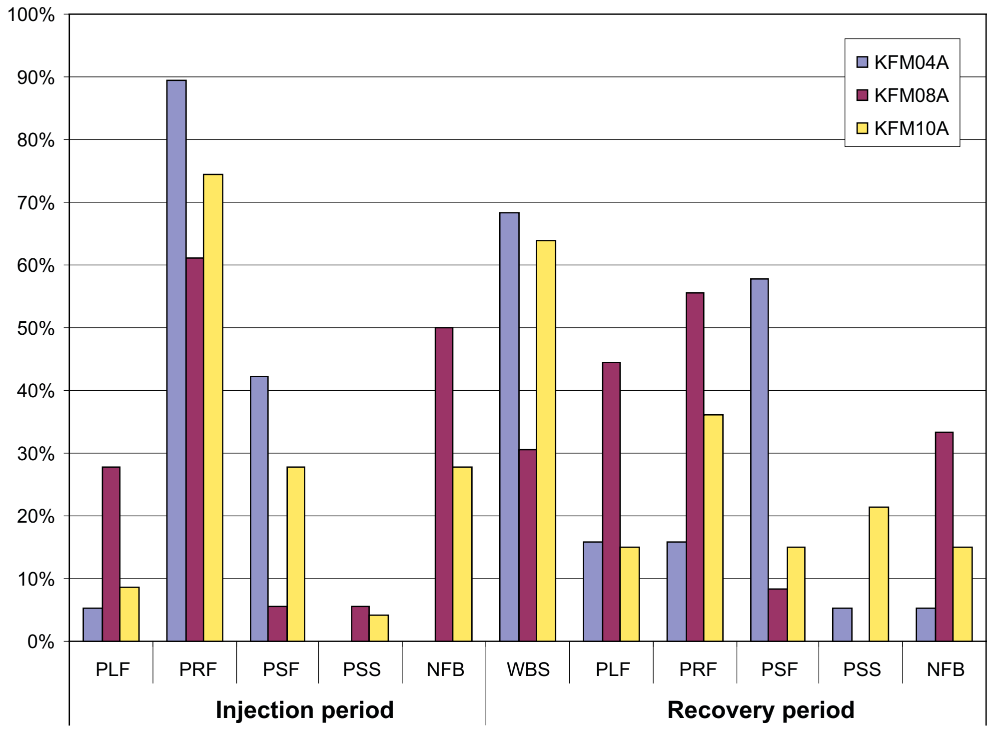

Figure 5-4. *Percentage of different types of flow regimes interpreted during the injection and recovery periods of injection tests in 5 m sections in KFM04A, KFM08A and KFM10A.*

5.2.3 Borehole length and flow regimes

In the overview plots of the boreholes, Figure 5-1, Figure 5-2 and Figure 5-3, the first two graphs in each plot show the interpreted flow regimes for each test plotted versus borehole length. If an obvious correlation between the flow regimes and the borehole length existed, the distribution of the flow regimes would be different along the borehole. However, no such obvious correlation may be observed in Figures 5-1 to 5-3. The three boreholes have approximately the same inclination, implying that there should not be any no obvious correlation between flow regime and depth either. Thus, the distributions of flow regimes are assumed to be relatively independent of borehole length (and depth).

5.3 Correlation of transmissivity and flow regimes

When analysing the correlation of flow regimes to the estimated transmissivity from the injection tests, several aspects may be considered. First of all, is it possible to find a correlation between the flow regimes and the reported transmissivity from the injection tests? Secondly, is there a correlation between the flow regimes and the difference between the transmissivity reported from the injection tests and difference flow logging, respectively?

5.3.1 Flow regimes and PSS3 transmissivity

The easiest way to study the correlation between the interpreted flow regimes and the reported (representative) transmissivity from the injection tests is to plot the test results in histograms as in Figure 5-5 and 5-6. In these plots the bins are divided by T_R and the number of tests within each bin may be viewed on the y-axis. The flow regimes showed in Figure 5-5 (PRF, PLF and PSS) and 5-6 (PSF and NFB) are interpreted from the injection period of the tests. No obvious correlation between the flow regimes and the transmissivity may be found in either Figure 5-5 (PRF, PLF and PSS) or Figure 5-6 (PSF and NFB) since the relative distribution of the flow regimes seems to follow the distribution of all tests.

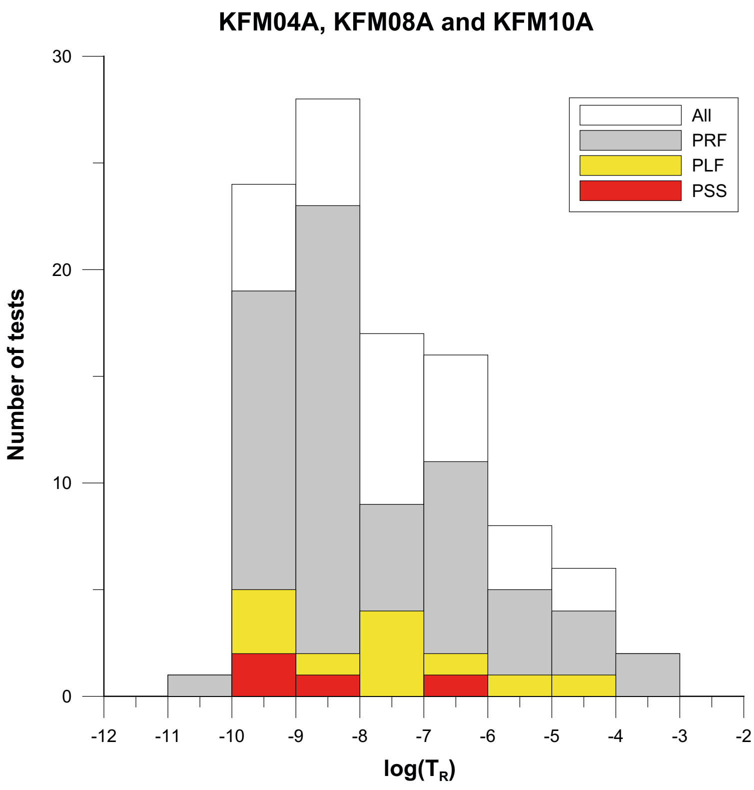

Figure 5-5. *Histogram showing the transmissivity distribution for all injection tests in KFM04A, KFM08A and KFM10A (white) together with the distribution of tests displaying PRF, PLF and PSS, respectively during the injection period.*

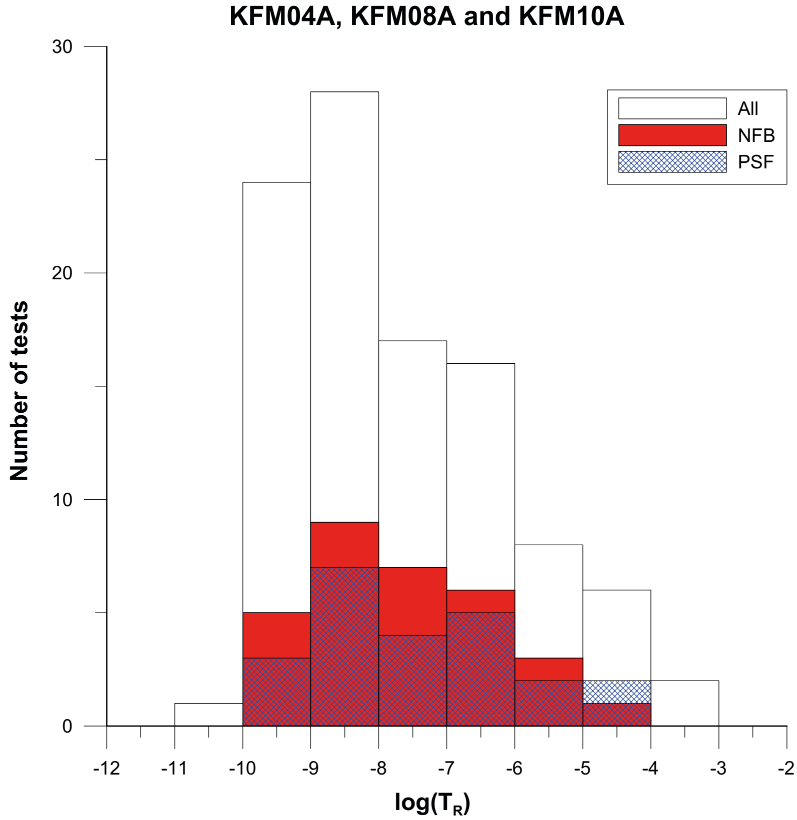

Figure 5-6. *Histogram showing the transmissivity distribution for all injection tests in KFM04A, KFM08A and KFM10A (white) together with the distribution of tests displaying NFB and PSF, respectively during the injection period.*

5.3.2 Flow regimes and the difference of PSS3 and PFL transmissivity

Two types of plots were used when analyzing the correlation between flow regimes and the difference between the PSS3 and PFL transmissivity; histograms and cross plots. In this chapter the sum of TD_a in 5 m sections was used as the PFL transmissivity instead of TD-5m. The main reason for this choice is that many of the TD-5m values are below the measurement limit. If the section below the measurement limit would be included in the cross plots and histograms below, they might conceal important results since the difference between T_R and TD-5m will not be correct if TD-5m is below the measurement limit. Hence, only injection tests with at least one identified TD_a within the section limits are included in the evaluations in this chapter.

The cross plots in Figure 5-7, 5-8 and 5-9 show the sum of TDa-5m on the x-axis and T_R on the y-axis. Each test section is indicated by a white circle filled with different colours and shapes according to the flow regimes interpreted during the injection period of that particular test. In general, most tests in Figures 5-7 to 5-9 are located above the 1:1-line indicating that T_R generally is higher than the sum of TDa-5m. This is especially true for KFM08A. KFM04A (Figure 5-7) only includes 8 tests so it may be hard to draw any decisive conclusions from this borehole regarding the importance of flow regimes and the difference between the sum of TD_a-5m and T_R. KFM08A (Figure 5-8) and KFM10A (Figure 5-9), on the other hand, include significantly more tests so they may be viewed in more detail. In KFM08A it is obvious that the tests showing NFB (indicated with +) are located far from the 1:1-line, indicating that tests with a NFB has a large discrepancy between the sum of TD_a-5m and T_R, the latter being significantly higher. This effect is also visible in KFM10A but not as pronounced as in KFM08A. Otherwise it is hard to see any obvious correlation between flow regimes and the difference between the sum of TDa-5m and T_R in Figures 5-7 to 5-9.

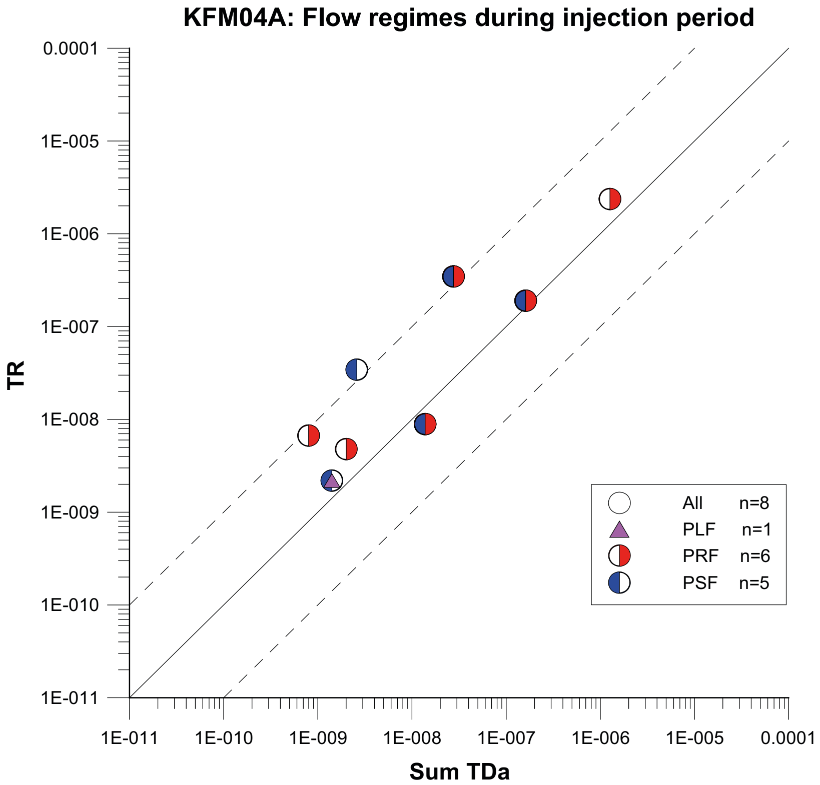

Figure 5-7. *Cross plot between the sum of TDa in 5 m sections versus TR in corresponding sections in KFM04A. Each ring corresponds to an injection test in which at least one flow anomaly from difference flow logging is reported. The flow regimes in each test are also marked.*

