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TECHNICAL REPORT 85-39

ANALYSIS OF PRESSURE AND FLOW DATA FROM THE LONG-TERM MONITORING TOOL IN BOETTSTEIN BOREHOLE

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ABSTRACT

In January 1984, a long-term monitoring system with 8 packers was installed in the Böttstein borehole. The system divides the borehole into hydraulically isolated zones of different lengths. The measurement period up till the beginning of November discussed in this report is divided into three monitoring phases:

- firstly, a pressure build-up until 4th October 1984,
- secondly, a flow test in the five lower zones from 4th - 23rd October 1984, and
- thirdly, a pressure build-up in all zones. The data used from this last phase is up till 6th November 1984 but investigations were still being continued after the copy dead-line for this report.

The measurement data obtained are evaluated in the present report using both analytical calculation methods and numerical models. Results are obtained for hydraulic pressure of the groundwater and for permeability values for the individual sections. All permeabilities obtained using different methods are compared with one another and with those from packer tests from the drilling phase and are then evaluated in detail.

ZUSAMMENFASSUNG

Im Januar 1984 wurde in der Sondierbohrung Böttstein ein Langzeit - Beobachtungssystem mit 8 Packern eingebaut, welches das Bohrloch in verschieden lange, hydraulisch isolierte Zonen unterteilt. Die Messdauer bis Anfang November gliedert sich in drei in diesem Bericht diskutierte Beobachtungsphasen, nämlich:

- erstens ein Druckaufbau bis zum 4. Oktober 1984,
- zweitens ein Ausfliessversuch an den unteren 5 Zonen vom 4. - 23. Oktober 1984,
- drittens ein Druckaufbau in allen Zonen, dessen Daten bis zum 6. November 1984 verwendet werden konnten, der aber auch nach Redaktionsschluss weiterhin Gegenstand der Untersuchung bleibt.

Die erhaltenen Messdaten werden im vorliegenden Bericht sowohl mit analytischen Rechenverfahren als auch mit Hilfe von numerischen Modellen ausgewertet. Daraus ergeben sich Resultate zum hydraulischen Druck des Gebirgwassers, sowie Durchlässigkeitswerte in den einzelnen Abschnitten. Alle diese, nach verschiedenen Methoden gewonnen Permeabilitäten werden sowohl untereinander als auch mit jenen der Packertests aus der Bohrphase verglichen und anschliessend bewertet.

RESUME

En janvier 1984, est installé, dans le forage de Böttstein, un système d'observation pour longue durée, qui comprend huit packers et permet d'isoler hydrauliquement des segments du forage de longueurs différentes. La période de mesure décrite dans ce rapport s'étend jusqu'au début novembre et se divise en trois phases d'observation: premièrement, und remontée de pression jusqu'au 4 octobre 1984, deuxièmement, une période d'écoulement des cinq zones inférieures du 4 au 23 octobre 1984, et enfin une remontée de pression de toutes les zones. Ces dernières valeurs ne peuvent être présentées ici que jusqu'au 6 novembre 1984 mais l'essai se prolonge au-delà de la date de rédaction du rapport.

Les données acquises sont traitées aussi bien par les méthodes de calcul analytique qu'à l'aide de modèles numériques et permettent de déterminer la pression hydraulique des eaux de formation et la perméabilité de chacun des segments. Toutes ces valeurs de perméabilité, obtenues par des méthodes différentes, sont ensuite comparées entre elles, puis à celles acquises à la suite des essais de packer de courte durée, et enfin évaluées en détail.

EXTENDED ABSTRACT

Long-term pressure recovery data and the results of flow and recovery tests from five packer-isolated zones (between 964 and 1411 metres below surface) in the Lynes eight-packer monitoring tool installed in the Boettstein borehole have been analyzed using analytic and numerical models. The objectives of the analyses, for each zone, are to obtain formation pressures and representative hydraulic heads from the long-term pressure recovery data and to obtain estimates of representative hydraulic conductivities from the results of the flow and recovery tests. Examination of the flow tests also provided information for assessing packer compliance effects and the existence of hydraulic communication between two of the packer-isolated zones.

The interpreted formation pressures, hydraulic heads and hydraulic conductivities for each of the packer-isolated zones were compared with those obtained during the hydraulic testing program and evaluated as to their representativeness. The recommended hydraulic conductivities and their corresponding depth interval are:

Zone	Depth (m)	Recommended Hydraulic Conductivity (m/s)
Z4	964.29-975.11	2×10^{-11}
Z5	976.51-1319.82	6×10^{-13}
Z6	1321.22-1331.46	1×10^{-12}
Z7	1332.86-1399.40	5×10^{-14}
Z8	1400.80-1410.99	2×10^{-14}

The hydraulic conductivities from the flow and recovery tests using the eight-packer monitoring tool tended to be lower in magnitude than those obtained during the hydraulic testing program. These differences are considered to be attributed to such factors as volume of rock being tested (radius of influence), measurement scale (length of tested interval) and hydraulic communication around packers (resulting in overestimates of hydraulic conductivity). The hydraulic conductivities reported above are considered to be accurate within about one order of magnitude.

The range of estimated hydraulic head is 365 to 371 metres above mean sea level for zone Z4 and 402 to 420 metres above mean sea level for zones Z6, Z7 and Z8. A vertical gradient between these zones cannot be determined with the presently existing data base but will require the collection of a much longer pressure build-up data record. The range in hydraulic heads given above for zones Z6 to Z8 compares well with values (405 to 420 metres above sea level) from two tests conducted in the hydraulic testing program at depth intervals 1332.61-1501.30 m and 1494.20-1501.30 m. The estimated formation hydraulic head for zone Z5 is not considered representative because of the great length of the borehole interval (and the expected large variation in hydraulic head along the interval) and the interpretation of hydraulic communication between zones Z5 and Z6.

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ANALYSIS OF PRESSURE AND FLOW DATA FROM THE LONG-TERM MONITORING TOOL IN BOETTSTEIN BOREHOLE

1. INTRODUCTION

The objective this report is to provide an evaluation of the pressure and flow data from the Lynes eight-packer monitoring tool in the Boettstein borehole and to obtain estimates of formation pressure, hydraulic head and hydraulic conductivity corresponding to the five packer-isolated intervals located between 964 and 1411 metres depth. The formation parameters determined from the above data base were compared to those obtained from the hydraulic testing program conducted during and subsequent to the drilling/testing phases.

A detailed description and explanation of the downhole equipment, installation activities and surface monitoring system is provided in NTB 85-11 (Schneider, 1985). A schematic illustration of the instrumentation including identification of the packer-isolated intervals is shown in Figure 1. The downhole equipment consists of a series of 1.4 m long packers mounted on a central 2 7/8 inch tubing string with a single inflation line connecting all packers. Each packer-isolated zone is connected by narrow diameter (1/4 and 1/2 inch) tubing to ground surface except for zone Z4 which is connected hydraulically to surface by the 2 7/8 inch tubing string. The downhole equipment was installed and tested during the period 20 - 30 January 1984 with inflation of the packers occuring on January 26. The packer-isolated borehole intervals were allowed to flow until they were shut in on January 30 by connecting to the surface pressure gauges. Manual pressure readings were taken with surface pressure gauges until the continuous pressure monitoring system (with strip chart records) was installed on July 23.

The data base available for analysis to obtain estimates of the formation parameters included:

1) long-term pressure recovery data for the period 30 January to 4 October 1984;

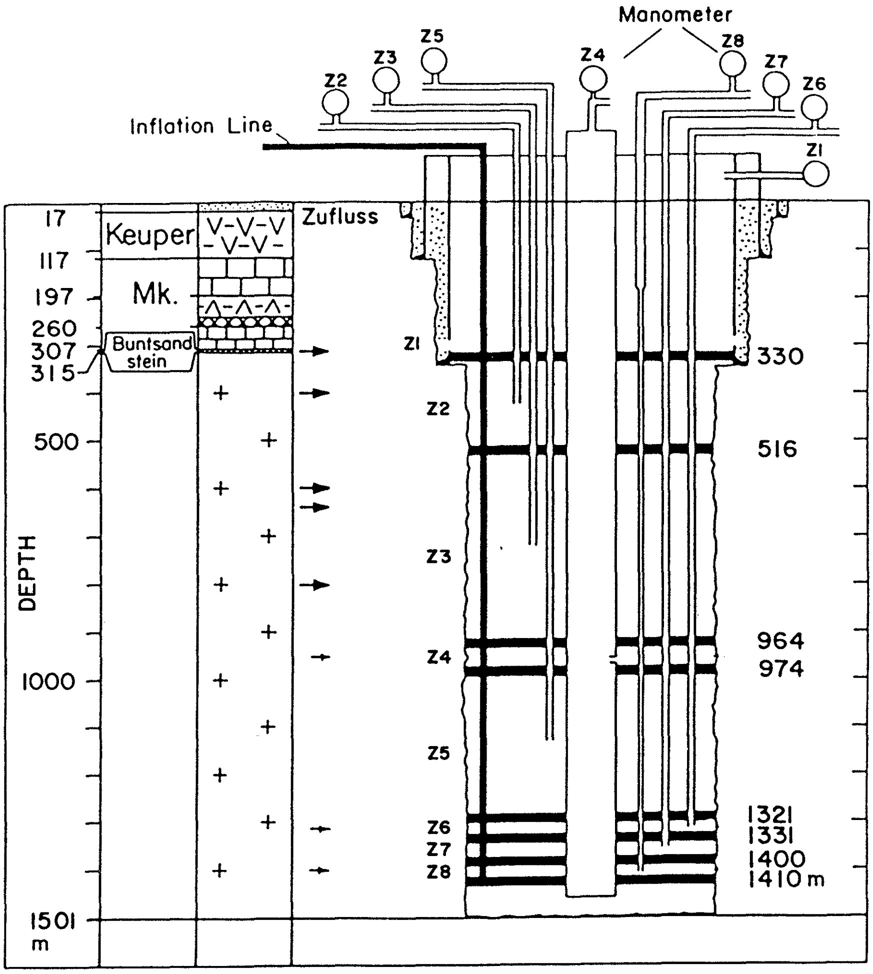

Figure 1. Schematic illustration of Lynes 8-packer monitoring tool at Boettstein borehole

2) outflow rates for the period 4 - 6 October to 23 October following the sequential opening of valves for zones Z5, Z6, Z7, Z8 and Z4, respectively; and

3) pressure recovery data for the period 23 October to 5 November 1984.

The monitored pressures for all zones Z4 - Z8 are presented in Figure 2 for the period 30 January to 5 November 1984, illustrating the sequence of long-term pressure build-up period, flow period and pressure recovery period. The test interval specifications, assumed formation and fluid properties, and documentation of the above sequence of flow and pressure recovery periods are summarized in Table 1.

The objectives of the flow and pressure recovery tests conducted during October - November 1984 were:

1) obtain flow and pressure recovery data suitable for hydraulic conductivity determination for the intervals corresponding to the packer-isolated zones of Z4, Z5, Z6, Z7 and Z8 and evaluate the interpreted hydraulic conductivity results including those obtained from the hydraulic testing program conducted during the drilling/testing phases (1982/1983);

2) evaluate evidence for packer compliance during sequential opening of the surface valves connected to the packer-isolated intervals;

3) evaluate the presence or absence of hydraulic communication between the packer-isolated zones occuring either at the packer/borehole wall interface or through the formation.