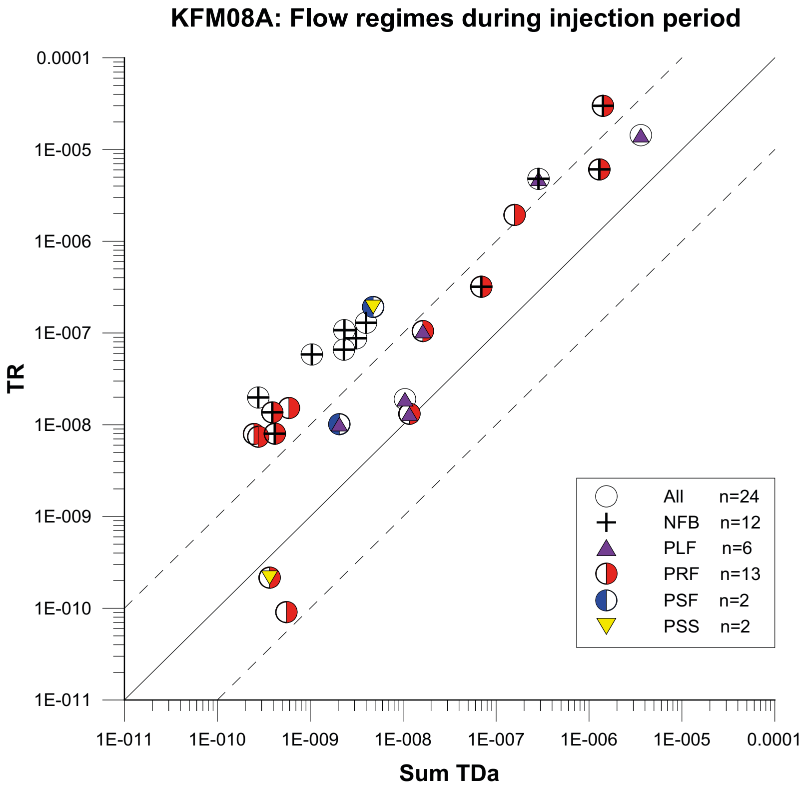

Figure 5-8. *Cross plot between the sum of TDa in 5 m sections versus TR in corresponding sections in KFM08A. Each ring corresponds to an injection test in which at least one flow anomaly from difference flow logging is reported. The flow regimes in each test are also marked.*

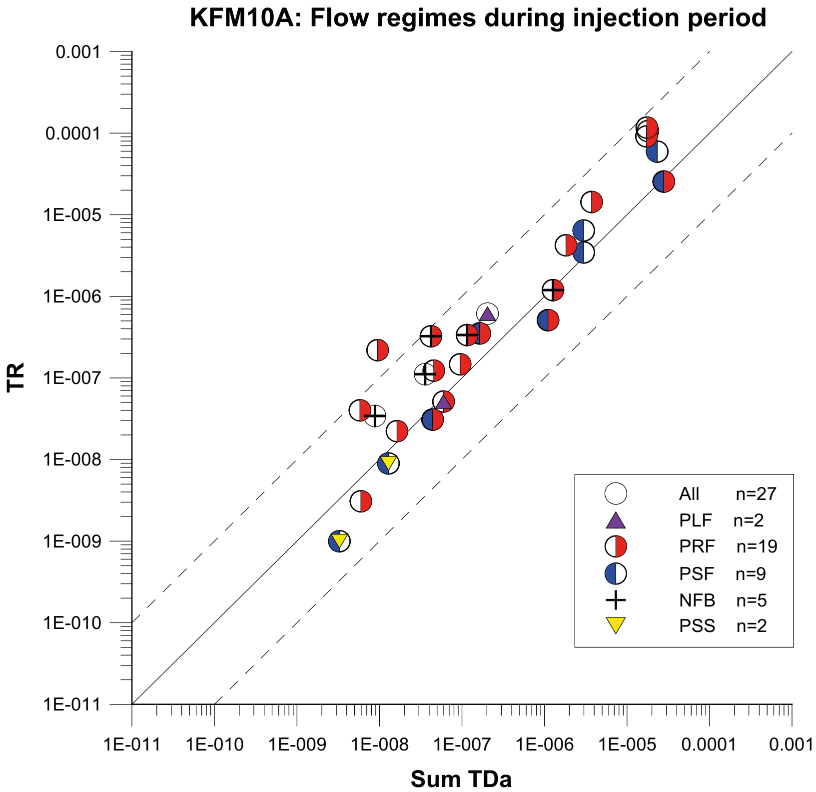

Figure 5-9. *Cross plot between the sum of TDa in 5 m sections versus TR in corresponding sections in KFM10A. Each ring corresponds to an injection test in which at least one flow anomaly from difference flow logging is reported. The flow regimes in each test are also marked.*

To study the effect of flow regimes on the difference between the sum of TDa-5m and T_R for the three boreholes together it is not practical with cross plots since the large number of tests will make the plots hard to analyse. Instead, histograms are presented in Figure 5-10 and 5-11 where the bins consist of the difference $\log(TD_a)$-$\log(T_R)$ and the number of tests within each bin may be viewed on the y-axis. Figure 5-10 displays the distribution of PRF and NFB while Figure 5-11 displays PLF, PSF and PSS. Both figures also display all tests included in the evaluation.

In both Figure 5-10 and 5-11 it seems that the distribution of all tests are rather symmetrical around c. –0.6 which means that the sum of TDa-5m generally are slightly lower than T_R. The distribution of PRF as visible in Figure 5-10 seems to follow the general distribution of all tests. Tests showing a NFB, on the other hand, are clearly shifted to the left in Figure 5-10, indicating that tests with a NFB during the injection period have a higher T_R than sum of TDa-5m than tests in general. This is consistent with observations in Figure 5-8 and 5-9 as discussed above.

The number of tests showing PLF, PSF and PSS during the injection period as displayed in Figure 5-11 is fewer than tests showing PRF and NFB, so the observations in Figure 5-11 are more uncertain than those in Figure 5-10. However, some interesting observations are made. The distribution of PLF seems to follow the general distribution of all tests as also PRF does. PSF, on the other hand, seems to be shifted to the right in the figure, indicating a rather small difference between T_R and the sum of TDa-5m when a PSF is interpreted during the injection period. There are only 4 tests indicating a PSS so any conclusions from this small population are very uncertain. However, three of the tests display a higher sum of TDa-5m than T_R while the last test has a much higher T_R than the sum of TDa-5m.

The median values of log(TDa)-log(TR), as presented in Table 5-2, support the observations made in Figure 5-10 and 5-11, i.e. the distributions of PRF and PLF are close to the general distribution of all tests; tests with NFB show a significantly lower median value while tests with PSF and PSS show a higher median value than the general distribution.

In the three studied boreholes, T_R is in general higher than the corresponding sum of TDa-5m. As shown above, the interpreted flow regime during the injection period is important for the magnitude of the difference between T_R and sum of TDa-5m for the individual tests. Tests with interpreted NFB has a predominance to have a much higher T_R than sum of TDa-5m while tests with PSF or PSS has a predominance to have a T_R close to sum of TDa-5m. Tests displaying PRF or PLF tend to follow the general difference between T_R and the corresponding sum of TD_a-5m.

The general discrepancy between T_R and TD_a-5m might be partly explained by the different pumping times for the two methods. In difference flow logging, the preceding flow period in the borehole before the flow measurements was much longer (several days) than the short flow period for the injection tests (20 min). Therefore, difference flow logging is assumed to predominantly measure interconnected, conductive fracture networks reaching further away from the borehole while the injection tests also may sample fractures with limited extension, close to the borehole.

Table 5-2. Median value of log(TDa)-log(TR) for all tests in KFM04A, KFM08A and KFM10A as well as tests displaying flow regimes during the injection period.

	All tests	PRF	PSF	PLF	NFB	PSS
log(TD_a)-log(T_R) median	–0.59	–0.52	–0.13	–0.48	–1.28	0.19

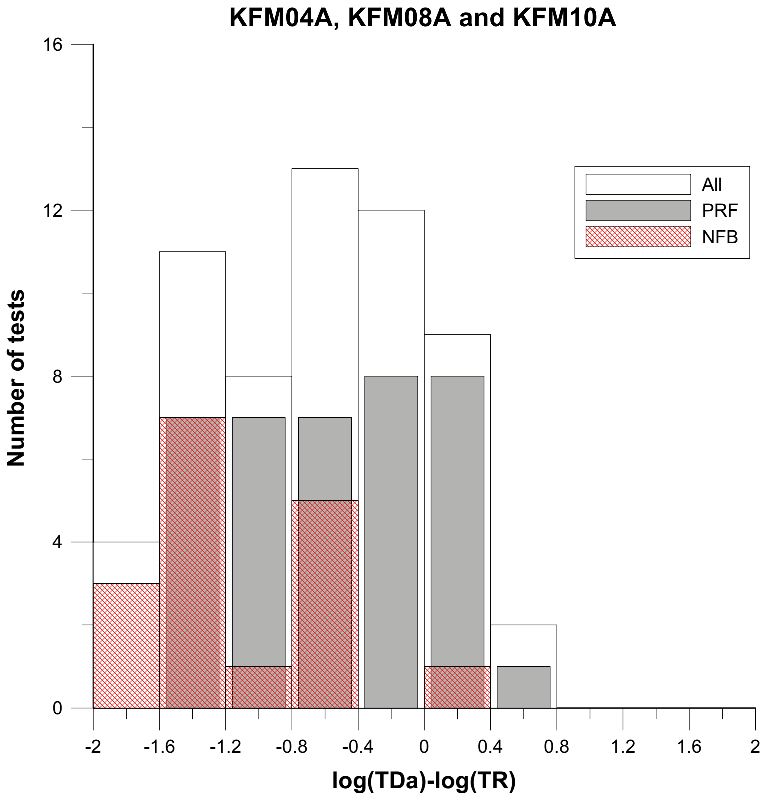

Figure 5-10. *Histogram showing the distribution of differences between the sum of TDa-5m and TR for all tests as well as tests displaying PRF and NFB in KFM04A, KFM08A and KFM10A.*

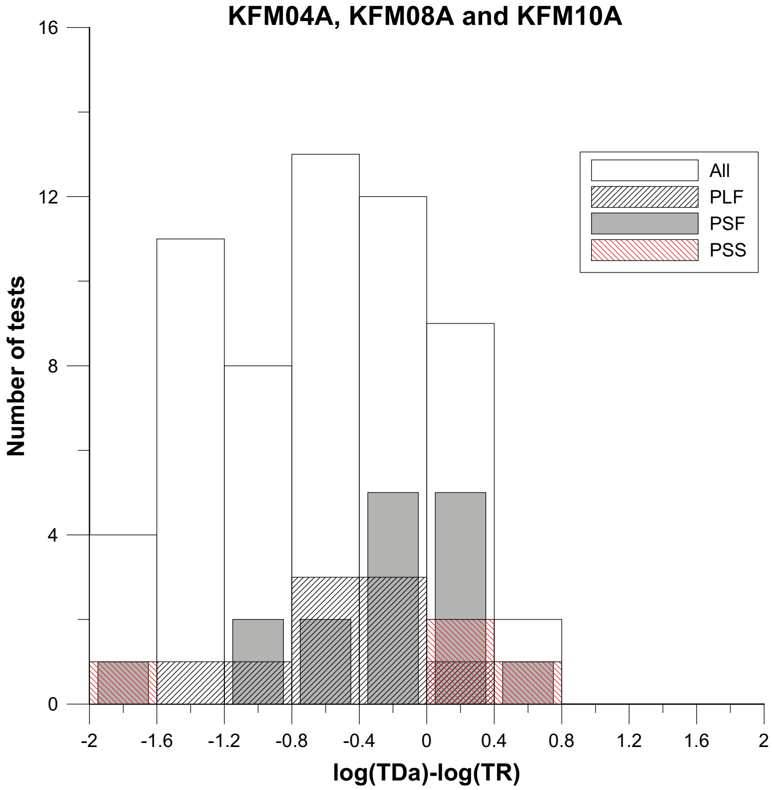

Figure 5-11. *Histogram showing the distribution of differences between the sum of TDa-5m and TR for all tests as well as tests displaying PLF, PSF and PSS in KFM04A, KFM08A and KFM10A.*

This fact may possibly explain the slightly higher T_R from the injection tests than the sum of TDa-5m from difference flow logging in some sections. It may be assumed that the fracture(s) in these sections have limited extent or decreasing aperture away from the borehole and are not connected to a larger fracture network. Thus, the flow capacity of such fractures is assumed to decrease with increasing flow times, frequently reflected by effects of apparent no-flow boundaries during the injection tests. However, during short injection tests, such effects may not always be seen. It should also be noted that the two methods differ regarding assumptions and associated uncertainties. Potential uncertainties for difference flow logging results are discussed in Ludvigson et al. (2002) and for injection tests in Andersson et al. (1993).

5.4 Flow regimes and pressure recovery

In this section selected results from the previous sections are presented in diagrams and discussed. In these diagrams the results from all studied boreholes are included. Figure 5-12 shows the distribution of pressure recovery (fraction) for all tests above the test-specific measurement limit and for tests showing PRF and NFB, respectively according to the interpreted flow regimes during the injection period in the overview Figures 5-1 to 5-3. The figure shows that the number of tests with low recovery is dominated by tests exhibiting NFB, particularly for a recovery lower than 0.4. As discussed above, several of these test sections show a rather high steady-state transmissivity from the injection period. This observation is consistent with the previous presentations in Section 5.4.

Some of the tests show a pressure recovery less than 0 and higher than 1, respectively. These conditions may arise when the pressure is slightly increasing after stop of injection in low-transmissive sections and when the final pressure goes slightly below the starting pressure, respectively.

Figure 5-13 shows the same distribution for all tests and for tests showing PLF, PSF and PSS, respectively. The figure shows that tests exhibiting PSF and PSS generally have a high recovery whereas tests with PLF have lower recovery. This observation is also consistent with previous presentations. However, during some of the latter tests PLF still continued at the end of the injection period which may indicate flow in a single fracture.