Estimates of formation pressure and hydraulic head were determined from the long-term pressure build-up data (January-October 1984) and estimates of hydraulic conductivity were determined from the flow data and subsequent pressure recovery data (October-November 1984). Full details on the data analysis techniques and their theoretical basis are provided in NTB 85-08.

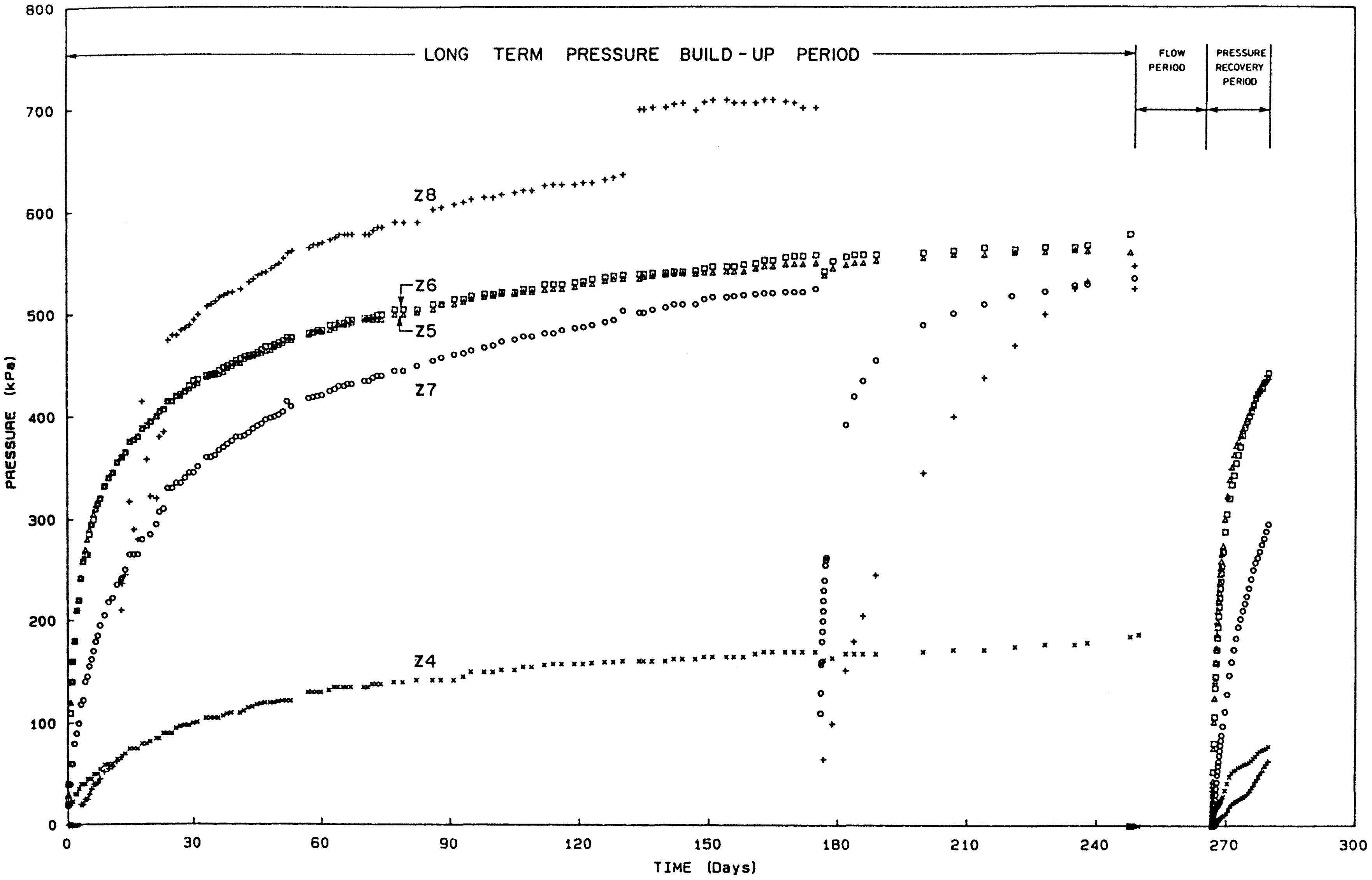

Figure 2. Monitored pressures in each packer-isolated borehole interval for the period 30 January to 5 November 1984

Test Interval Designation	Z4	Z5	Z6	Z7	Z8
Test interval Depth (m below surface)	964.29-975.11	976.51-1319.82	1321.22-1331.46	1332.86-1339.40	1400.80-1410.99
Length	10.8	343	10.2	66.5	10.2
Average Diameter (m)	0.212	0.178	0.160	0.166	0.159
System Volume (m^3)	4.16	7.14	0.44	1.17	0.20
Porosity	0.005	0.005	0.005	0.005	0.005
Formation Compressibility (1/Pa)	2E-11	2E-11	2E-11	2E-11	2E-11
Fluid Compressibility (1/Pa)	4.30E-10	4.30E-10	4.33E-10	4.33E-10	4.33E-10
Fluid Density (kg/m^3)	993	992	989	989	989
Storage Coefficient	2.3E-6	7.4E-5	2.2E-6	1.4E-5	2.2E-6
Average Temperature	48°C	54°C	61°C	62°C	63°C
Time/Date Valve Opened for Flow Test	09:35, 6/10	09:25, 4/10	09:36, 4/10	09:10, 5/10	09:35, 5/10
Time/Date Valve Closed for Recovery Test	14:00, 23/10	14:01, 23/10	14:02, 23/10	14:03, 23/10	14:04, 23/10

Table 1: Summary of Test Interval Specifications and Model Parameters for Analysis of Flow and Pressure Recovery Data

2. FLOW TEST DATA

During the period 4 - 6 October 1984, the valves were open sequentially on the zones Z5, Z6, Z7, Z8 and Z4, respectively (see Table 1 for times and dates). The timing of opening of the valves, after the first zone Z5, was determined based on the observed pressure response in adjacent zones. If there was evidence of significant hydraulic communication with an adjacent zone, then the valve to the adjacent zone was opened within about 0.5 hour. In this way, the effect of hydraulic communication on modifying representative flow rates from each zone was minimized. If hydraulic communication was not interpreted, the time elapsed between opening valves was about 1 day.

The flow rates for the zones Z4 to Z8 of the eight-packer monitoring tool are presented in Figure 3 (zero time is referenced to the opening of the valve to zone Z5 at 09:25 on October 4). The flow rates were calculated based on the fluid volume of outflow collected over a specific time period and are shown plotted at the midpoint for each of these time periods. The longer term yields for the zones are for decreasing magnitude in the order Z5, Z4, Z6, Z7 and Z8.

2.1 Jacob-Lohman Graphical Solutions

The Boettstein flow tests represent a situation that can be approximated as having constant drawdown with the discharge rate varying with time. Under these conditions, the straight line semi- logarithmic solution of Jacob and Lohman (1952) can be used to determine the formation parameter T and S (transmissivity and storativity). The solution, which is similar to the straight line solution of Cooper and Jacob (1946), assumes that for large times the well function, W(u), can be approximated as follows:

$$W(u) = 2.30 \log_{10} 2.25\, Tt/r_w^2 S \qquad (3\text{-}1)$$

where t = time and r_w = discharging well (or borehole) radius. Using this equation and solving the partial differential equation for nonsteady radial flow, a solution can be given, written as:

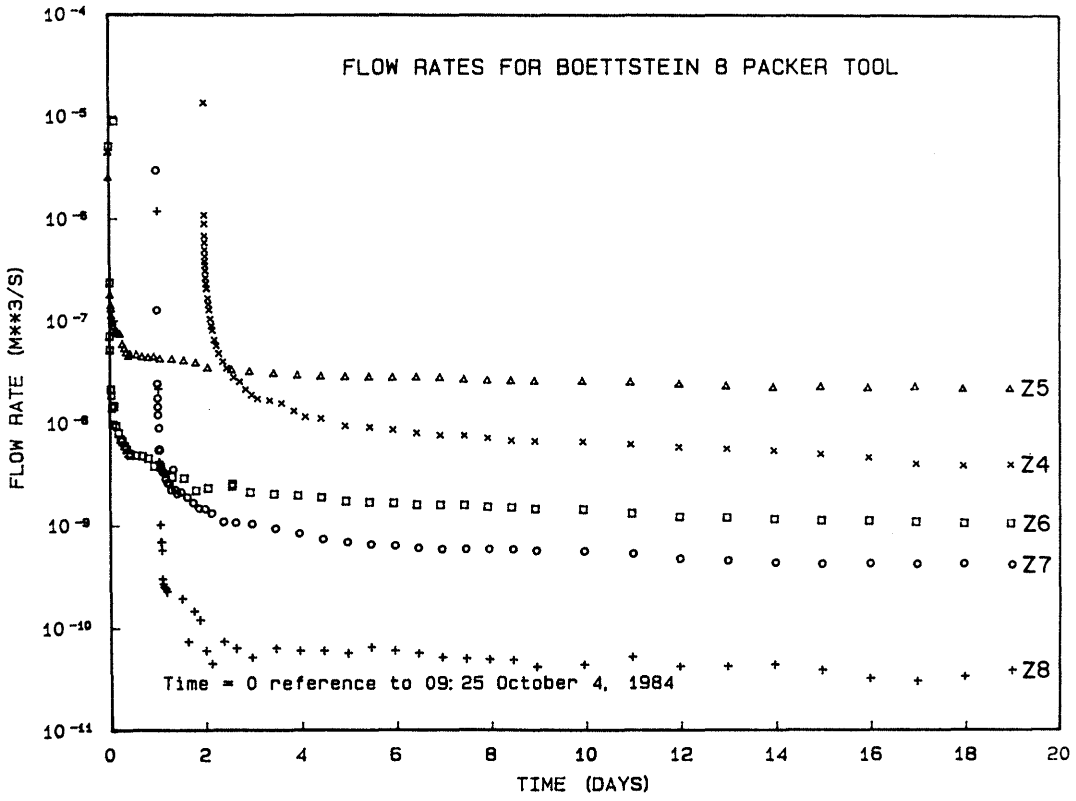

Figure 3. Measured flow rates for each of the zones Z4, Z5, Z6, Z7 and Z8 for the period 4 - 23 October 1984

$$T = \frac{2.30Q}{4\pi S_w} \log_{10} \frac{2.25Tt}{r_w^2 S} \qquad (3\text{-}2)$$

where S_w is the constant drawdown in the discharging well. Differentiating this equation and changing from infinitesimals to finite values yields the following solution as is given by Jacob and Lohman (1952):

$$T = \frac{2.30}{4\pi\Delta(Sw/Q)/\Delta\log_{10} t/r_w^2} \qquad (3\text{-}3)$$

Thus by plotting S_w/Q versus $\log_{10} t/r_w^2$, the values of $\Delta(S_w/Q)$ and $\Delta\log_{10} t/rw^2$ can be determined graphically and equation 3-3 solved to yield the transmissivity. The average hydraulic conductivity (K) corresponding to the full length of each of the packer-isolated borehole intervals was calculated as the transmissivity divided by the interval length (b):

$$K = \frac{T}{b} \qquad (3\text{-}4)$$

This method was used to determine the hydraulic conductivities from the flow test results of intervals Z4, Z5, Z6, Z7 and Z8. The graphical solutions and flow test data are presented in Appendix A. The value of S_w for each interval was taken as either the maximum pressure reading during the long term recovery period or the pressure reading immediately before opening the valves. At the time of opening of the valves, the long-term pressure recovery in each zone was, with the exception of Z8, within 7 to 13 percent of the estimated formation pressure. Therefore, the pressure skin radially surrounding the borehole is relatively constant at any level and is approximately equal to the measured pressure before opening the valves. Several of the zones had experienced a significant pressure drop when the continuous monitoring system was installed on July 23, 1984. Zone Z8 had not recovered to near its measured level prior to July 23 and, therefore, the uncertainty associated with the constant drawdown assumption is larger for this zone.

These pressures noted above were converted to an equivalent head in metres of water above the surface datum corresponding to the elevation of the surface monitoring system. The values of S_w are 18, 57, 57 and 53 metres for intervals Z4, Z5, Z6, and Z7, respectively. Values for S_w of 56 and 72 metres were utilized for interval Z8. The well radius used in the calculations was determined from the borehole caliper logs and represents an average integrated over the length of each interval. The values of r_w used in the calculations are 0.105, 0.089, 0.080, 0.083 and 0.079 metres for intervals Z4, Z5, Z6, Z7 and Z8, respectively.

In each interval the hydraulic conductivity was approximated from the late time flow data because this data is least likely to be affected by flows caused by pressure/volume expansion or temperature/volume contraction. (These aspects are discussed in greater detail in Section 2.3). The use of the late time data is also consistent with the requirement that u in the well function W(u) be less than 0.01. Using representative storage coefficients from Table 1 the requirement of u less than 0.01 holds for all intervals at late time except for interval Z8. Zone Z8 then has the greatest uncertainty associated with the hydraulic conductivity calculated by the Jacob-Lohman method.

In each interval, the flow test data does not plot as a straight line but plots as a smooth curve. The reasons for the poor data fit to a straight line cannot be fully explained; however, nonconstant head radially in the formation, volume expansion/contraction due to pressure/temperature changes, or inadequacies of a porous media analysis approach (in contrast to using fractured porous media based models) could contribute to the deviation from the straight line expected from theoretical considerations. To obtain an approximate solution the straight line was drawn throughout the flatest part of the late time data.

The calculations and semi-logarithmic plots using the Jacob-Lohman method are given in Appendix A and yield the following hydraulic conductivities for each interval:

Zone	Test Interval Depth (m)	Hydraulic Conductivity (m/s)
Z4	964.29 - 975.11	7×10^{-12}
Z5	976.51 - 1319.82	6×10^{-13}
Z6	1321.22 - 1331.46	6×10^{-13}
Z7	1332.86 - 1399.40	5×10^{-14}
Z8	1400.80 - 1410.99	1×10^{-14} (for S_w = 72 m) 2×10^{-14} (for S_w = 56 m)

It should be noted that a straight line fit to the very late time data would yield a lower hydraulic conductivity which could either reflect a larger volume of rock of lower hydraulic conductivity being tested or the limitations of a porous media approach to analysis of data from a fractured porous media.

2.2 GTFM Flow Test Simulations

The GTFM model was used to simulate flow into each borehole interval for various hydraulic conductivities and the results were then compared to the measured flow data. By comparison to the simulated flows a hydraulic conductivity for each interval was determined.

The model input parameters for each interval are given in Table 1. The assumed reference pressure (D_O) for each interval was taken either as the highest recorded interval pressure prior to the opening of the valves or the pressure reading immediately before opening of the valves. Reference pressures of 180, 560, 560 and 520 kPa were used for intervals Z4, Z5, Z6 and Z7, respectively.

As noted in Section 2.1, zone Z8 had not recovered totally from a large pressure drop resulting from the installation of the continuous monitoring system and therefore, pressures of 550 and 710 kPa were utilized for that zone.

At the start of the flow test, the pressure in a zone was allowed to drop and remain at zero pressure by opening a valve and the flows due to this change in pressure were recorded for the duration of the flow test. Flow rates were simulated using the GTFM model under the same conditions but at various hydraulic conductivities. The GTFM model-calculated flows were then compared to the field data for each interval.

The results of the simulations for each interval are given in Appendix B. The best-fit hydraulic conductivities are given below:

Zone	Test Interval Depth (m)	Best-fit Hydraulic Conductivity (m/s)
Z4	964.29 - 975.11	2×10^{-11}
Z5	976.51 - 1319.82	7×10^{-13}
Z6	1321.22 - 1331.46	1×10^{-12}
Z7	1332.86 - 1399.40	5×10^{-14}
Z8	1400.80 - 1410.99	2×10^{-14} (for D_o = 710 kPa) 3×10^{-14} (for D_o = 550 kPa)

The fit of the early time data in the flow tests is generally poor but the late time data (i.e., after the first several days) appears suitable to determine a representative hydraulic conductivity.

2.3 Discussion

2.3.1 Packer Compliance and Hydraulic Communication Effects

The significance of packer compliance or packer readjustment during testing of low permeability geologic formations is poorly understood because of the very limited data base available in the literature. The packer readjustment occurs in response to the head differential from zones above and below each of the packers as well as to the head differential from inside and outside of the packers. Observations of the pressure response in adjacent zones as the valves were opened to specific zones during the flow tests has provided further insight to assessing this problem.

Opening of the valve to zone Z5 resulted in a minor and short-term pressure decrease in zone Z4 and a more significant and continuous pressure decrease in zone Z6. The pressure decrease in zone Z4 recovered within several hours and is felt to be a consequence of packer compliance. The more significant pressure decrease observed in zone Z6 is felt to be a consequence of hydraulic communication through the formation surrounding the packer between zones Z5 and Z6. The pressure responses in zone Z4 and Z6 as a consequence of opening the valve to zone Z5 are shown in Figure 4. The smaller pressure change observed in zone Z4 in comparison to zone Z6 is partially the result of the much larger system volume that is shut in.

Opening of the valve to zone Z7 resulted in a significant and continuous pressure decrease in zone Z8. Considering the large difference in observed pressures for zones Z7 and Z8 during the long-term pressure build-up period, hydraulic communication between these zones was not expected. An alternative explanation is that packer compliance effects have caused this pressure response as a consequence of the very low hydraulic conductivity and the short length of the borehole zone Z8 (i.e., ideal conditions to maximize packer compliance effects).

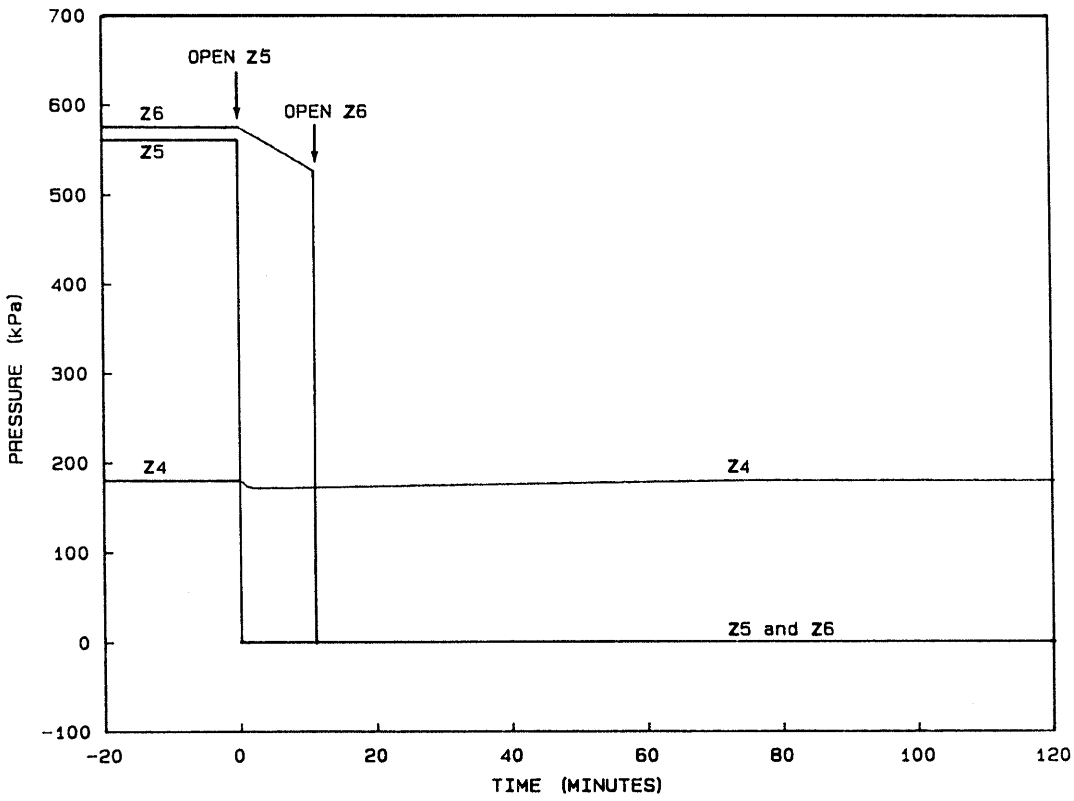

Figure 4. Schematic illustration of pressure responses in zones Z4 and Z6 after opening the valve to zone Z5. The observed responses are considered to be a consequence of packer compliance for zone Z4 and hydraulic communication for zone Z6

Although some additional information on the nature of packer compliance has been obtained from the flow tests, the significance of packer compliance on hydraulic testing and pressure measurements remains unquantified.

2.3.2 Fluid Expansion or Contraction Effects

During the flow test, contributions to the flow are likely to occur from fluid contraction and expansion due to temperature and pressure changes respectively. At the start of the flow test, the opening of the valve causes an instantaneous change in pressure and consequently flow will occur that is due solely to the expansion of the fluid. Simple volume expansion/ pressure change calculations indicate that the volume change is small in comparison to the total volume of the interval. In all cases the large flows for all intervals that occur at the very early time is likely due in part to a volume expansion effect. The theoretical volume expansion after the initial release to zero pressure for the zones Z4, Z5, Z6, Z7 and Z8 are 340, 1630, 48, 257 and 64 mL respectively. Examination of the early time flow rates indicates that these volumes would have been obtained in less than a minute and up to several minutes for the various zones (Note: Exact times are difficult to estimate because the flow rates vary significantly during the early time of the flow period).

Volume expansion will also affect the fluid as it flows from the interval towards the surface. This type of flow occurs in the narrow diameter tube as a result of a pressure decrease as it rises in the tube and therefore a small contribution to the total flow could be attributed to this volume expansion. The field data indicates much higher flow rates at the early time (e.g., interval Z4 and Z7).

Fluid temperature changes during the flow test would have the opposite effect on the fluid volume. Due to the thermal gradient that occurs with depth, fluid rising up the tubing will undergo a temperature decrease and will contract causing a volume decrease and a reduction in flow. Theoretical calculations of the flow increase caused by pressure reduction (volume expansion) and flow decrease caused by temperature decrease (volume reduction) for zone Z5 indicate that the net effect of these factors is relatively minor and should cause less than a 0.5 percent change on the late time flow rates during the flow test. The GTFM simulations did not include flow that occurs due to fluid contraction from a temperature decrease or fluid expansion from a pressure decrease.