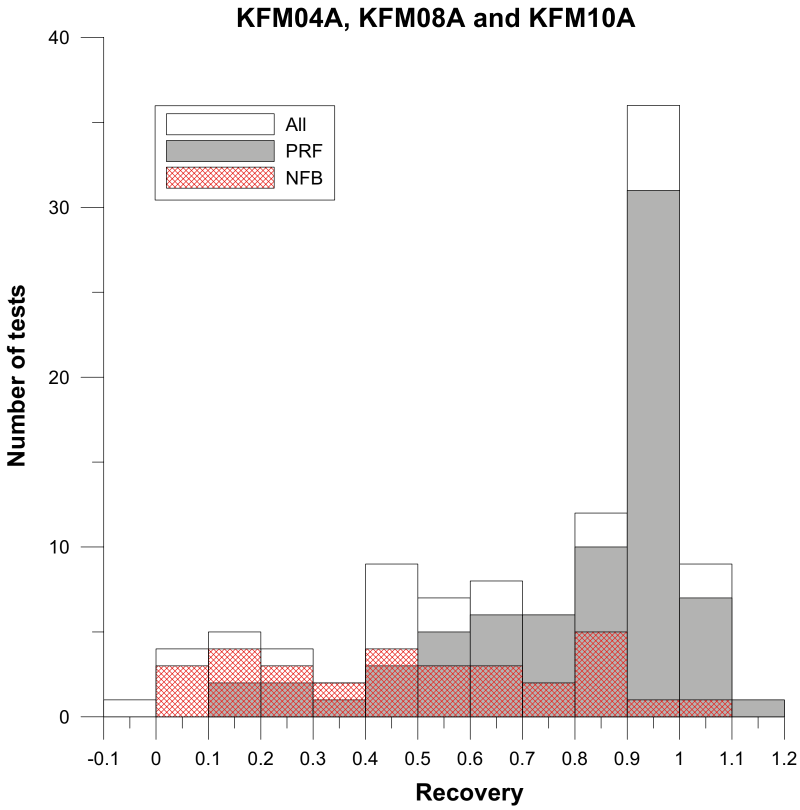

Figure 5-12. *Distribution of pressure recovery (fraction) for all injection tests above the measurement limit and for tests showing PRF and NFB, respectively in 5 m sections in boreholes KFM04A, KFM08A and KFM10A.*

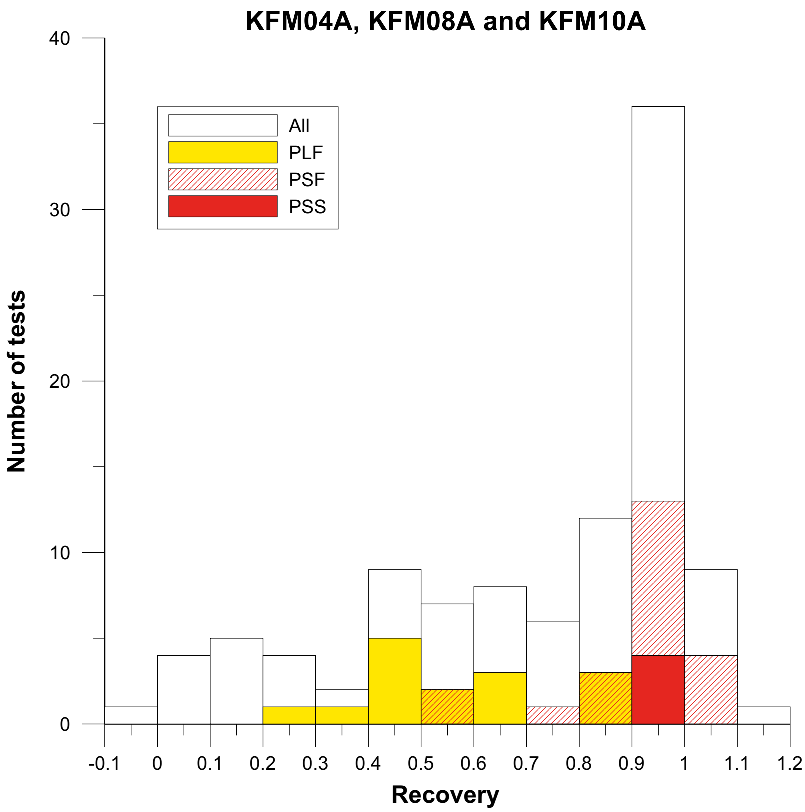

Figure 5-13. *Distribution of pressure recovery (fraction) for all injection tests above the measurement limit and for tests showing PLF, PSF and PSS, respectively in 5 m sections in boreholes KFM04A, KFM08A and KFM10A.*

5.5 Flow regimes and fracture frequency

In Sicada, all the fractures in the cores are reported and classified (Carlsten et al. 2004, 2005, 2006). As described in Chapter 4.1.2 they are separated in three categories: sealed, partly open and open, respectively. In this study the partly open and open fractures were summed up together. The total number of fractures is the sum of open and sealed. For a detailed view of the number of fractures within each test section, refer to Figures 5-1 to 5-3. No Terzaghi corrections are performed within this study of fracture frequency. As previously mentioned in this report, a certain test may be accounted for several times if more than one flow regime was interpreted during the test.

Table 5-3 shows the median number of fractures found in the tested sections of the boreholes for all studied sections together as well as divided into tests displaying different flow regimes. Table 5-3 also shows the number of tests within each category in the bottom row. Generally, there are more sealed fractures than open fractures. The fracture frequency for different flow regimes in Table 5-5 is rather similar. However, some differences may be seen. Injection tests displaying PSF and also to some extent PRF generally has a higher fracture frequency than injection tests with a PLF or NFB. The tendency is the same for both open and sealed fractures. However, it is more pronounced for open fractures. Obviously, the same tendency is visible for total fracture frequency. There are only four tests overall that have a PSS, hence any conclusions about PSS will be rather uncertain.

The data used in Table 5-3 may also be shown graphically. The fracture frequency distribution for different flow regimes as well as for all tests above the measurement limit is shown in histograms in Figures 5-14 to 5-19. The x-axis shows the number of fractures found in the injection test sections while the y-axis shows the number of injection tests within each group. Figure 5-14 and 5-15 show the total number of fractures, Figure 5-16 and 5-17 the open fractures and Figure 5-18 and 5-19 the sealed fractures.

In Figures 5-14 to 5-19 it may be seen that the distributions of PSF and also PRF are shifted more to the right (more fractures) than the distribution of NFB and PLF. The difference between the flow regimes seems to be more distinct for the open fractures (Figures 5-16 and 5-17) than the sealed (Figure 5-18 and 5-19). The general distribution is closely correlated to PRF which is natural since a majority of the tests display PRF. These results are consistent with the results in Table 5-3.

Table 5-3. The median number of fractures in 5 m injection test sections with a transmissivity above the lower measurement limit in KFM04A, KFM08A and KFM10A.

			Flow regime during injection period				
	Fracture type	All tests	PRF	PSF	PLF	NFB	PSS
Median number of fractures	Sealed	25	26	26	20	23	19.5
	Open	11	12	15	8	6	5.5
	Total	36.5	37	45	25	28	23.5
Number of injection tests		102	74	23	15	31	4

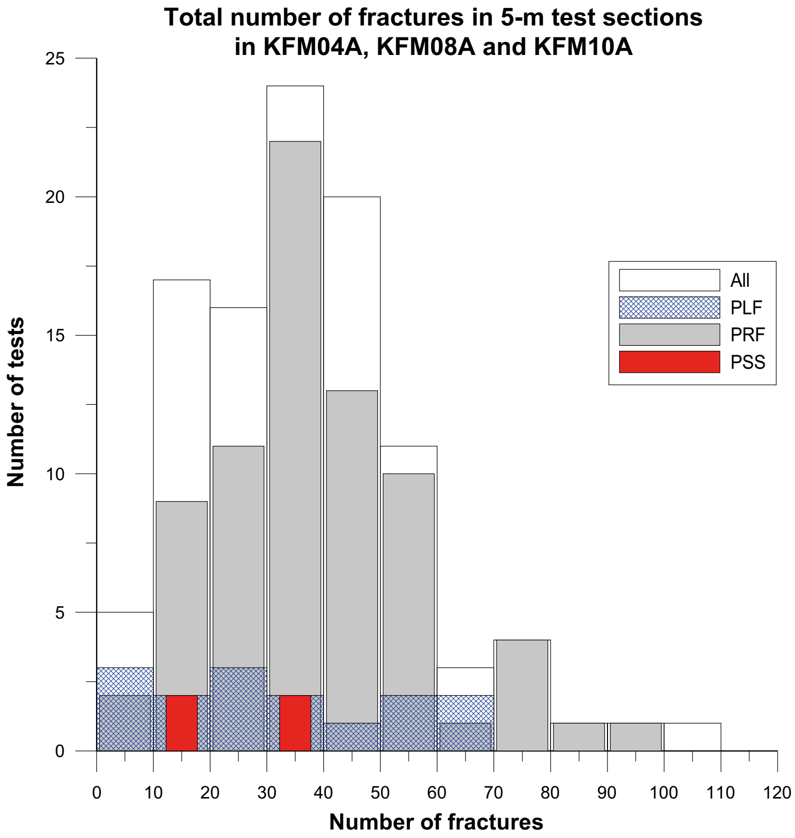

Figure 5-14. Distribution of the total number of fractures in injection tests section with a detectable flow rate, overall and for the flow regimes PLF, PRF and PSS.

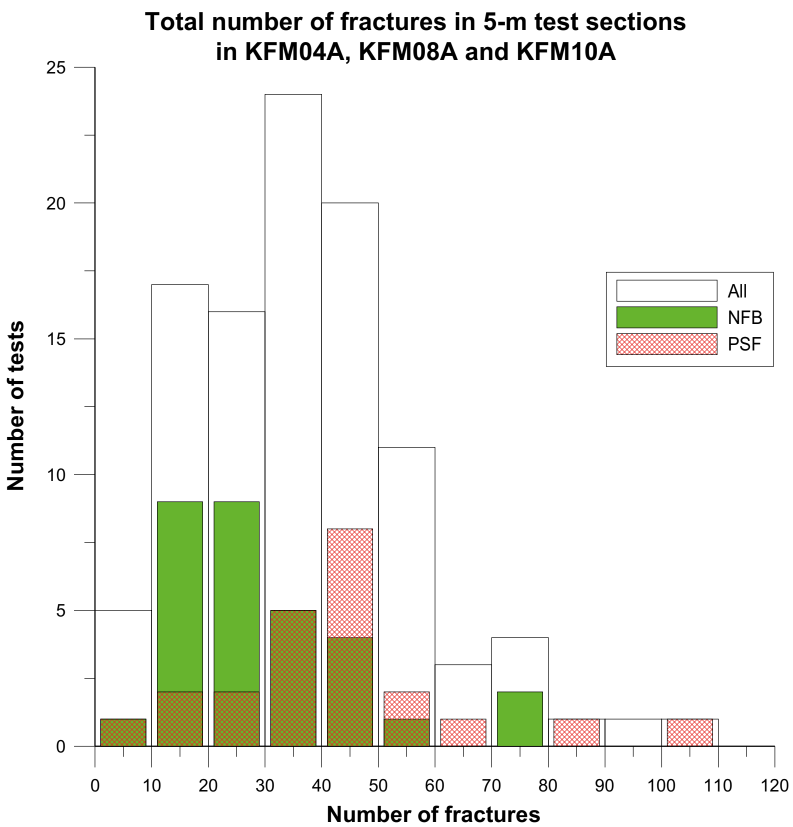

Figure 5-15. Distribution of the total number of fractures in injection tests section with a detectable flow rate, overall and for the flow regimes PSF and NFB.

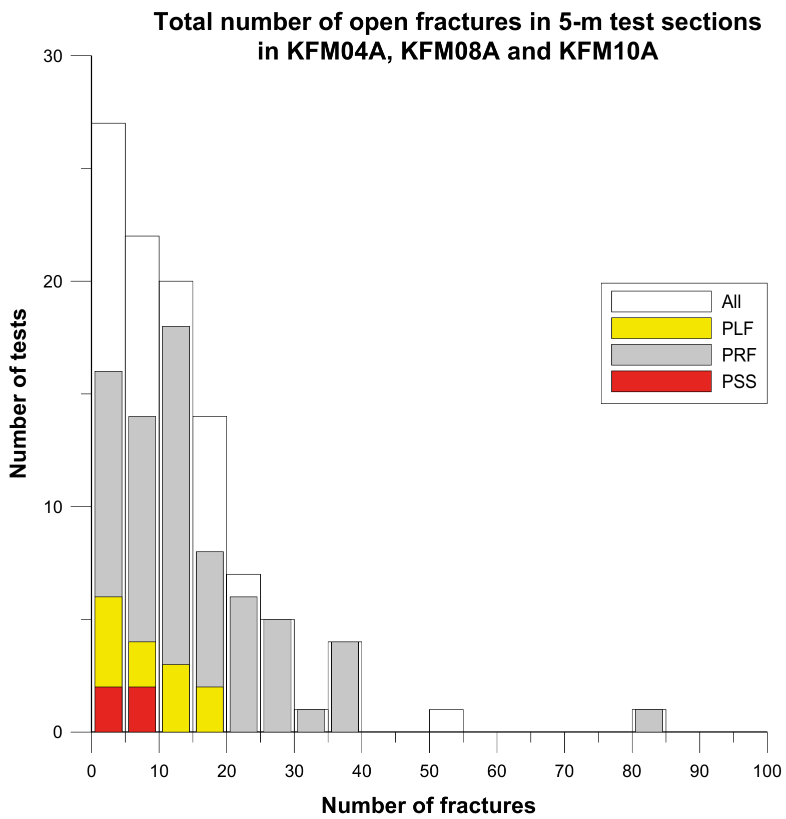

Figure 5-16. *Distribution of the open number of fractures in injection tests section with a detectable flow rate, overall and for the flow regimes PLF, PRF and PSS.*