2.3.3 Boundary Effects

Flow towards the interval in each of the flow tests could be affected by boundaries (i.e., changes in hydraulic conductivity radially from the borehole) which could limit the flow at a later time. Examples of a boundary could include a fracture intersecting the borehole but of finite length or the intersection of a fracture with a highly permeable shear zone. Each of these features could have a dramatic effect on the flow to the interval. The finite fracture length would be analogous to a no flow boundary and would result in a decrease in flow with time. The intersection of a fracture with a highly (or higher) permeable zone would cause the flow rate to reach a pseudo-constant valve after a short time period which is analogous to a constant head boundary. In this case, the flow would reach steady state after a short period of flow.

For field testing programs utilizing single boreholes, definite boundaries are difficult to determine. The flow response for zones Z4 - Z8 tend to tail off towards low flows at late times as opposed to reaching an approximate steady state. It may be possible that at late times, as the radius of influence of the tested region reaches larger volumes of rock, some finite no-flow boundary near the borehole may be reached. Pressure profiles from the GTFM simulations for the flow period indicate a radius of influence of less than 10 metres for all zones. (Note that the method of analysis assumes a porous media conceptualization of the flow regime.) This radius of influence of tested rock corresponds to the radius to which the change in pressure in the formation is 10 percent of the change in pressure in the borehole. Therefore, reduced flow could occur as larger volumes of bulk lower hydraulic conductivity rock are influenced. Boundary effects and their influence on the flow tests have not been quantitatively addressed in this study.

3. PRESSURE RECOVERY DATA

Following the flow test, the surface valves of the Lynes 8 packer tool were closed and the pressures in each interval were allowed to recover. The valves were closed sequentially at one minute intervals starting at 14:00 hours on October 23, 1984 with Z4 closed first followed by Z5, Z6, Z7 and Z8.

The pressure recovery for each of the zones Z4 to Z8 of the eight-packer tool are presented in Figure 5 (zero time is referenced to the closing of the valve for interval Z4). The pressure recovery test is compared to the long term pressure build-up in Figure 2. The pressure recovery data utilized in GTFM simulations was for the period from October 23 to November 5, 1984. Total duration of the data record for the recovery test was approximately 310 hours or 12.9 days. The pressure recovery during this period was much faster in comparison to the long-term pressure build-up period. The faster recovery is the result of a much shorter duration of borehole pressure history at zero pressure conditions at surface for the recovery test (i.e., histories of 17 to 19 days prior to the recovery test and 8 to 10 months prior to the long-term pressure build-up period).

3.1 GTFM Model Simulations

The pressure recovery data (Figure 5), obtained after the valve were closed to end the flow test, was analyzed using the GTFM simulation model. The model included an approximate 19 day flow period at zero pressure prior to the recovery test as a borehole pressure history period. The input parameters to the GTFM model are given in Table 1. The assumed reference pressure used in the simulations was taken as the maximum recorded pressure during the long term pressure build-up period or the pressure reached just prior to the opening of the valve. In the case of Z8 which had not fully recovered from the installation of the automatic recorder, simulations were conducted at both pressures. Assumed reference pressures used in the simulations for intervals Z4, Z5, Z6 and Z7 were 180, 560, 560 and 520 kPa respectively. Assumed reference pressures for interval Z8 were 710 kPa, the maximum recorded pressure and 550 kPa, the interval pressure just prior to the opening of the valve for the flow test.

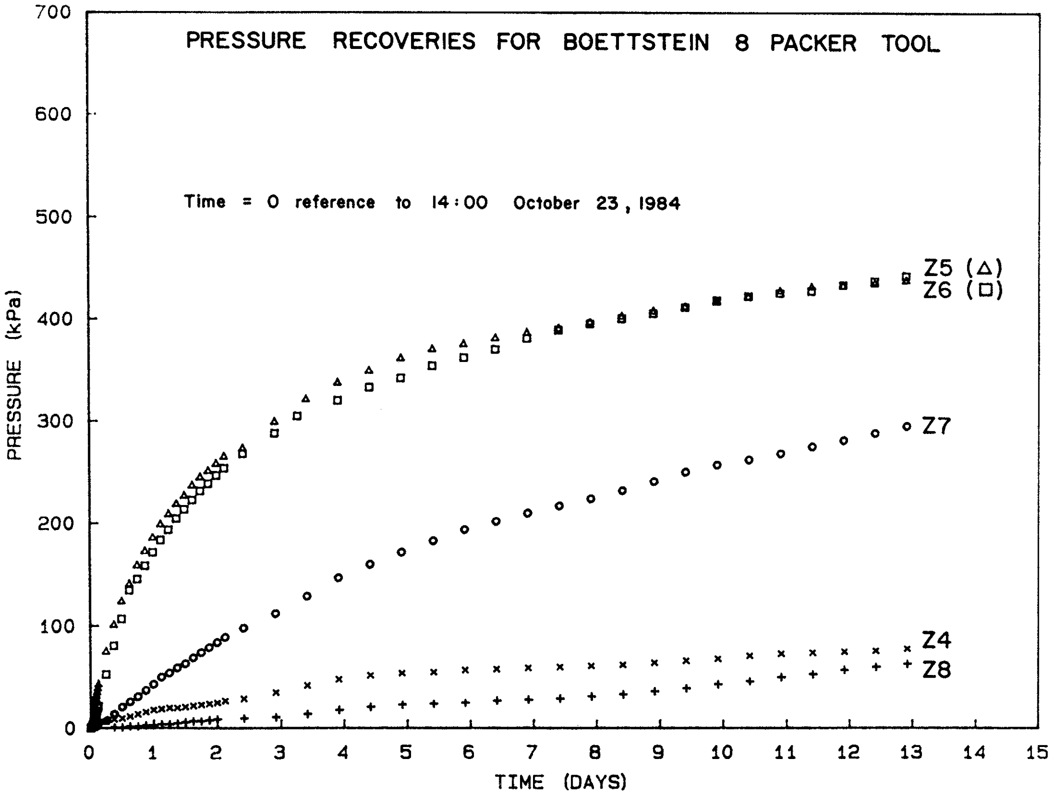

Figure 5. Measured pressure recoveries for each of the zones Z4, Z5, Z6, Z7 and Z8 for the period 23 October to 5 November 1984

Simulations were conducted at different hydraulic conductivities and then compared to the interval field- measured pressure response. In this manner the approximate hydraulic conductivity for the recovery data can be determined. The recovery test simulations are shown in Appendix C. In all cases, the fit of the field data to a representative hydraulic conductivity was good except for interval Z4 in which the field data had an irregular shape in comparison to the simulated pressure response. Best-fit hydraulic conductivities based on the GTFM simulations of the recovery data are as follows:

Zone	Test Interval Depth (m)	Best-Fit Hydraulic Conductivity (m/s)
Z4	964.29 - 975.11	1×10^{-12}
Z5	976.51 - 1319.82	3×10^{-13}
Z6	1321.22 - 1331.46	5×10^{-13}
Z7	1332.86 - 1399.40	3×10^{-14}
Z8	1400.80 - 1410.99	1×10^{-15} (D_o = 710 KPa)
Z8	1400.80 - 1410.99	2×10^{-15} (D_o = 550 kPa)

All GTFM simulations of the recovery data were sensitive to changes in hydraulic conductivity. The shape of the simulated recovery curves accurately match those of the field data for intervals Z5, Z6, Z7 and Z8. Interval Z4, exhibited an irregular shaped curve but has a general trend that matches the shape of the simulated curves. The irregular shape of the recovery curve for Z4 could possibly be due to a fracture flow recovery response rather than that due to porous media flow.

The recovery response of interval Z8 was also unusual in that the best-fit hydraulic conductivity is exceedingly low. It is not known whether this is a true formation response or possibly the result of equipment compliance or equipment difficulties. A similar hydraulic conductivity (5×10^{-15} m/s) was also suitable to simulate the pressure recovery after the installation of the automatic recording device in July 1984, thus providing further evidence that the hydraulic conductivity of the zone is very low. The different reference pressures (710 kPa and 550 kPa) used in the simulations for zone Z8 has the effect of increasing the hydraulic conductivity for a lower reference pressure. However, the increase in hydraulic conductivity (1×10^{-15} versus 2×10^{-15} m/s) at the different reference pressures is minor.

4. LONG TERM PRESSURE BUILD-UP DATA

The measured pressure build-up data for the period 30 January to 4 October 1984 for zones Z4 - Z8 are presented in Figure 2. The pressure drops shown at a time of about 180 days after shut-in of the zones on January 30 are the result of the pressure release during installation of the continuous monitoring system. Several of the pressure increases and decreases in the pressure response for zone Z8 are a direct consequence of pressure changes applied to the inflation line and packer system. These correlatable responses are considered to be caused by packer compliance. However, the pressure response for zone Z8 does exhibit anomolous behaviour. For example, the slow pressure recovery during the first 13 days and the very rapid increase during the subsequent several days cannot be explained. Therefore, the measured pressure response for zone Z8 is considered to have greater uncertainty in comparison to the other zones.

4.1 GTFM Model Simulations

The GTFM model was utilized to simulate the long-term pressure build-up data to obtain estimates of formation pressure and hydraulic conductivity. The model simulations included the effects of the borehole pressure history corresponding to the average time that each interval was open to annulus pressure conditions between drilling and shut in on January 30.

The best-fit hydraulic conductivities from all of the zones Z4 to Z7 were very low (in the range 3×10^{-14} to 3×10^{-13} m/s). The hydraulic conductivities from these analyses are not considered representative especially for zones such as Z4 and Z6. Because of the anomolous and erratic pressure response of zone Z8, the pressure build-up data for this zone was not simulated.

The hydraulic communication between zones Z5 and Z6 was identified during the flow test and would have the net effect of increasing the shut-in borehole fluid volume used in the data analysis by a factor of 16. Additional simulations using the larger volume confirmed that the low interpreted hydraulic conductivity could have been caused by uncertainties regarding the effect of the hydraulic communication between the zones.

A full explanation for the reason for the low interpreted hydraulic conductivity for zone Z4 from the long term pressure build-up data is not considered possible based on analyses conducted to date. Possible reasons which could contribute to the low interpreted hydraulic conductivity are: (1) inadequacies of a porous media based conceptualization of the formation for modeling purposes; and (2) possible boundary effects such as finite fracture lengths thus causing slow pressure build-up following the long borehole pressure history at annulus pressure conditions.

Modeling approaches utilizing a fractured porous media conceptualization could be conducted to evaluate the significance of the conceptualization of the medium. Sensitivity analyses could also be conducted to evaluate the effects of low hydraulic conductivity boundaries at specified radial distances from the borehole. These types of model simulations have not been conducted as part of the data analysis presented in this report.

Considering the length of zone Z5 (343 metres) and the estimated formation pressures of 200 kPa for zone Z4 and 625 kPa for zones Z6, it should be expected that the in-situ formation pressure will vary within this zone between 200 kPa at the top and 625 kPa at the bottom. Therefore, the measured pressure for zone Z5 is averaging over a very large formation pressure range over the borehole interval length. Because of this pressure variation, flow is likely inward to the borehole in the lower portion of the Z5 interval and outward over the upper portion of the interval. For this reason, both the interpreted hydraulic conductivity and formation pressure from analysis of the long-term pressure build-up data cannot be considered representative.

Calculations involving hydraulic heads and formation pressures require estimates of fluid density and must take into account the elevation at which the pressure is measured. All formation pressures and hydraulic heads must be evaluated in a consistent manner to allow a comparison of the calculated hydraulic heads corresponding to the different test intervals. The formation pressures that have been measured with the Lynes eight-packer monitoring tool have used surface gauges connected to tubing extending to the packer-isolated borehole intervals. The variation in fluid density with depth is an important factor affecting the calculation of representative formation pressures. The factors affecting fluid density are pressure, temperature and salinity. The relative importance of pressure and temperature effects have been quantified in tables and illustrated graphically in NTB 85-08.

The effect of fluid salinity on the pressure measurements from the eight-packer monitoring tool are expected to be minimal for zones Z4 to Z8 since the borehole was flushed immediately prior to equipment installation and the formation inflows at the corresponding depths are low. The specific conductance of the outflow of these zones from the tubings at surface during the flow test are relatively low (i.e., 500 to 1540 uS/cm). Significant salinity variations with depth in the tubings are not expected considering the relatively low inflows from the formation.

The highest measured pressures during the long-term pressure build-up period are presented in Table 2. For zones Z4, Z5, Z6 and Z7 these pressures are less than the expected formation pressure whereas for zone Z8 which has experienced equipment compliance the highest measured pressure is considered to be higher than the formation pressure (see pressure response in Figure 2). From these measured pressures, corresponding hydraulic heads were calculated utilizing a reference fluid density of 10^3 kg/m^3.

The best-fit formation pressures from the GTFM simulations are presented in Table 2. Because there is uncertainty in the representativeness of the interpreted hydraulic conductivities for the zones, precise estimates of the formation pressures cannot be determined. However, the estimated formation hydraulic heads are considered to be within the range 365 to 371 metres above mean sea level for zone Z4 and within the range 402 to 420 metres above mean sea level for zones Z6, Z7 and Z8. Within the range of accuracy of the hydraulic head estimates for the zones Z6, Z7 and Z8, a vertical gradient

Zone	Interval Depth (m)	Highest Measured Pressure (HMP)* (kPa)	Hydraulic Head Calculated from HMP (m)	GTFM Estimated Formation Pressure (EFP) (kPa)	Hydraulic Head Calculated from EFP (m)
Z4	964.29- 975.11	185	365	200	366
Z5	976.51-1319.82	560	403 **	625	410 **
Z6	1321.22-1331.46	580	405	625	410
Z7	1332.86-1399.40	530	402	610	408
Z8	1400.80-1410.99	710	419 ***	not simulated	-

* Pressures are referenced to a zero datum at the elevation of the surface pressure gauges or continuous monitoring system. These elevations correspond to approximately 346 metres above mean sea level for zones Z4, Z5, Z6, and Z7 and 347 metres above mean sea level for zone Z8.

** The hydraulic head for zone Z5 is not considered representative because of the great length of the borehole interval (and the expected large variation in hydraulic head along this interval) and the interpretation of hydraulic communication between zones Z5 and Z6.

*** The hydraulic head for zone Z8 is considered to be less than 419 metres since the highest measured pressure appears to have been affected by equipment compliance with measured pressures decreasing at a later time of the long-term build-up period.

Table 2: Summary of Formation Pressures and Hydraulic Heads from Analysis of Long Term Pressure Build-Up Data from Eight-Packer Monitoring Tool

between these zones cannot be determined. It is emphasized that the estimated (calculated) hydraulic heads are affected by the method of pressure measurement (i.e., surface pressure gauges connected with tubing to the test interval).

5. SUMMARY AND COMPARISON OF FORMATION PARAMETER DETERMINATIONS

5.1 Formation Pressures and Hydraulic Heads

The formation pressures and hydraulic heads interpreted from the long-term pressure build-up data are summarized in Table 2 (see discussion in Section 4) and the hydraulic heads are shown plotted in Figure 6. Representative formation pressures and hydraulic heads were determined for zones Z4, Z6, Z7 and Z8. The estimated formation pressure for zone Z5 is not considered representative because of the great length of the borehole interval (and the expected large variation in hydraulic head along the interval) and the interpretation of hydraulic communication between zones Z5 and Z6. The hydraulic head for zone Z8 is considered to be less than 419 metres since the highest measured pressure appears to have been affected by equipment compliance with measured pressures decreasing at a later time in the long-term build-up period (see Figure 2).

The formation hydraulic heads were calculated based on the pressures measured at the surface gauges and estimated using GTFM simulations. As discussed in Section 4, there is some uncertainty associated with the representativeness of the interpreted hydraulic conductivities and formation pressures from the simulations. Nonetheless, reasonable range estimates for the formation hydraulic heads are 365 to 371 metres above mean sea level for zone Z4 and 402 to 420 metres above mean sea level for zones Z6, Z7 and Z8. A vertical gradient between zones Z6, Z7 and Z8 cannot be determined with the presently existing data base. More precise estimates of the formation pressures and hydraulic heads will be possible in the future after the collection of a much longer pressure-build up data record.

The interpreted hydraulic heads from zones Z6, Z7 and Z8 were also compared with estimates from the hydraulic testing program for depths below 964 metres. The appropriate hydraulic tests were the double-packer tests 1326.2D using the pressure build-up data from below the bottom packer and the single-packer test 1497.8S. The monitored depth

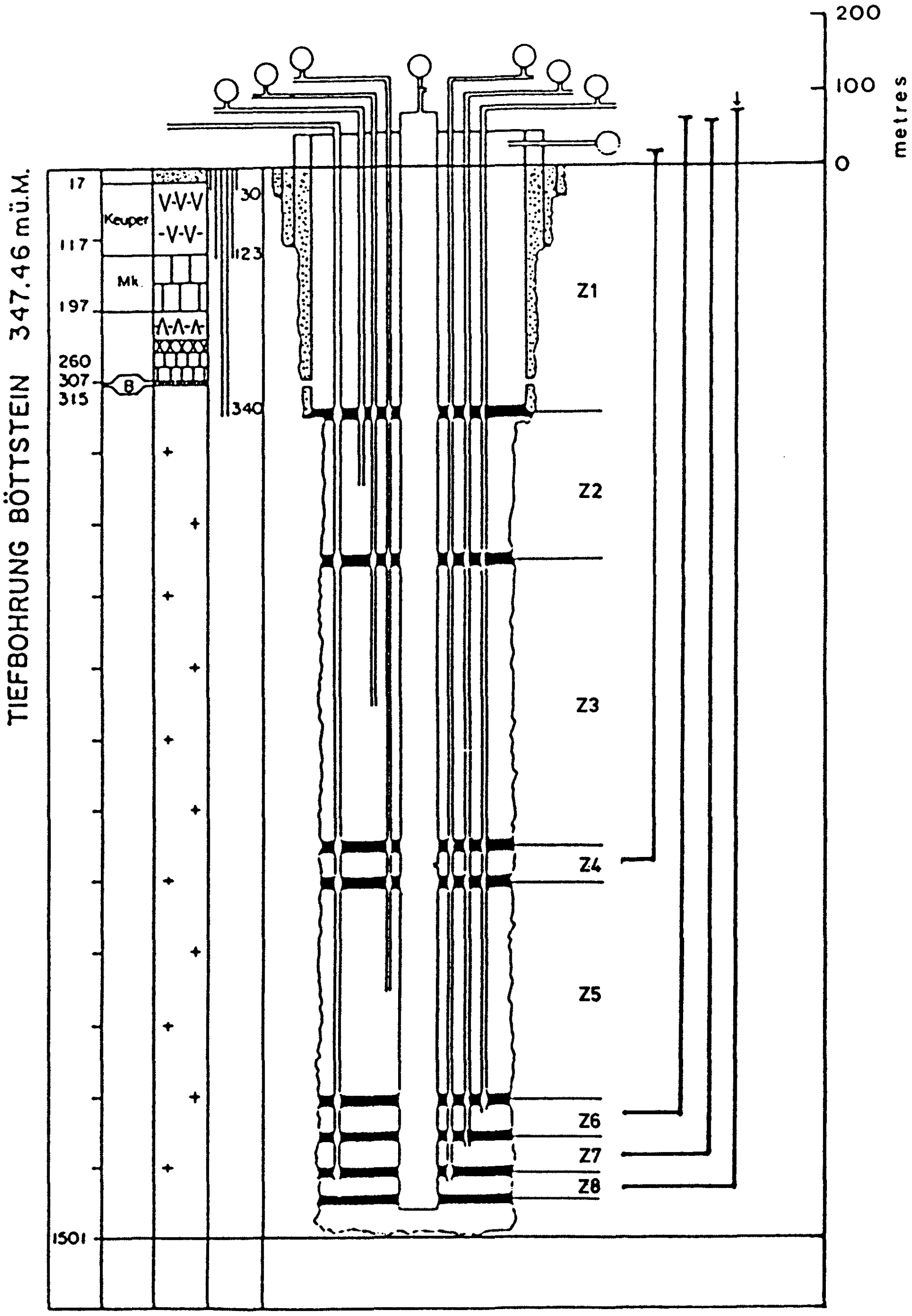

Figure 6. Estimated formation hydraulic heads from pressures obtained from long-term pressure build-up period

intervals were 1332.61 - 1501.30 metres and 1494.20 - 1501.30 metres for tests 1326.2D and 1497.8S respectively. Although the test interval for 1497.8S is below the depth of zones Z4 to Z8, it was included for comparison purposes since it represents hydraulic head conditions at the greater depths of the borehole.

As discussed in Section 4, it is necessary to use a consistent basis for comparing formation pressures and hydraulic heads from different measurement conditions. The formation pressures from the eight-packer monitoring tool are measured at ground surface with gauges connected via tubing to the packer-isolated intervals. The fluid density will vary along these tubes as a consequence of pressure and temperature effects. The formation pressure estimates from tests 1326.2D and 1497.8S were measured downhole with pressure transducers in the hydrologic tool. The test specifications, estimated formation pressures and calculated hydraulic heads from the above two tests are summarized as follows:

Test Designation	1326.2D	1497.8S
Depth Interval (m)	1332.61-1501.30	1494.20-1501.30
Transducer Depth (m)	1314.92	1488.19
Estimated formation pressure (kPa) at transducer depth	13650	15179
Surface reference datum elevation (m)	347.45	347.45
Integrated average fluid density (kg/m^3) over full depth	996	995
Hydraulic Head (m)	420	405

The hydraulic heads were calculated using an integrated average fluid density over the full depth to be consistent with the hydraulic heads determined from the estimated formation pressures from the for the tests 1326.2D and 1497.8S are in the range 405 to 420 metres above mean sea level. These hydraulic heads compare favourably with the values of 402 to 419 metres above mean sea level estimated for zones Z6 to Z8.

5.2 HYDRAULIC CONDUCTIVITY PROFILE

Hydraulic conductivities obtained from the hydraulic testing program conducted during 1982/83 and from analysis of the data from the eight-packer monitoring tool during the period January 30 to November 5, 1984 are summarized in Table 3. The hydraulic conductivity values for the hydraulic testing program were calculated as a weighted average over each of the depth intervals corresponding to the zones Z4 to Z8. The hydraulic conductivities obtained from analysis of the data from the eight-packer monitoring tool have been presented and discussed in Sections 2, 3 and 4.