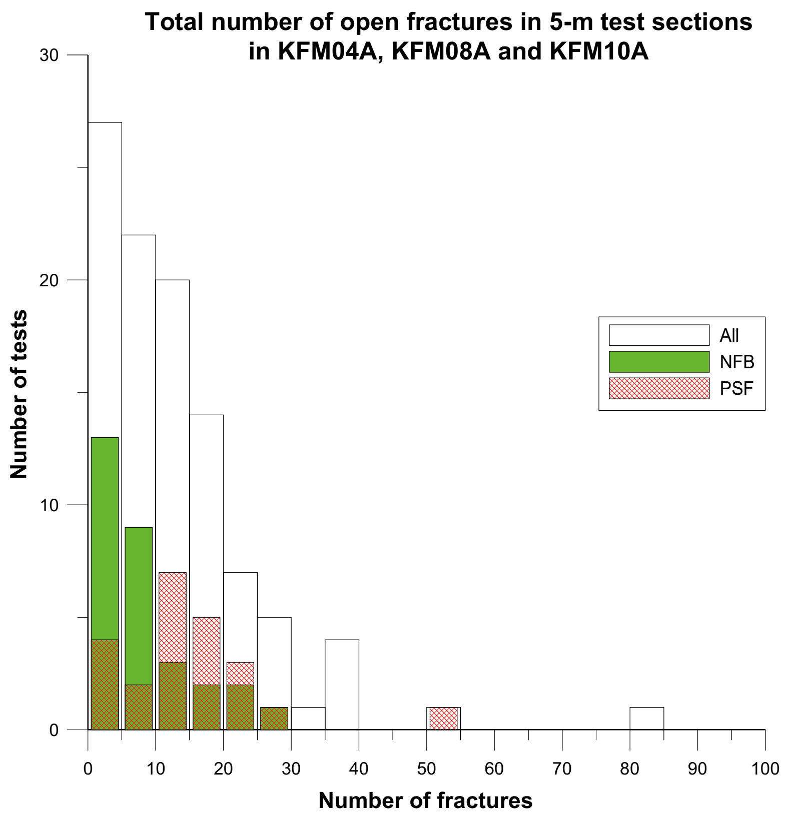

Figure 5-17. *Distribution of the open number of fractures in injection tests section with a detectable flow rate, overall and for the flow regimes PSF and NFB.*

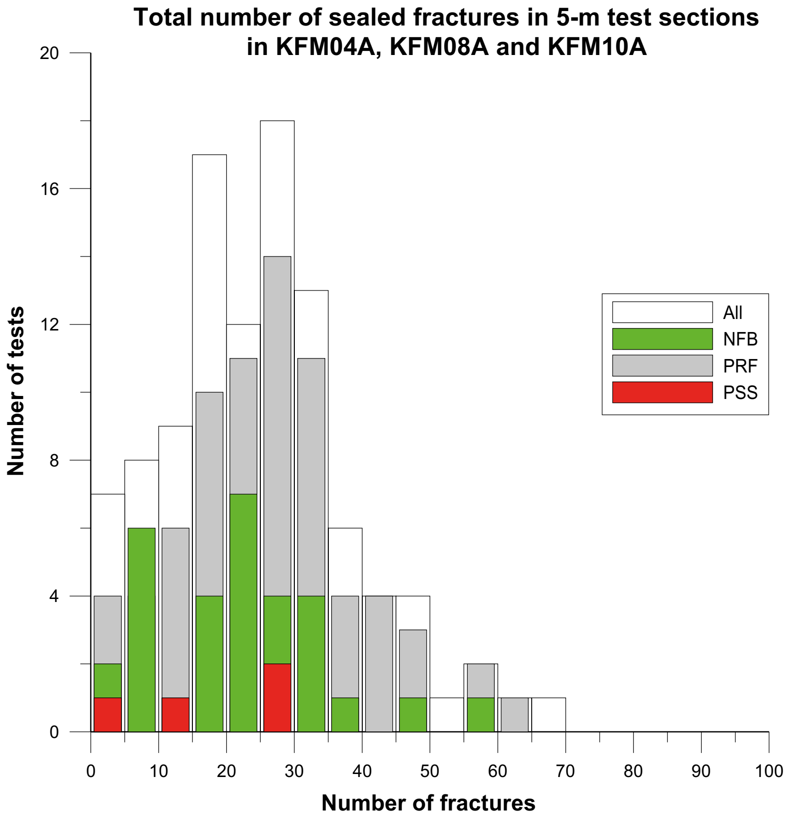

Figure 5-18. *Distribution of the sealed number of fractures in injection tests section with a detectable flow rate, overall and for the flow regimes PRF, PSS and NFB.*

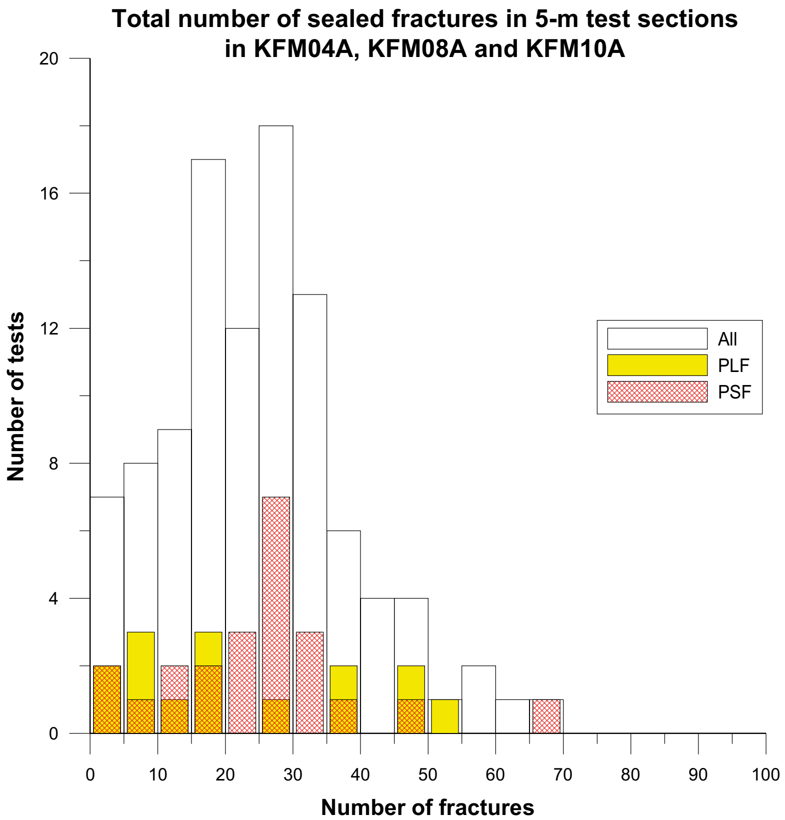

Figure 5-19. *Distribution of the sealed number of fractures in injection tests section with a detectable flow rate, overall and for the flow regimes PSF and PLF.*

5.6 Flow regimes and deformation zones

Within the Forsmark site investigation, the boreholes KFM04A, KFM08A and KFM10A, are divided into sections of either deformation zones or fracture domains (Carlsten et al. 2004, 2005, 2006). These domains or zones might appear in several boreholes and is therefore assigned names in Sicada for comparisons between boreholes. In this study the specific domains and zones are not analysed individually which of course is possible. However, in many domains and zones very few tests are performed and conclusions about the data would be difficult. Hence, the injection tests are only divided into fracture domains and deformation zones. For a detailed view of the fracture domains and deformation zones within the studied borehole sections, refer to Figures 5-1 to 5-3.

Table 5-4 below shows the distribution of tests for different flow regimes between fracture domains and deformation zones. The number of tests for each flow regime is also displayed. In total, approximately half of the tests are performed in fracture domains and half in deformation zones. Tests with NFB and PLF are more common in fracture domains than in deformation zones while the opposite is true for tests displaying PSF. Noticeable is also that tests with PSS are only found in fracture domains, however only four tests display PSS why this results is rather uncertain.

Table 5-4. Number of tests in fracture domains or deformation zones and their interpreted flow regimes during the injection period for KFM04A, KFM08A and KFM10A.

	Tests (Value type 0)					
	Total	PLF	PRF	PSF	PSS	NFB
Total number of tests	102	15	74	23	4	31
% in fracture domains	52%	67%	45%	26%	100%	77%
% in deformation zones	48%	33%	55%	74%	0%	23%

5.7 Flow regimes and rock domains

The rock volume within the Forsmark site investigation is divided into different rock domains (Carlsten et al. 2004, 2005, 2006). Five different rock domains are found in the three boreholes studied; RFM012, RFM018, RFM029, RFM032 and RFM034. However, injection tests with a 5 m test section were only performed in three of them as listed in Table 5-7. Only RFM029 were found in all three of the boreholes. For a detailed view of the rock domains in the boreholes, refer to over view plots in Figures 5-1 to 5-3.

Table 5-7 below shows the distribution of tests for different flow regimes between the different rock domains. The number of tests for each flow regime is also displayed. As seen in the table, the majority of the tests were performed in RFM029 (81%) and 18% in RFM012. RFM012 only appears in KFM04A within this study (c.f. Figure 5-1). In Table 5-5 it is evident that no NFB, PLF or PSS are displayed during the injection period in sections situated in rock domain RFM012 even though 18% of all tests included in this study were performed in RFM012. Hence, only PRF and PSF are found in RFM012. However, the lack of NFB or PLF in RFM012 may depend on the fact that RFM012 only is found in KFM04A within this study. Hence, this result may be an artefact of some other unknown characteristic of KFM04A rather than a true characteristic of RFM012. With the data set available in this study it is not possible to judge whether it is the character of RFM012 or KFM04A that excludes NFB and PLF. Note that only four tests with PSS exist within the study so conclusions about PSS are thus uncertain.

Table 5-5. Injection tests in rock domains and their interpreted flow regimes during the injection period for KFM04A, KFM08A and KFM10A.

	Tests (Value type 0)					
	Total	PLF	PRF	PSF	PSS	NFB
Total number of tests	102	15	74	23	4	31
% of tests in RFM012	18%	0%	23%	30%	0%	0%
% of tests in RFM029	81%	100%	76%	70%	100%	100%
% of tests in RFM032	1%	0%	1%	0%	0%	0%

6 Conclusions

It should be emphasised that the following conclusions are only based on the three studied boreholes (KFM04A, KFM08A and KFM10A). To obtain more certain conclusions about flow regimes and their dependence on other factors a larger data set would be preferable in some parts of this study. Similar studies has previously been made by Follin et al. (2011) for boreholes KFM02A, KFM03A and KFM06A in Forsmark. However, several aspects of flow regimes such as correlation with fracture frequency and rock domain included in the present study were not analysed by Follin et al. (2011).

The following conclusions may be drawn from the results regarding KFM04A, KFM08A and KFM10A presented in Chapter 5 in this report:

- The overall distribution of interpreted flow regimes deviate considerably between the three studied boreholes. In all boreholes a certain period of pseudo-radial flow (PRF) could be identified during the injection period in most of the tests. However, in KFM04A and KFM10A a higher frequency of PRF and higher flow dimensions (PSF) were observed. In KFM08A, an increased frequency of lower flow dimensions e.g. pseudo-linear flow (PLF) was found. Furthermore, apparent no-flow boundaries (NFB) are much more common in KFM08A than in KFM04A and KFM10A.
- No clear relationship between interpreted flow regimes and borehole length (or depth) could be found in the three studied boreholes.
- No obvious correlation between the interpreted flow regimes and the magnitude of the representative transmissivity from the injection tests could be found for the three studied boreholes. For example, tests with e.g. PLF and PSF seem to render similar transmissivity distributions.
- The representative PSS3 transmissivity is generally higher than the PFL transmissivity. The magnitude of this discrepancy is in most cases correlated to the interpreted flow regimes during the injection tests. In particular, tests with interpreted NFB during the injection period frequently have a much higher PSS3 transmissivity than PFL transmissivity. On the other hand, tests with higher flow dimensions (PSF or PSS) predominantly have a PSS3 transmissivity close to the PFL transmissivity. Tests displaying PRF or PLF tend to follow the general difference between PSS3 and PFL transmissivity. Besides the importance of flow regimes for the discrepancy between transmissivity from injection tests and difference flow logging other conceptual differences between the two test types are important and is further discussed in Follin et al. (2007, 2011).
- There is a tendency that test sections displaying NFB or PLF has a lower fracture frequency while test sections displaying PSF.display an increased fracture frequency.
- An increased frequency of NFB, and to some extent also PLF, may be observed in test sections located in fracture domains. In deformation zones an increase of tests with PSF may be observed.
- No tests with NFB, PLF or PSS are displayed during the injection period in sections located in the rock domain RFM012. Hence, only PRF and PSF are found in RFM012. However, RFM012 is only found in KFM04A why the lack of NFB, PLF and PSS in RFM012 may be due to some other (unknown) characteristic of KFM04A instead of a true characteristic of RFM012.
- A low degree of pressure recovery (particularly for a recovery less than c. 40%) during the recovery period of the injection tests is generally associated with PLF and apparent NFB, independently of the magnitude of transmissivity of the test section. On the other hand, tests with higher flow dimensions (PSF and PSS) generally have a high degree of recovery (except very low-transmissive test sections).

7 Suggestions to future studies

Below, some suggestions for future work related to this study are made. It should be pointed out that some of the conclusions in this report may possibly be based on a too small data set, e.g. the conclusions on the correlation between flow regimes to geological parameters such as rock domains, fracture domains and deformation zones. A larger data set might alter some of the conclusions. Therefore, analysis of a larger data set, including additional boreholes is suggested. Since the methodology adopted in this report proved to be successful, the methodology should basically be unchanged. A larger data set would also permit more statistical correlation analyses.

A larger data set would firstly include results from injection tests with PSS3 and difference flow logging in 5 m sections in additional boreholes together with the corresponding geological data. Secondly, results from injection tests, difference flow logging and geology in longer sections, e.g. 20 m would be studied and compared with the results from the 5 m test sections.

Finally, numerical simulation of responses from injection tests, both the injection and recovery period, regarding flow regimes is suggested. In such a study it should be possible to simulate both individual flow regimes in different fracture networks together with transitions between these regimes. Furthermore, effects of the internal geometry of fracture planes, e.g. flow channelling, should be investigated.

In addition, numerical simulation of selected issues discussed in this study is proposed, e.g. responses of test sections intersecting factures of limited extent and decreasing aperture during the injection and recovery period. Also tests with unexpectedly fast recovery should be simulated.

References

SKB's (Svensk Kärnbränslehantering AB) publications can be found at www.skb.se/publications.

Andersson P, Andersson J-E, Gustafsson E, Nordqvist R, Voss C, 1993. SITE-94. Site characterization in fractured crystalline rock. A critical review of geohydrologic measurement methods. SKI Technical report 93:23, Statens kärnkraftsinspektion (Swedish Nuclear Power Inspectorate).