The hydraulic conductivities from analysis of the long-term pressure build-up data are all very low in magnitude and are not considered representative (see discussion in Section 4). The hydraulic conductivities determined from analysis of the flow test data using graphical and GTFM simulation methods and from analysis of the pressure recovery test data are in reasonable agreement for each of the zones Z4 to Z8. The hydraulic conductivity estimated from the pressure recovery test data was up to about one order of magnitude lower than that from the flow test data.

The recommended hydraulic conductivities corresponding to each of the packer-isolated zones Z4 to Z8 are listed in Table 3. Variations between the hydraulic conductivities from the hydraulic testing program, the flow test, the recovery test and the recommended hydraulic conductivities for the zones are discussed as follows. Hydraulic conductivities for the interval corresponding to zone Z4 and Z5 are consistent from the various tests to within about one order of magnitude. Because of the great length of interval Z5, the recommended average hydraulic conductivity of 6×10^{-13} m/s is relatively low in magnitude even though there may exist shorter zones of higher

		Hydraulic Conductivity (m/s)					
Zone	Interval Depth (m)	Hydraulic Testing Program	Long-Term Pressure Build-up Data*	Flow Test Data		Recovery Test	Recommended Hydraulic Conductivity (m/s)
				Jacob Lohman Analysis	GTFM Analysis		
Z4	964.29-975.11	5×10^{-11}	3×10^{-13}	7×10^{-12}	2×10^{-11}	1×10^{-12}	2×10^{-11}
Z5	976.51-1319.82	4×10^{-12}	2×10^{-13}	6×10^{-13}	7×10^{-13}	3×10^{-13}	6×10^{-13}
Z6	1321.22-1331.46	4×10^{-10}	2×10^{-13}	6×10^{-13}	1×10^{-12}	5×10^{-13}	1×10^{-12}
Z7	1332.86-1399.40	9×10^{-11}	3×10^{-14}	5×10^{-14}	5×10^{-14}	3×10^{-14}	5×10^{-14}
Z8	1400.80-1410.99	4×10^{-11}	not simulated	1×10^{-14} - 2×10^{-14}	2×10^{-14} - 3×10^{-14}	1×10^{-15} - 2×10^{-15}	2×10^{-14}

* The hydraulic conductivities interpreted from the long-term pressure data are not considered to be representative (see discussion in Section 4).

Table 3: Summary and Comparison of Hydraulic Conductivities from Hydraulic Testing Program and from Analysis of Pressure Monitoring Data from the Eight-Packer Tool at Boettstein for Depths Between 964 and 1411 metres.

hydraulic conductivity (i.e., by one or more orders of magnitude) within this interval. The effect of measurement scale on interpreted hydraulic conductivity is discussed in greater detail in NTB 85-08.

From the pressure and recovery test the hydraulic conductivities tend to be lower (up to 3 orders of magnitude) than those obtained from the hydraulic testing program. Factors that may contribute to these differences are:

(1) The flow and pressure recovery tests conducted using the eight-packer monitoring tool were a factor of 30 to 75 longer in duration than the pulse, slug or drill-stem tests conducted in the hydraulic testing program. A much larger volume of rock is tested during the longer duration tests.

(2) The intervals tested during the hydraulic testing program are different than those corresponding to zones Z4 to Z8. Thus, the average hydraulic conductivities reported in Table 3 are for a tested interval that may be somewhat larger and may possibly include a higher permeability zone. It must be noted that the borehole intervals corresponding to the packer locations of the eight-packer tool have not been directly tested during the flow and pressure recovery tests.

(3) Hydraulic communication from above and below the upper packer of the hydrologic tool could not be identified during the hydraulic testing program. Because the borehole was flowing at the wellhead, the monitored pressure for the borehole interval above the upper packer always remained relatively constant and a hydraulic communication to the interval being tested could not be identified. Several of the double-packer tests with packer settings at the same depth as the packer between zones Z5 and Z6 did show communication from above and below the lower packer (e.g., test 1321.OD). This type of hydraulic communication cannot be identified when it is the upper packer that it is located at the same depth.

The recommended hydraulic conductivities reported in Table 3 are considered to be accurate within about one order of magnitude.

6. REFERENCES

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ACKNOWLEDGEMENTS

The contributions by Dr. A. Schneider (NAGRA) to the successful completion of the flow and pressure build-up tests are gratefully acknowledged.

APPENDIX A

Jacob-Lohman Graphical Plots for Flow Test Data

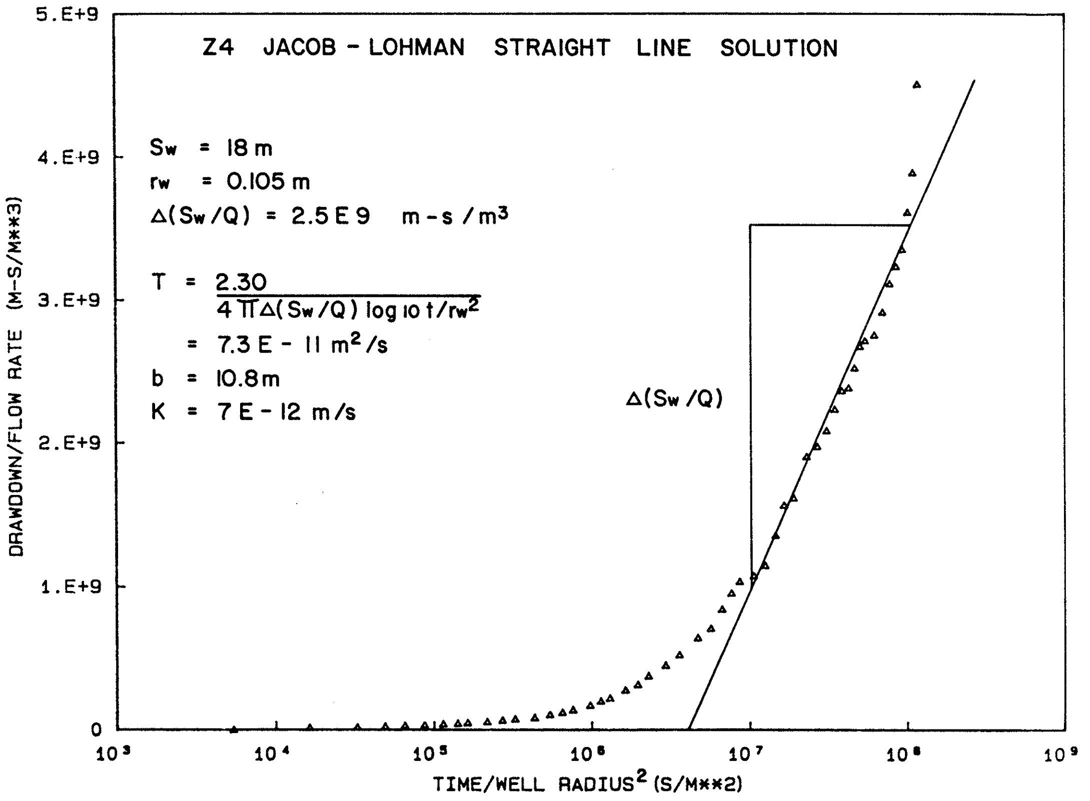

Figure A-1 Jacob-Lohman solution for the flow test of interval Z4

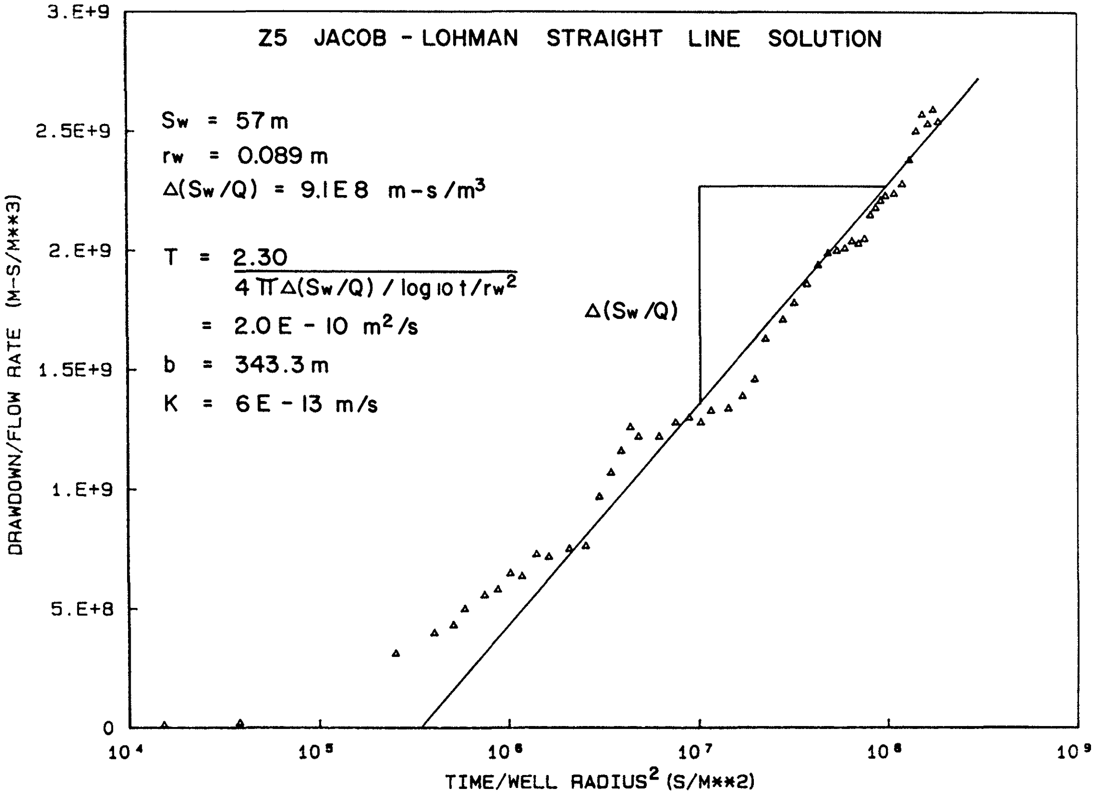

Figure A-2 Jacob-Lohman solution for the flow test of interval Z5

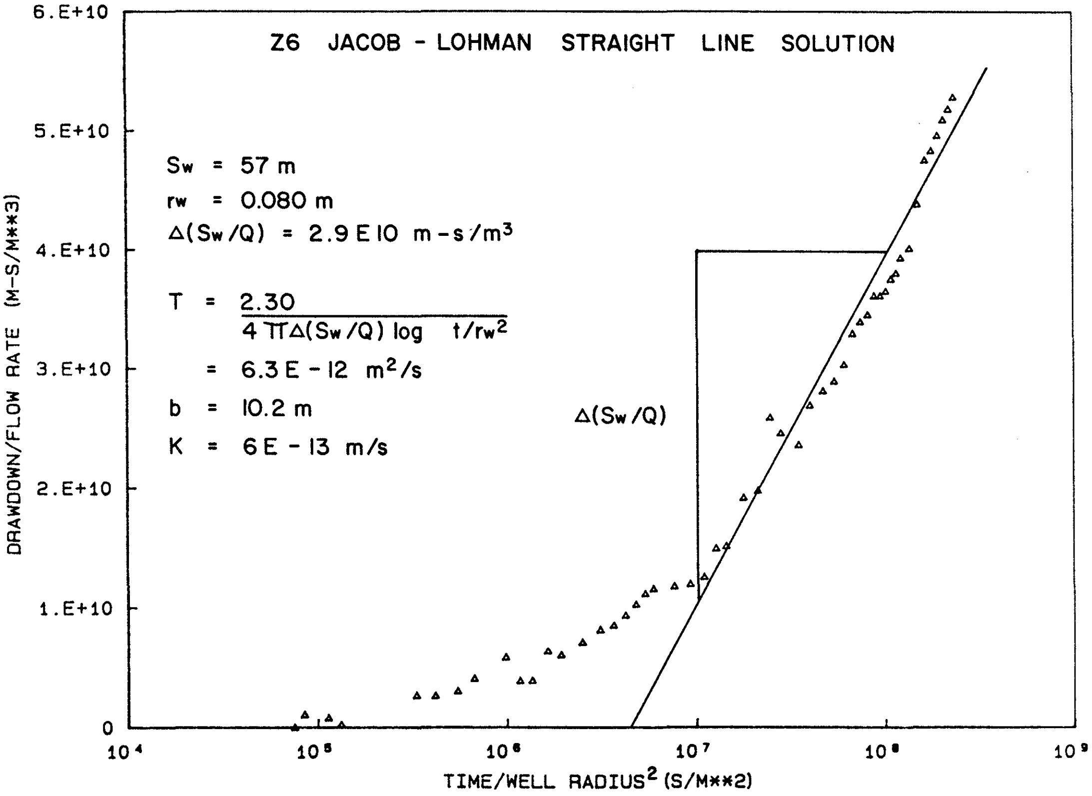

Figure A-3 Jacob-Lohman solution for the flow test of interval Z6

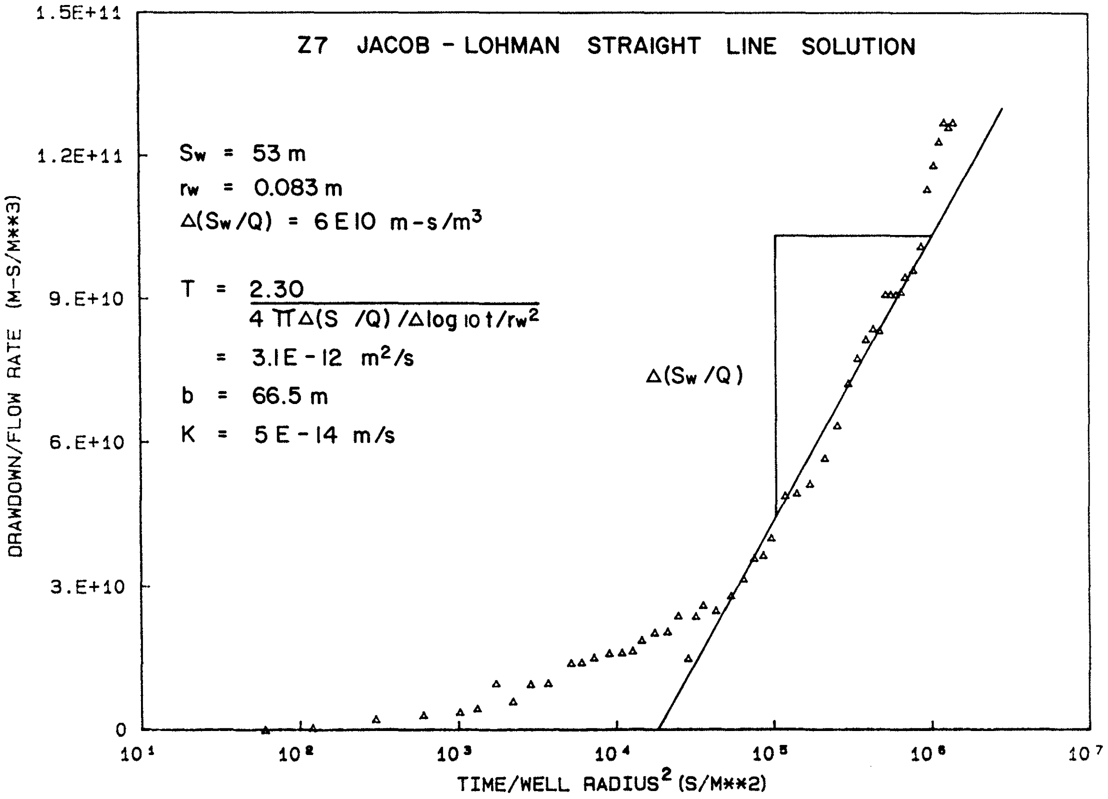

Figure A-4 Jacob-Lohman solution for the flow test of interval Z7

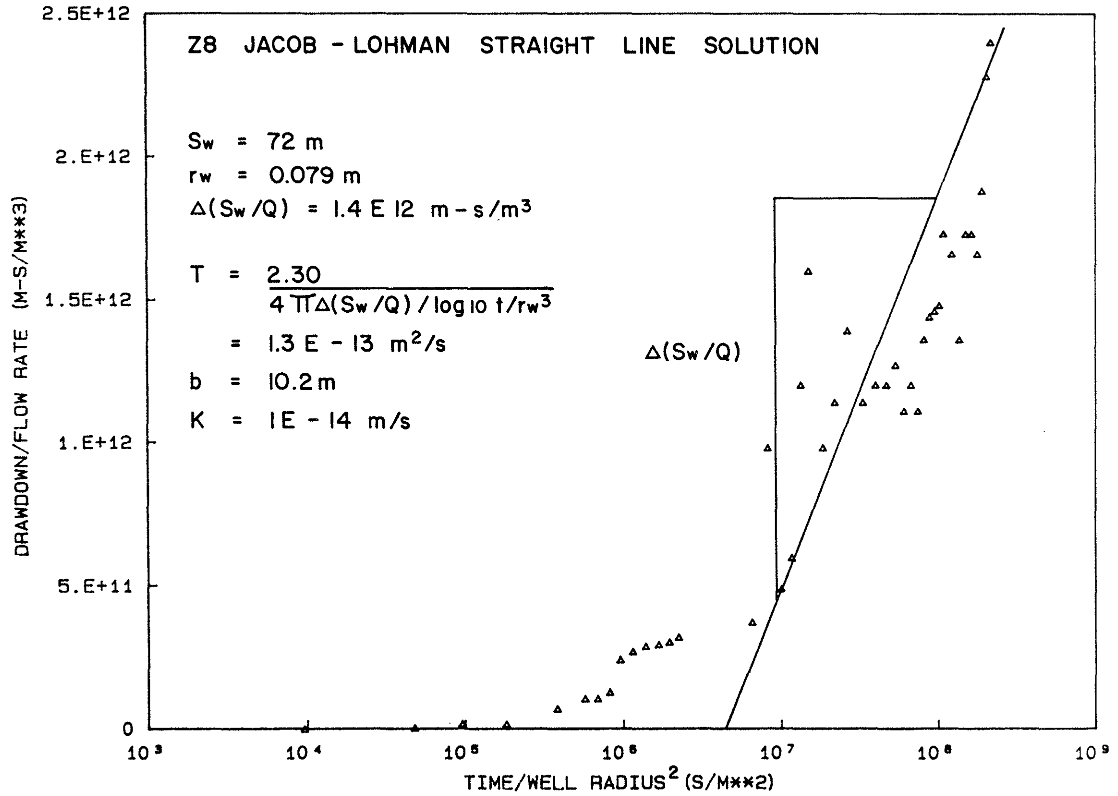

Figure A-5a Jacob-Lohman solution for the flow test of interval Z8 for drawdown (S_W) of 72 m

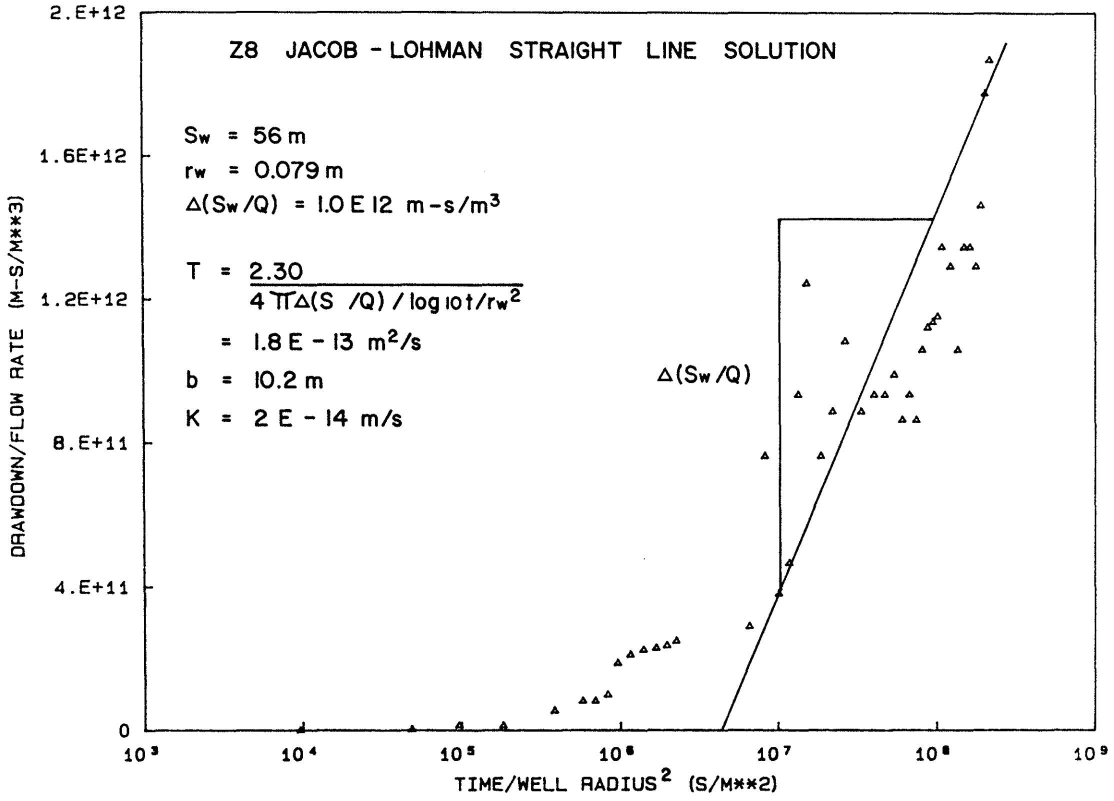

Figure A-5b Jacob-Lohman solution for the flow test of interval Z8 for drawdown (S_w) of 56 m