Carlsten S, Petersson J, Stephens M, Mattsson H, Gustafsson J, 2004. Forsmark site investigation. Geological single-hole interpretation of KFM04A and HFM09–10 (DS4). SKB P-04-119, Svensk Kärnbränslehantering AB.

Carlsten S, Gustafsson J, Mattsson H, Petersson J, Stephens M, 2005. Forsmark site investigation. Geological single-hole interpretation of KFM08A, KFM08B and HFM22 (DS8). SKB P-05-262, Svensk Kärnbränslehantering AB.

Carlsten S, Döse C, Samuelsson E, Petersson J, Stephens M, Thunehed H, 2006. Forsmark site investigation. Geological single-hole interpretation of KFM08C, KFM10A, HFM23, HFM28, HFM30, HFM31, HFM32 and HFM38. SKB P-06-207, Svensk Kärnbränslehantering AB.

Dougherty D E, Babu D K, 1984. Flow to a partially penetrating well in a double-porosity reservoir. Water Resourses Research 20, 1116–1122.

Earlougher R C, 1977. Advances in well test analysis. New York : Society of Petroleum Engineers of AIME.

Follin S, Levén J, Hartley L, Jackson P, Joyce S, Roberts D, Swift B, 2007. Hydrogeological characterisation and modelling of deformation zones and fracture domains, Forsmark modelling stage 2.2. SKB R-07-48, Svensk Kärnbränslehantering AB.

Follin S, Ludvigson J-E, Levén J, 2011. A comparison between standard well test evaluation methods used in SKB's site investigations and the generalised radial flow concept. SKB P-06-54, Svensk Kärnbränslehantering AB.

Hantush M S, 1959. Nonsteady flow to flowing wells in leaky aquifer. Journal of Geophysical Research 64, 1043–1052.

Hantush M S, Jacob C E, 1955. Non-steady radial flow in an infinite leaky aquifer. Transactions, American Geophysical Union 36, 95–100.

Hjerne C, Ludvigson J-E, 2005. Forsmark site investigation. Single-hole injection tests in borehole KFM04A. SKB P-04-293, Svensk Kärnbränslehantering AB.

Hurst W, Clark J D, Brauer E B, 1969. The skin effect in producing wells. Journal of Petroleum Technology 21, 1483–1489.

Jacob C E, Lohman S W, 1952. Nonsteady flow to a well of constant drawdown in an extensive aquifer. Transactions, American Geophysical Union 33, 559–569.

Ludvigson J-E, Hansson K, Rouhiainen P, 2002. Methodology study of Posiva difference flow meter in borehole KLX02 at Laxemar. SKB R-01-52, Svensk Kärnbränslehantering AB.

Ludvigson J-E, Hansson K, Hjerne C, 2007. Forsmark site investigation. Method evaluation of single-hole hydraulic injection tests at site investigations in Forsmark. SKB P-07-80, Svensk Kärnbränslehantering AB.

Moye D G, 1967. Diamond drilling for foundation exploration. Transactions of the Institution of Engineers, Australia, Civil Engineering, 95–100.

Ozkan E, Raghavan R, 1991a. New solutions for well test analysis: Part 1 – Analytical considerations. SPE Formation Evaluation 6, 359–368.

Ozkan E, Raghavan R, 1991b. New solutions for well test analysis: Part 2 – Computational considerations and applications. SPE Formation Evaluation 6, 369–378.

Rhén I (ed), Gustafson G, Stanfors R, Wikberg P, 1997. Äspö HRL – Geoscientific evaluation 1997/5. Models based on site characterization 1986–1995. SKB TR 97-06, Svensk Kärnbränslehantering AB.

Rhén I, Forsmark T, Forssman I, Zetterlund M, 2006a. Hydrogeological single-hole interpretation of KSH01A, KSH02, KSH03A, KAV01, KLX02 and HSH01–03. Simpevarp subarea – version 1.2. SKB R-06-20, Svensk Kärnbränslehantering AB.

Rhén I, Forsmark T, Forssman I, Zetterlund M, 2006b. Hydrogeological single-hole interpretation of KLX02, KLX03, KLX04, KAV04A and B, HAV09–10 and 9 HLXxx boreholes. Laxemar subarea – version 1.2. SKB R-06-21, Svensk Kärnbränslehantering AB.

Rouhiainen P, Pöllönen J, 2004. Forsmark site investigation. Difference flow logging in borehole KFM04A. SKB P-04-190, Svensk Kärnbränslehantering AB.

Sokolnicki M, Rouhiainen P, 2005. Forsmark site investigation. Difference flow logging in borehole KFM08A. SKB P-05-43, Svensk Kärnbränslehantering AB.

Sokolnicki M, Pöllönen J, Pekkanen J, 2006. Forsmark site investigation. Difference flow logging in borehole KFM10A. SKB P-06-190, Svensk Kärnbränslehantering AB.

Walger E, Hjerne C, Ludvigson J-E, Harrström J, 2006. Forsmark site investigation. Single-hole injections tests and pressure pulse tests in borehole KFM08A. SKB P-06-194, Svensk Kärnbränslehantering AB.

Walger E, Hjerne C, Ludvigson J-E, 2007. Forsmark site investigation. Single-hole injections tests in borehole KFM10A. SKB P-07-31, Svensk Kärnbränslehantering AB.

Appendix 1

Detalied comparison of steady-state and transient transmissivity from PSS3 versus PFL transmissity

In this appendix a comparison of the estimated steady-state and transient transmissivity from injection tests (PSS3) in 5 m sections relative to the transmissivity estimated from difference flow logging (PFL) in boreholes KFM04A, KFM08A and KFM10A is performed. The comparison is based on the interpreted transient flow regimes and estimated skin factors from the transient evaluation of the injection period of the PSS3 tests together with the degree of pressure recovery in the sections after injection. At the end of the section, selected observations using all three boreholes together are discussed.

Table A1-1 shows the measured borehole intervals with both PSS3 (only injection tests) and PFL in 5 m sections. In addition, the number of compared 5 m sections between PSS3 and PFL together with the number of sections below the (practical) measurement limit for the PSS3 tests and difference flow logging, respectively and for both methods in the same sections are presented in the actual boreholes. In KFM08A pressure pulse tests were performed in very low-transmissive sections. These tests are not included in Table A1-1. The number of compared 5 m sections between PSS3 and PFL equals the number of tests above the practical measurement limit for PSS3.

Table A1-1firstly indicates that a major part of the tested 5 m sections was below the practical measurement limit, particularly for the PFL-measurements. For example, in borehole KFM04A, c. 84% of the latter measurements (27 of 32) was below this limit. The highest number of compared sections measured with both PSS3 and PFL is found in KFM10A. Secondly, Table A1-1 (last column) shows that all PSS3 injection tests (except one) below the measurement limit was also below the measurement limit in the PFL measurements. In addition, several other sections were below the limit for the latter method.

Table A1-1. Measured borehole intervals with PSS3 and PFL in 5 m sections, the total number of PSS3 injection tests in 5 m sections and the number of compared 5 m sections within the intervals together with the number of tests below the practical measurement limit (LML).

Borehole	Measured intervals (m) with both PSS3 tests and PFL in 5 m sections	Total number of PSS3 tests[1] in 5 m sections in the interval	Number of compared 5 m sections by PSS3 and PFL	Number of 5 m tests below LML within the measured interval		
				PSS3[1]	PFL-5m	Both PSS3 and PFL
KFM04A	297–437	28	18	10	23	10
	517–537	4	1	3	4	3
KFM08A	104–304	31	29	2	25	2
	404–424	1	1	0	3	0
	444–484	4	4	0	6	0
	684–704	1	1	0	3	0
	784–804	1	1	0	4	0
KFM10A	63–183	24 (26)[2]	21	3 (5)[2]	12	3
	263–383	24	16	8	14	7
	423–493	14	10	4	10	4

[1] Only injection tests are included (not pulse tests).
[2] 2 overlapping sections.

Methodology

Only injection tests in 5 m sections with a transmissivity above the (test-specific) measurement limit for PSS3 are included in the comparison. In most cases, the transmissivity of the sections below the practical measurement limit for PSS3 are also below the (practical) measurement limit of difference flow logging in corresponding 5 m sections, see Table A1-1. The steady-state (T_M) and transient transmissivity (T_T) from the injection tests are compared with the transmissivity from difference flow logging in the same 5 m sections (TD-5m). The procedures for correlating 5 m sections with slightly shifted positions along the borehole during the PSS3 and PFL measurements are described in Section 4.2.

The same comparison of transmissivities can also be performed using the transmissivity determined from the detailed difference flow logging in overlapping sections (TD_a-5m). However, in the latter type of flow logging the lower measurement limit has not been defined which is considered as a drawback in this comparison. In addition, the number of sections below the measurement limit in the difference flow logging is quite high in some boreholes, see Table A1-1. Thus, histograms are used in the comparison rather than cross plots. The agreement between the results of difference flow logging in 5 m sections and the detailed overlapping logging has been found to be quite good, see Figure A1-1. The main conclusions in this chapter are valid independently of whether the results from difference flow logging in 5 m sections or from detailed overlapping logging are used.

The a)-figures below show the estimated steady-state and transient transmissivity (T_M and T_T) in 5 m sections above the measurement limit for the PSS3 tests together with the calculated transmissivity from difference flow logging in corresponding 5 m sections (TD-5m). The estimated lower (practical) measurement limit of the difference flow logging in 5 m sections is also shown. For better resolution on the length scale the borehole is divided in two length intervals in the presentations and discussions. If no transient evaluation of the actual test was possible, either due to a highly deviating flow regime from pseudo-radial (eg. dominating NFB) or due to scattered or highly fluctuating data, the columns for T_T and skin factor are missing in the diagrams.

In addition, the interpreted transient flow regimes during the injection period and the estimated skin factors from the transient evaluation of the PSS3 tests (corresponding to T_T) and degree of pressure recovery (fraction) after injection are shown in the corresponding b)-figures for the same test sections as described above. For simplicity, the dominating flow regimes during the tests are transformed to tentative numerical codes (1–3.5), see Table A1-2. The complete flow regimes interpreted during both the injection and recovery period of the PSS3 tests in each borehole are shown in the overview Figures 5-1 to 5-3.

The estimated skin factors from the injection period of the PSS3 tests in the actual 5 m sections are shown on the right Y-axes. In crystalline rock, a negative skin factor is assumed to reflect conductive fracture(s) intersecting the test section whereas a positive skin can be assumed to reflect various kinds of head losses (eg. due to turbulent flow) or alternatively, a higher flow dimension than 2 (e.g. pseudo-spherical flow) assumed by the evaluation of the test.

The degree of pressure recovery after injection is here defined as the ratio of the applied injection pressure (p_p–p_i) and the observed pressure recovery (p_p–p_F) during the recovery period of the test. Complete recovery (100%) thus corresponds to "1" in the figures. A low degree (below c. 0.5) of pressure recovery may be associated with the presence of an apparent no-flow boundary (NFB) during the injection period of the test whereas (almost) complete recovery may be expected in sections showing pseudo-radial flow or higher flow dimensions (except in very low-transmissive test sections).

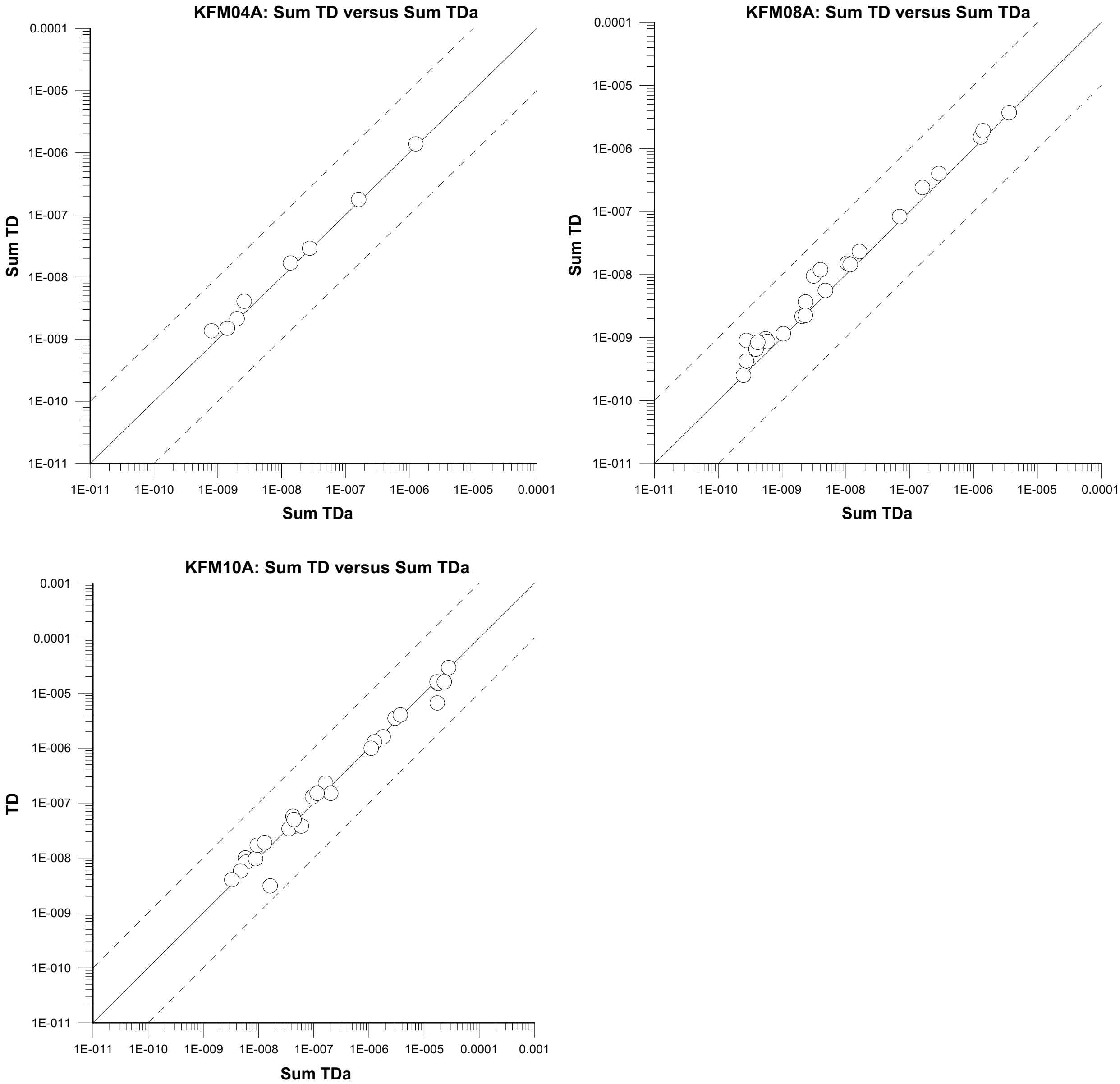

Figure A1-1. *Comparision of sum TD-5m and sum of TDa.*

Table A1-2. Tentative codes used for transforming interpreted dominating flow regimes during the injection period of the PSS3 tests.

Dominating flow regime during the injection period	Code
Apparent no-flow boundary (NFB)	0.5
Pseudo-linear flow (PLF)	1
Pseudo-radial flow (PRF)	2
PRF → NFB	1.5
Pseudo-spherical (leaky) flow (PSF)	3
PRF → PSF	2.5
Apparent constant head boundary (CHB)	3.5
Pseudosteady-state (PSS)	3.5

Borehole KFM04A

Only a limited interval in KFM04A was measured with PSS3 in 5 m sections, see Table A1-1. Figure A1-2a shows the estimated steady-state and transient transmissivity (T_M and T_T) in 5 m sections for the PSS3 tests together with the calculated transmissivity from difference flow logging in corresponding 5 m sections (TD-5m) in the borehole length interval 297–537 m in KFM04A. The practical measurement limit for TD-5m, which was c. $2 \cdot 10^{-9}$ m^2/s in this interval of KFM04A (Rouhiainen and Pöllänen 2004), is also shown in the figure. In Figure A1-2b the interpreted transient flow regimes, estimated skin factors during the injection period and degree of recovery (fraction) after injection for the PSS3 tests are shown for the same sections.

Figure A1-2a shows that the transmissivity generally is rather low in this borehole interval. In general, the transient transmissivity TT and steady-state transmissivity TM agrees well. TT is slightly higher or lower than TM depending on the actual value of the corresponding skin factors in the sections. The transmissivity from difference flow logging TD-5m is close to, or below the measurement limit in most sections. In remaining sections TD-5m is close to TT and TM (except section 337 m).

Figure A1-2b shows that the estimated skin factors are generally varying around zero. The dominating flow dimensions in all sections except one (517 m) are 2 or higher and the pressure recovery is almost complete (1) in most of the sections. The sections below 392 m (secup) showing lower recovery are low-transmissive. In these sections TD-5m is close to, or below the measurement limit. The transient response in the low-transmissive section 517 m (secup) is dominated by an apparent NFB transitioning to an apparent PSF by the end. However, the transient evaluation of the injection period is very uncertain in this section and TD-5m is below the practical measurement limit.

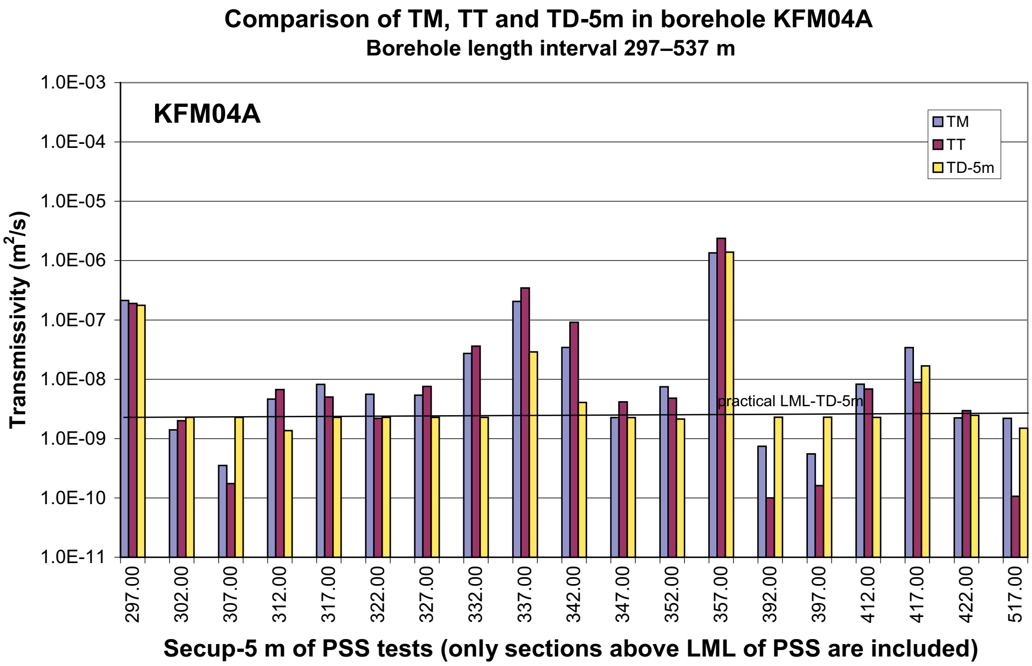

Figure A1-2a. *Comparison of steady-state (TM) and transient transmissivity (TT) together with transmissivity from difference flow logging in 5 m sections (TD-5m) in borehole length interval 297–537 m in KFM04A.*

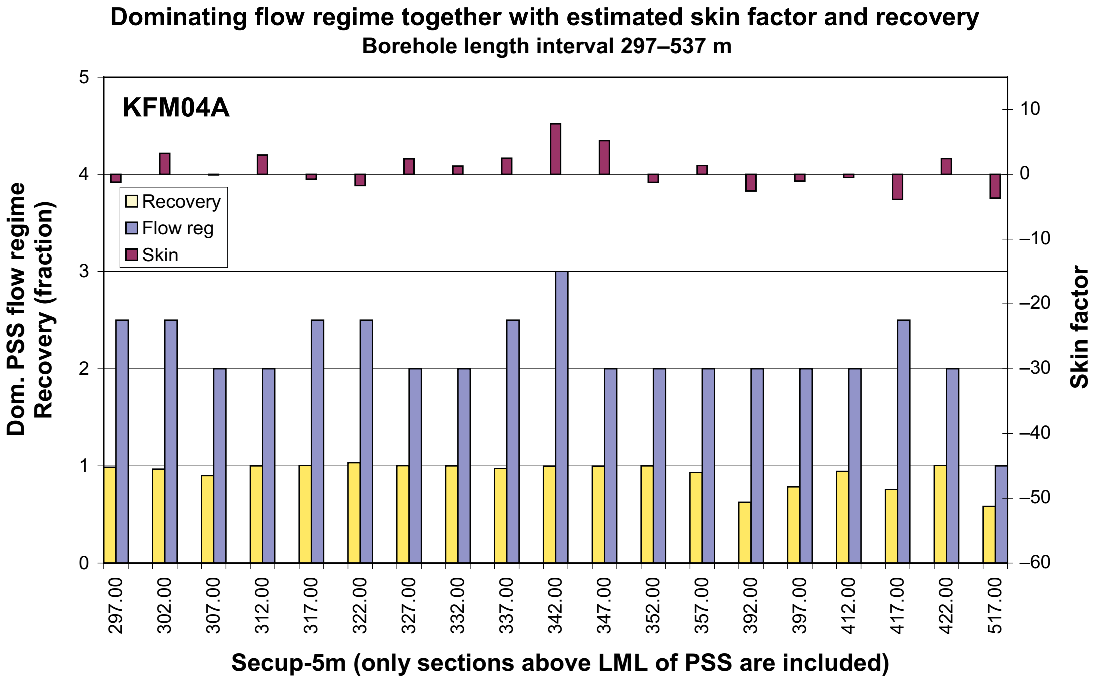

Figure A1-2b. *Dominating transient flow regimes together with estimated skin factors and degree of pressure recovery during the injection period of the PSS3 tests in the same test sections as in Figure A1-2a.*

Borehole KFM08A

Borehole interval 100–200 m

Figure A1-3a shows the estimated steady-state and transient transmissivity (TM and TT) in 5 m sections for the PSS3 tests together with the calculated transmissivity from difference flow logging in corresponding 5 m sections (TD-5m) in the borehole length interval 100–200 m in KFM08A. The PSS3 tests started at 104 m borehole length. The practical measurement limit for TD-5m, which was c. $8 \cdot 10^{-10}$ m^2/s in KFM08A (Sokolnicki and Rouhiainen 2005), is also shown in the figure. In Figure A1-3b the interpreted transient flow regimes, estimated skin factors during the injection period and degree of recovery (fraction) after injection for the PSS3 tests are shown for the same sections.

Figure A1-3a shows that the transient transmissivity TT generally is slightly lower than the steady-state transmissivity TM in most sections in the borehole interval 100–200 m in KFM08A. However, in several sections it was not possible to perform a representative transient evaluation. In most sections, TD-5m was significantly lower than both TT and TM. Figure A1-3b shows that the slight discrepancy between TT and TM is due to the values of the estimated skin factors in these sections. In most sections a negative skin factor was determined resulting in that TT is lower than TM. In sections (secup) 149 m and 174 m the opposite is the case. The correlation between the estimated skin factor and the difference of TT and TM for all three boreholes together is presented in Section 5.4.5.

Figure A1-3b also shows that the responses during the injection period in most sections were affected by, or dominated by, apparent no-flow boundaries (NFB), i.e. the dominating flow dimension was 1.5 or lower in the diagram. Furthermore, in all these sections the pressure recovery was low (less than c. 0.4) despite rather high transmissivities in some of the sections indicating fractures of limited extent or fractures with decreasing aperture away from the borehole. In most of the sections showing effects of NFB and low recovery, the transmissivity TD-5m from the difference flow logging is significantly lower than both TT and TM.

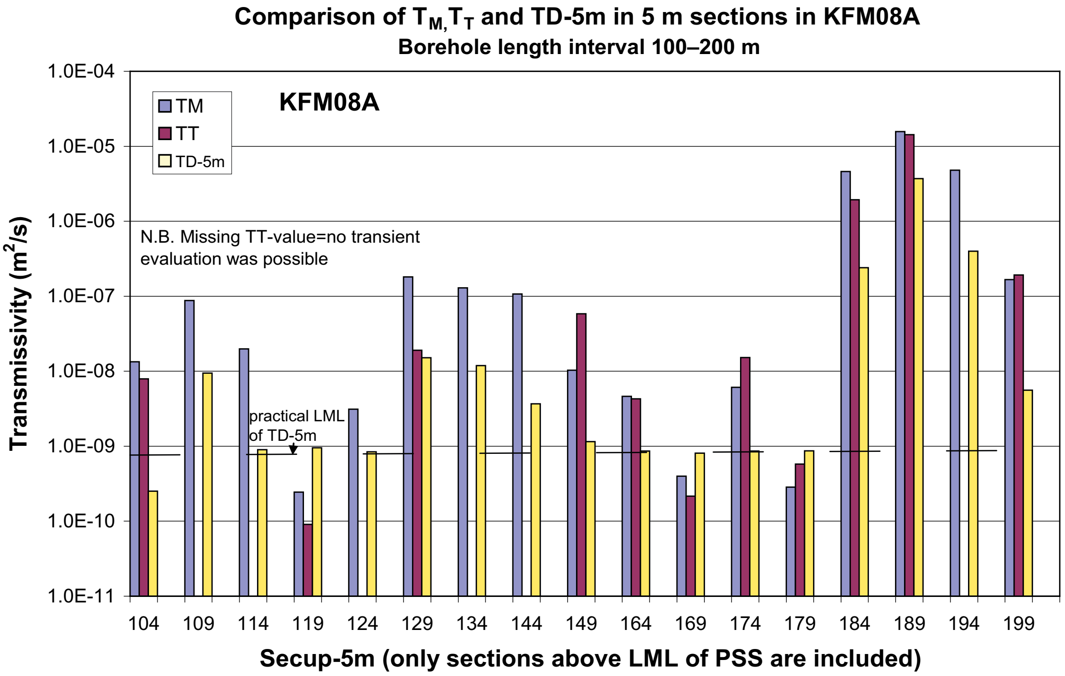

Figure A1-3a. *Comparison of steady-state (TM) and transient transmissivity (TT) together with transmissivity from difference flow logging in 5 m sections (TD-5m) in borehole length interval 100–200 m in KFM08A.*

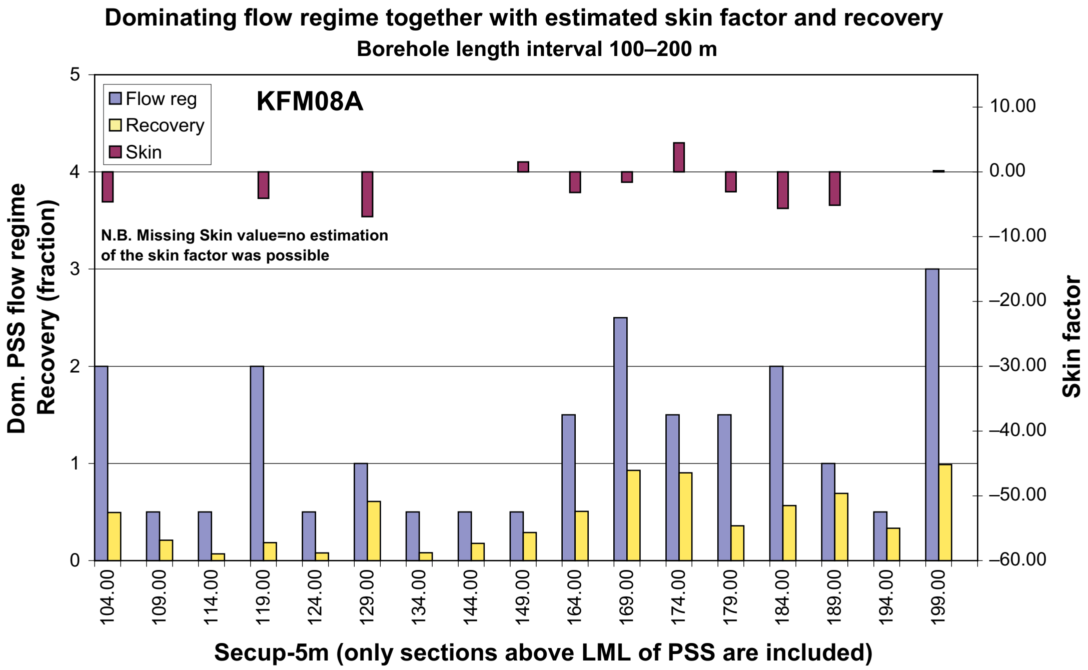

Figure A1-3b. *Dominating transient flow regimes together with estimated skin factors and degree of pressure recovery during the injection period of the PSS3 tests in the same test sections as in Figure A1-3a.*

Borehole interval 200–800 m

Figure A1-4a shows the estimated steady-state and transient transmissivity (TM and TT) in 5 m sections for the PSS3 tests together with the calculated transmissivity from difference flow logging in corresponding 5 m sections (TD-5m) in the borehole length interval 200–800 m in KFM08A. The deepest 5 m section tested with PSS3 was at a borehole length (secup) of 794 m. In Figure A1-4b the interpreted transient flow regimes, estimated skin factors during the injection period and degree of recovery (fraction) for the PSS3 tests are shown for the same sections.

Figure A1-4a indicates that the transient transmissivity TT generally is slightly lower than the steady-state transmissivity TM in the borehole interval 200–800 m in KFM08A as in the interval 100–200 m. The transmissivity TD-5m from the difference flow logging was in most sections significantly lower than both TT and TM in this borehole interval. In several sections the transmissivity TD-5m is below the practical measurement limit.

Figure A1-4b shows firstly that the estimated skin factors are generally negative in the interval 200–800 m. Secondly, the responses during the injection period were in most sections affected by, or dominated by, apparent no-flow boundaries (NFB), i.e. the dominating flow dimension was 1.5 or lower as in the borehole interval 100–200 m. Furthermore, in almost all of these sections the pressure recovery was low (less than c. 0.4) despite rather high transmissivities in some of the sections, indicating fractures of limited extent or fractures with decreasing aperture away from the borehole. In most of the sections showing effects of NFB and low recovery, the transmissivity TD-5m from the difference flow logging is significantly lower than both TT and TM. For example, in the high-transmissivity section (secup) 684 m TD-5m is more than one order of magnitude lower than TT and TM. In the five sections showing pseudo-radial flow or higher flow dimension the pressure recovery was generally higher.

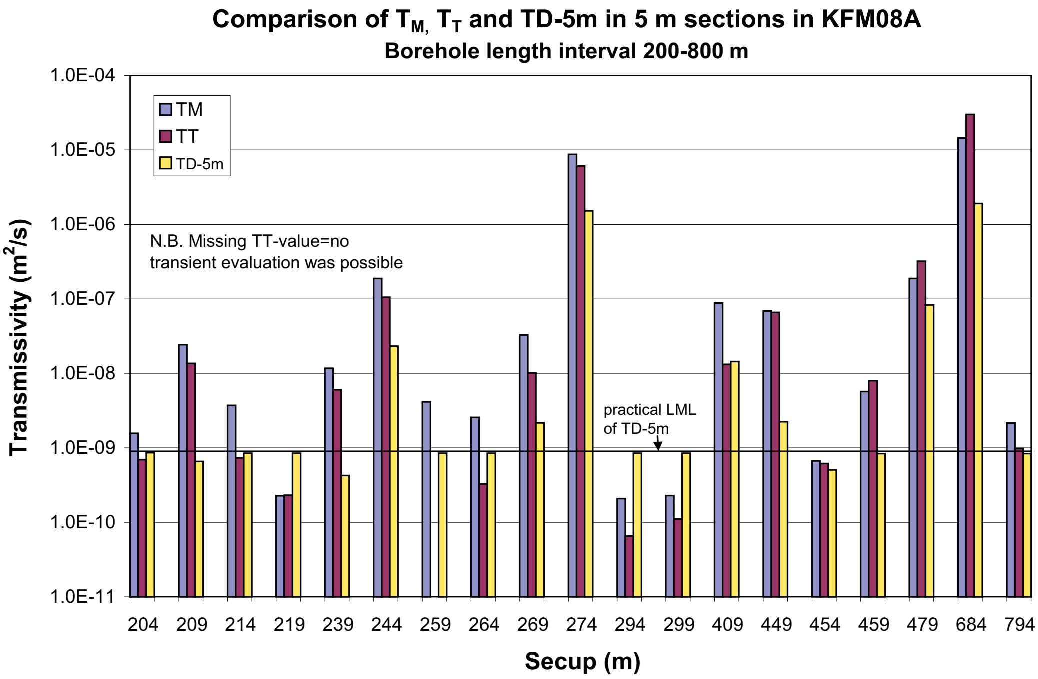

Figure A1-4a. Comparison of steady-state (TM) and transient transmissivity (TT) together with transmissivity from difference flow logging in 5 m sections (TD-5m) in borehole length interval 200–800 m in KFM08A.

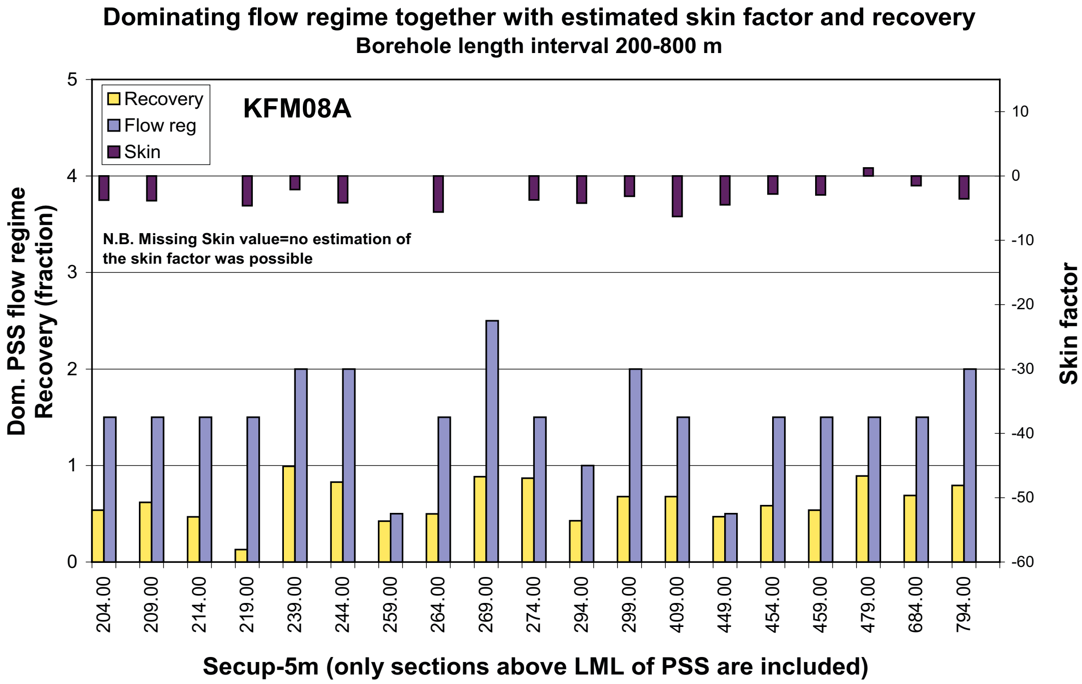

Figure A1-4b. *Dominating transient flow regimes together with estimated skin factors and degree of pressure recovery during the injection period of the PSS3 tests in the same test sections as in Figure A1-4a.*

Borehole KFM10A

Borehole interval 0–200 m

Figure A1-5a shows the estimated steady-state and transient transmissivity (TM and TT) in 5 m sections for the PSS3 tests together with the calculated transmissivity from difference flow logging in corresponding 5 m sections (TD-5m) in the borehole length interval 0–200 m in KFM10A. The measurements started at c. 63 m borehole length. The practical measurement limit for TD-5m, which was c. $3 \cdot 10^{-9}$ m^2/s in KFM10A (Sokolnicki et al. 2006), is also shown in the figure. In Figure A1-5b the interpreted transient flow regimes, estimated skin factors during the injection period and degree of recovery (fraction) after injection for the PSS3 tests are shown for the same sections.

Figure A1-5a shows that the transmissivity is high and that the transient transmissivity TT generally is higher than the steady-state transmissivity TM in the upper part (down to c. 123 m) of this borehole interval in KFM10A. In these sections it seems that TM agrees well and also better with TD-5m from the difference flow logging. Figure A1-5b shows that the main reason for the discrepancy between TT and TM is the estimated high, positive skin factors in these sections. The dominating flow dimensions are 2 or higher and the pressure recovery is complete (1) in all these sections.

As discussed in Walger et al. (2007) this borehole interval partly corresponds to a thick deformation zone. The high skin factors estimated may possibly be explained by the observed hydraulic interaction between several of the tested sections in the zone or alternatively, by turbulent flow in high-transmissivity fractures within the zone. Although tests with higher flow dimensions occur within the zone, the flow rate derivatives in several tests also indicate pseudo-radial flow in combination with a high positive skin factor during both the injection and recovery period. The pressure recovery was generally fast in these sections.

In the lower part of the borehole length interval 0–200 m (below c. 123 m) with transmissivities approaching the lower measurement limit in several sections, TT is generally close to or slightly lower than TM, reflected by slightly negative skin factors. It should be observed that all values of TD-5m (except for section 142.9 m) in this interval are below the practical measurement limit for TD-5m from difference flow logging and may thus give a false impression in the diagram. The dominating flow regime in this interval is pseudo-radial, eventually transitioning to an apparent no-flow boundary (NFB) by the end of the injection period in some sections. The pressure recovery is high despite the relatively low transmissivity of these sections.

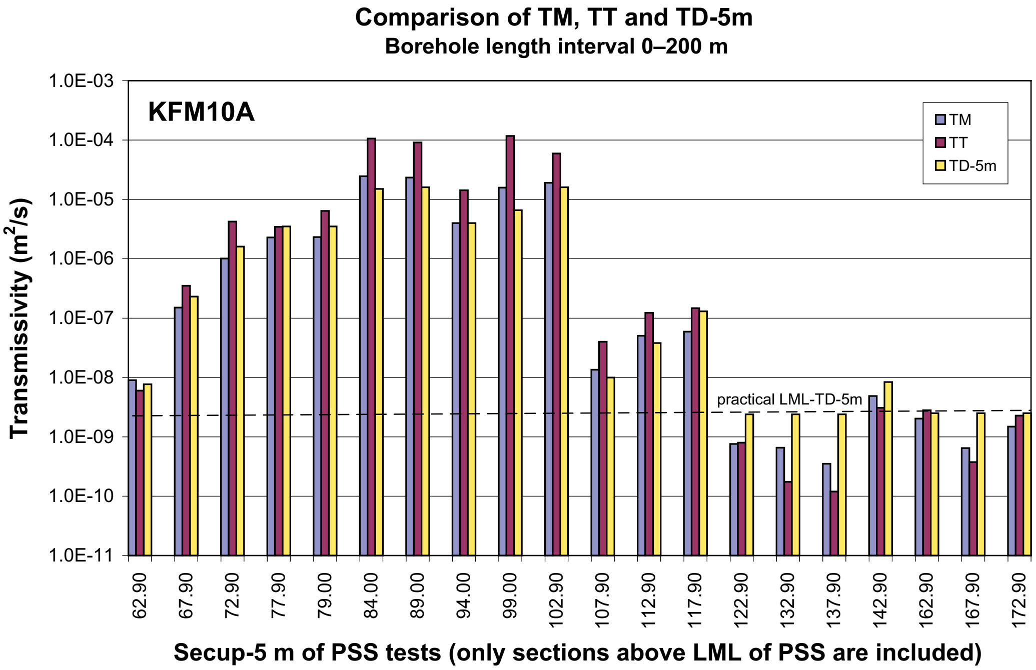

Figure A1-5a. Comparison of steady-state (TM) and transient transmissivity (TT) together with transmissivity from difference flow logging in 5 m sections (TD-5m) in borehole length interval 0–200 m in KFM10A.

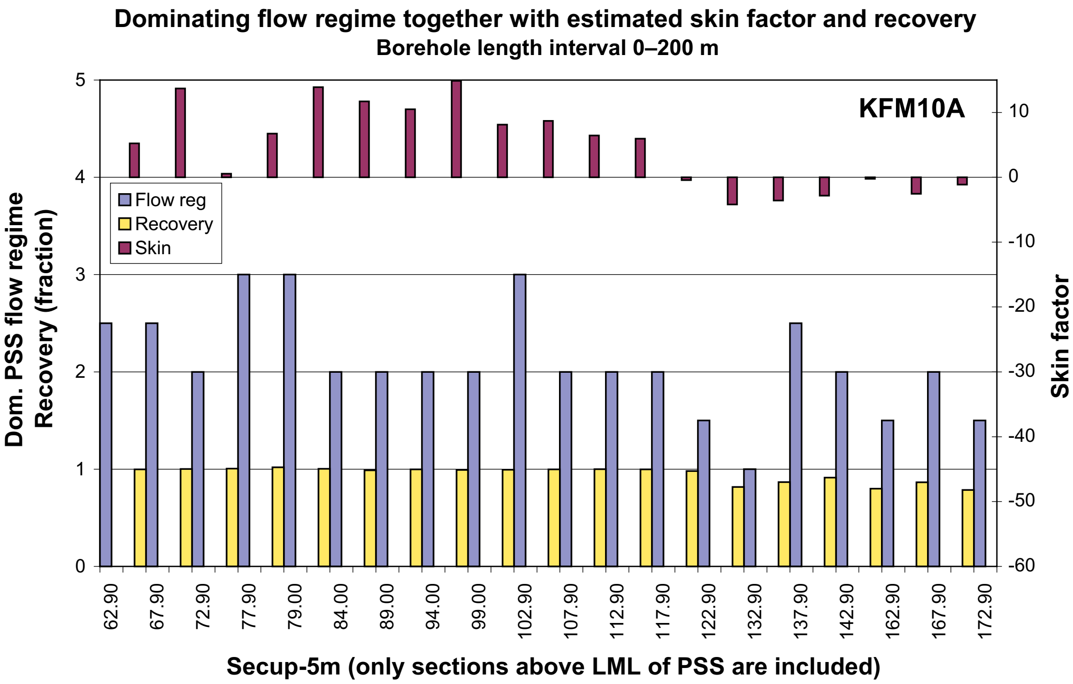

Figure A1-5b. Dominating transient flow regimes together with estimated skin factors and degree of pressure recovery during the injection period of the PSS3 tests in the same test sections as in Figure A1-5a.

Borehole interval 200–500 m

Figure A1-6a shows the estimated steady-state and transient transmissivity (TM and TT) in 5 m sections for the PSS3 tests together with the calculated transmissivity from difference flow logging in corresponding 5 m sections (TD-5m) in the borehole length interval 200–500 m in KFM10A. The deepest 5 m section tested was at a borehole length of c. 488–493 m. In Figure A1-6b the interpreted transient flow regimes, estimated skin factors during the injection period and degree of recovery (fraction) for the PSS3 tests are shown for the same sections.

Figure A1-6a shows that the transient transmissivity TT generally is slightly lower than the steady-state transmissivity TM in the borehole interval 200–500 m in KFM10A. In sections (secup) 372.9 m and 377.9 m no transient evaluation of the PSS3 tests was possible. The transmissivity TD-5m from the difference flow logging was generally close to TM and TT or lower than both TT and TM in the upper part of this borehole interval. In the more low-transmissive lower part (from c. 440 m) the transmissivity TD-5m is below the practical measurement limit in most sections except two as discussed above. Figure 5-16b shows that the estimated skin factors are generally slightly negative along the borehole interval 200–500 m. The dominating (early) flow dimensions are 2 or higher in many sections and the pressure recovery is generally good in this interval.

However, in several sections apparent NFB are observed by the end of the injection period. Furthermore, in sections (secup) 297.9 m, 307.9 m, 377.9 m and 467.9 m apparent NFB dominated the entire injection period while in section 312.9 m (secup) pseudo-linear flow (PLF) dominated. In all of the latter sections the pressure recovery was low (less than c. 0.4) despite rather high transmissivities, indicating fractures of limited extent or fractures with decreasing aperture away from the borehole. In most of the sections showing effects of NFB, the transmissivity TD-5m from the difference flow logging is significantly lower than both TT and TM. Sections (secup) 377.9 m and 467.9 m are below the practical measurement limit of TD-5m.

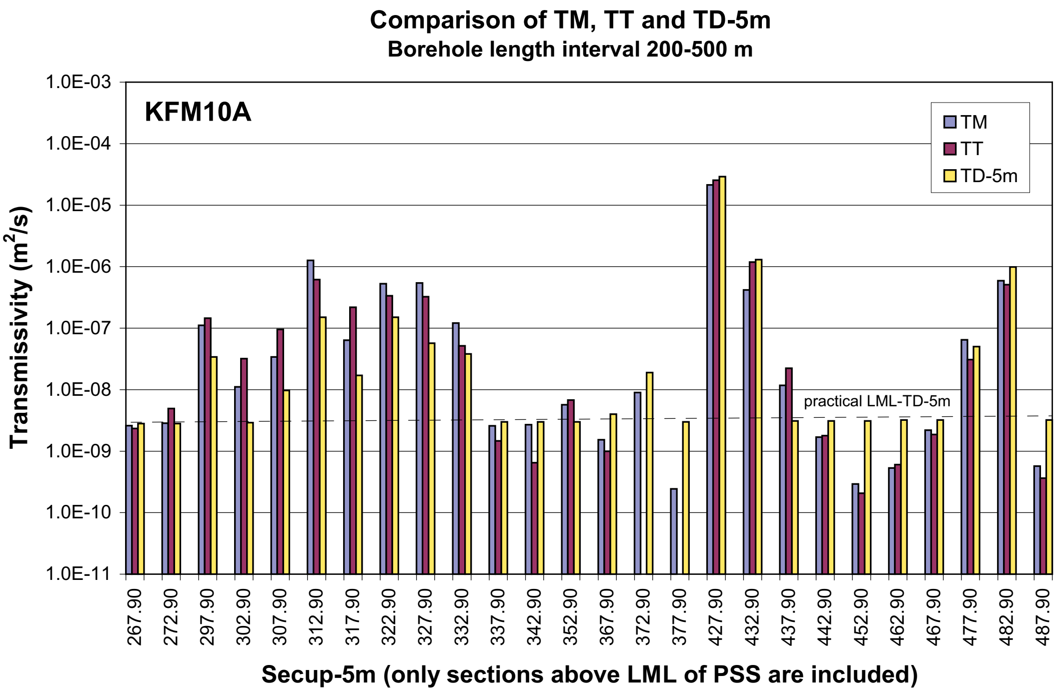

__Figure A1-6a.__ Comparison of steady-state (TM) and transient transmissivity (TT) together with transmissivity from difference flow logging in 5 m sections (TD-5m) in borehole length interval 200–500 m in KFM10A.

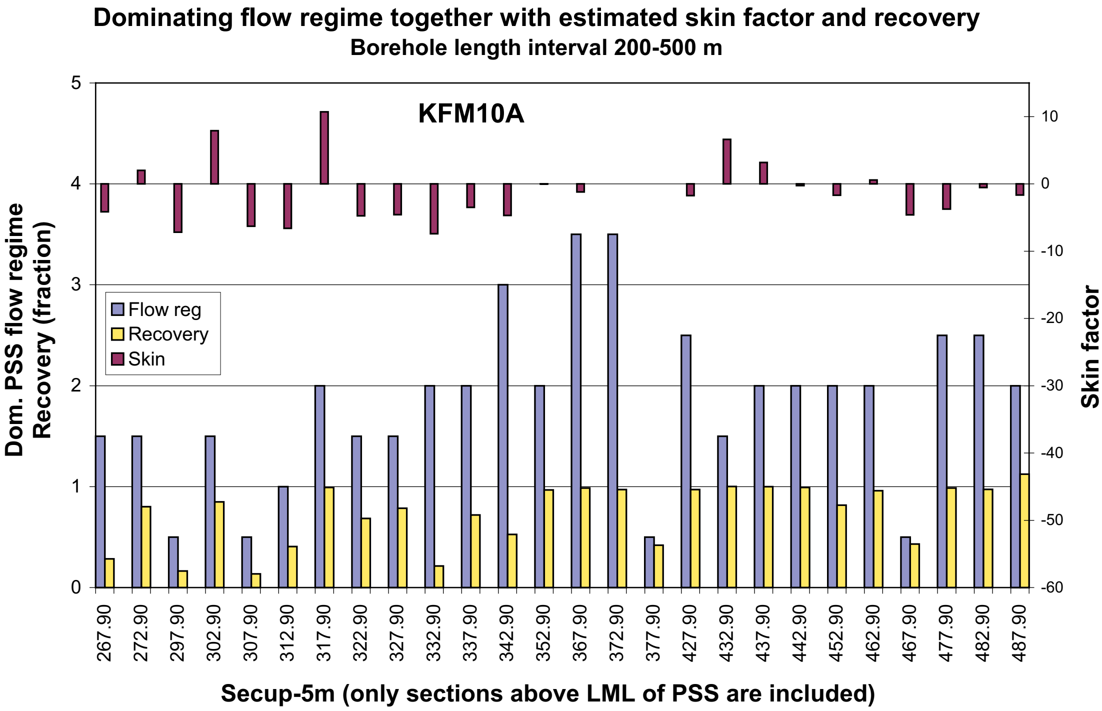

Figure A1-6b. *Dominating transient flow regimes together with estimated skin factors and degree of pressure recovery during the injection period of the PSS3 tests in the same test sections as in Figure A1-6a.*

Skin factor

Figure A1-7 shows the estimated skin factors versus the divergence of transmissivity TT and TM as estimated from the injection period of the tests. The figure clearly shows that the magnitude of the estimated skin factor reflects the degree of divergence between TT and TM. When TT is higher than TM the skin factor is generally positive and vice versa. The figure also shows that the estimated skin factors from the injection period generally are negative as can be expected in fractured rock. These observations are consistent with the previous presentations.

Summary and discussions

In some boreholes the transient transmissivity agrees better with the transmissivity from difference flow logging than in other boreholes. Deviations between the transient and stationary transmissivity may depend on both the interpreted flow regimes during the tests, the magnitude of the estimated skin factors and the degree of recovery during the recovery period of the injection tests.

Importance of flow regimes

For tests with higher flow dimensions the transient (T_T) and stationary transmissivity (T_M) seem to be rather independent of the flow regime. On the other hand, for lower flow dimensions (PLF) and in particular for tests with NFB the flow regime may have a strong impact on the estimated transient and stationary transmissivity respectively. In boreholes KFM04A and KFM10A, which are dominated by higher flow dimensions (PRF and higher), the transient and stationary transmissivity from the injection tests are thus rather similar. However, in borehole KFM08A, which is dominated by lower flow dimensions (PLF) and in particular, by apparent no-flow boundary effects, larger deviations occur between these transmissivities. As discussed above, these deviations are in most cases also accompanied by large deviations between T_M and TD-5m.

The degree of deviations between the transient and stationary transmissivity also depends on from which test period (injection or recovery) the transient transmissivity T_T is selected. Furthermore, deviations also depend on the magnitude of the estimated skin factors from the transient evaluation and the observed degree of pressure recovery during the recovery period of the injection tests.

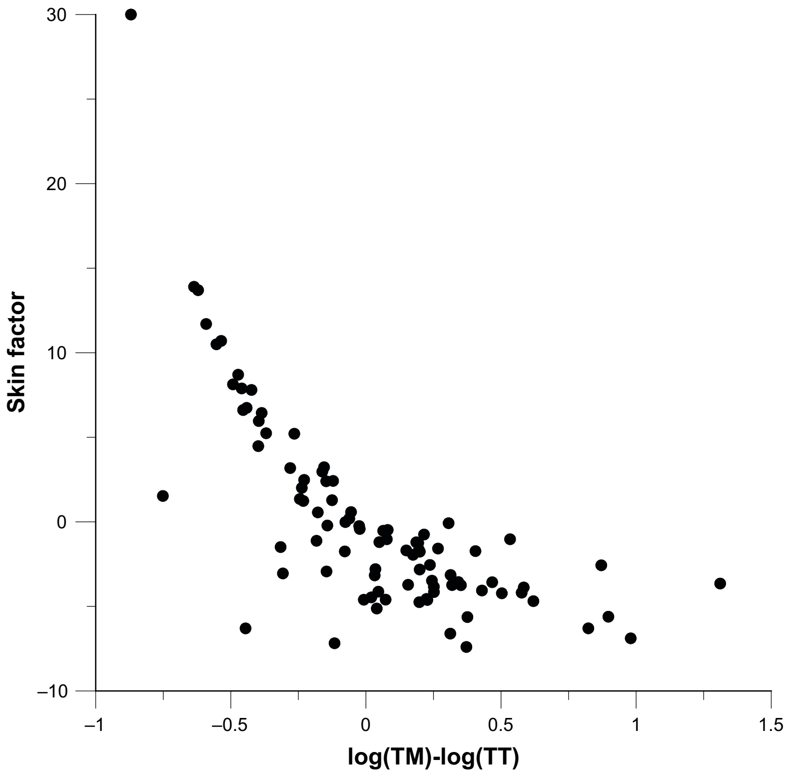

Figure A1-7. *Estimated skin factors versus the divergence of transmissivity TT and TM as estimated from the injection period of tests in KFM04A, KFM08A and KFM10A.*

Transient transmissivity from the injection and recovery period

The type of flow regime during the injection and recovery period may have a large impact on the estimated transient transmissivity from the two periods. The transient transmissivity T_T thus depends on which of those periods is selected. In particular, tests dominated by NFB during the injection period may often be difficult to evaluate with transient methods. Such tests may often show a slow and limited degree of pressure recovery during the recovery period, see below, and a different flow regime compared to the injection period. Nevertheless, in some cases a representative transient evaluation is possible from the recovery period. In such sections, large discrepancies may also be obtained between the representative transmissivity T_R from the injection tests and difference flow logging as discussed above. It is likely that these tests represent fractures with limited extent or decreasing aperture with distance from the borehole.

Inconsistent flow regimes (and transmissivity) during the injection and recovery period may also occur in other situations, e.g. tests with fast pressure recovery. This fact may result in deviations between the estimated transmissivity from the injection and recovery period. Inconsistent flow regimes may in many cases also be explained by disturbing factors such as limited test time, unstable initial injection pressure and wellbore storage effects (WBS).

At Forsmark, the transient transmissivity T_T was in most cases selected from the injection period. However, in test sections showing an apparent NFB during the injection period followed by a slow and limited pressure recovery, the transmissivity from the recovery period was generally selected. In cases when no reliable transient evaluation could be done from neither the injection nor the recovery period the stationary transmissivity T_M was selected as T_R.

Importance of the skin factor

The deviation between the transient (T_T) and stationary transmissivity (T_M) was also found to be correlated to the estimated skin factor. A negative skin factor (which is most common) generally results in a slightly lower transient transmissivity than the stationary transmissivity and vice versa. The lack of skin factor (and flow regime) consideration in T_M may cause an increased discrepancy between T_M and T_T (and also between T_M and T_D-5m).