APPENDIX B

Plots of GTFM Simulations for Flow Test Data

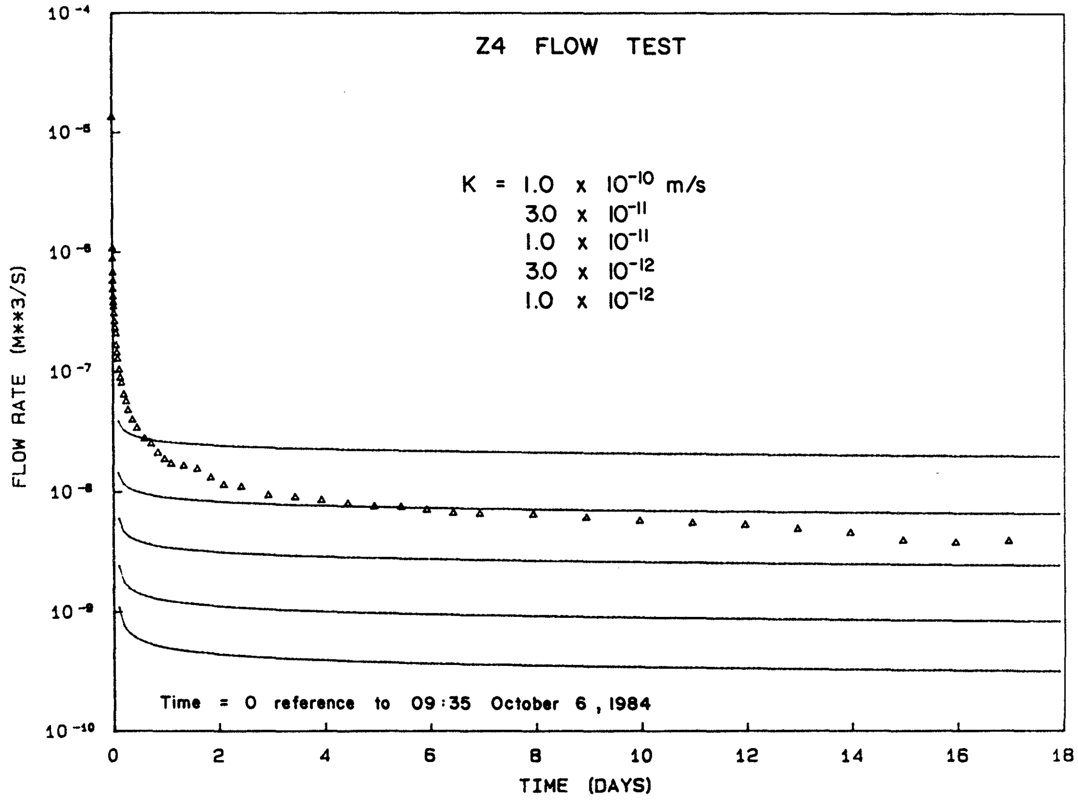

Figure B-1 Measured flow data (Δ) and GTFM simulations for various hydraulic conductivities for flow test of interval Z4

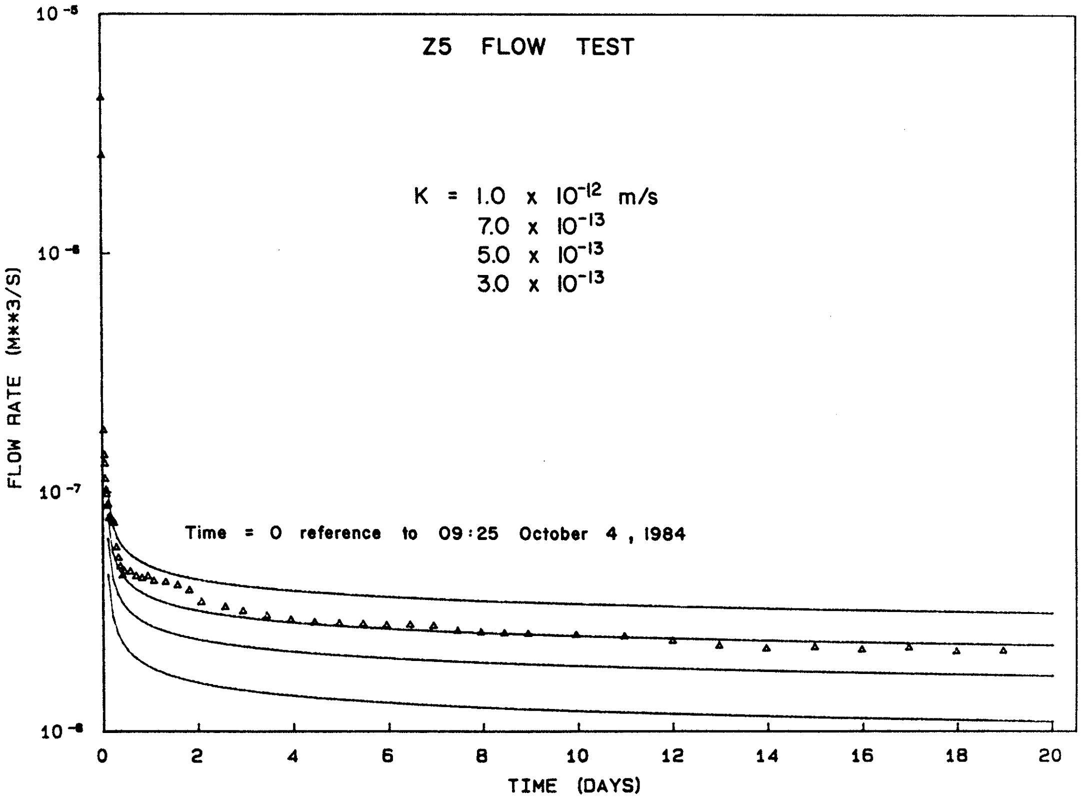

Figure B-2 Measured flow data (△) and GTFM simulations for various hydraulic conductivities for flow test of interval Z5

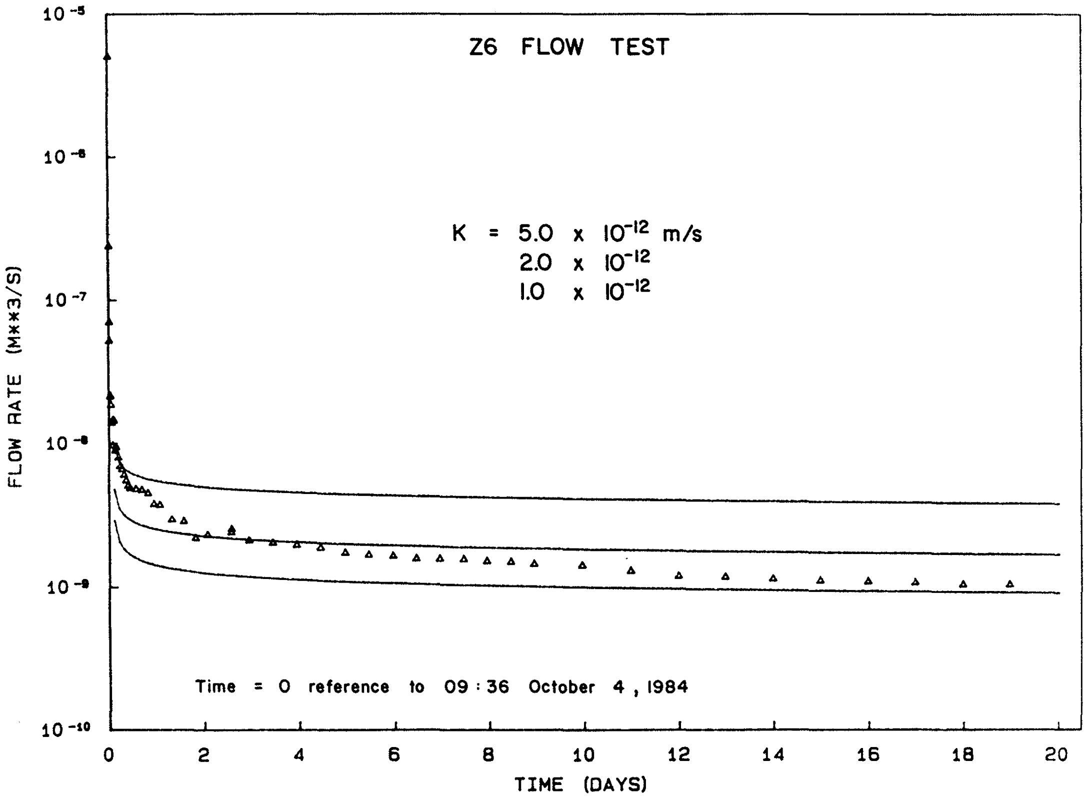

Figure B-3 Measured flow data (△) and GTFM simulations for various hydraulic conductivities for flow test of interval Z6

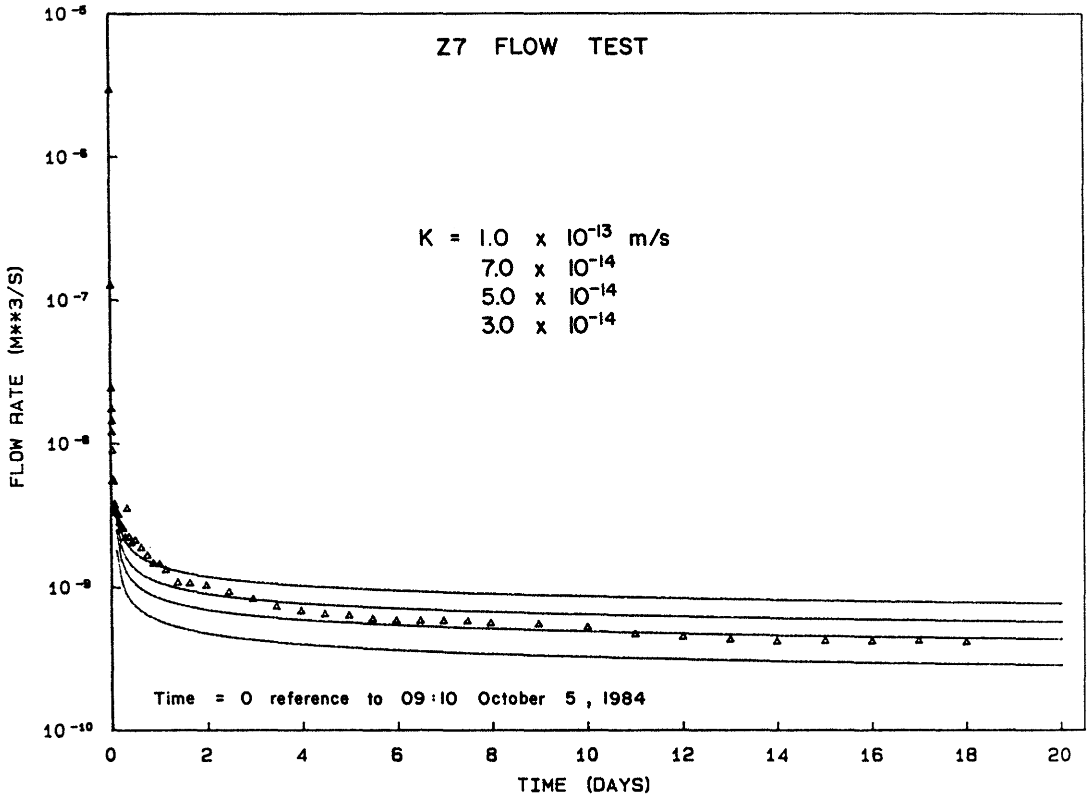

Figure B-4 Measured flow data (Δ) and GTFM simulations for various hydraulic conductivities for flow test of interval Z7

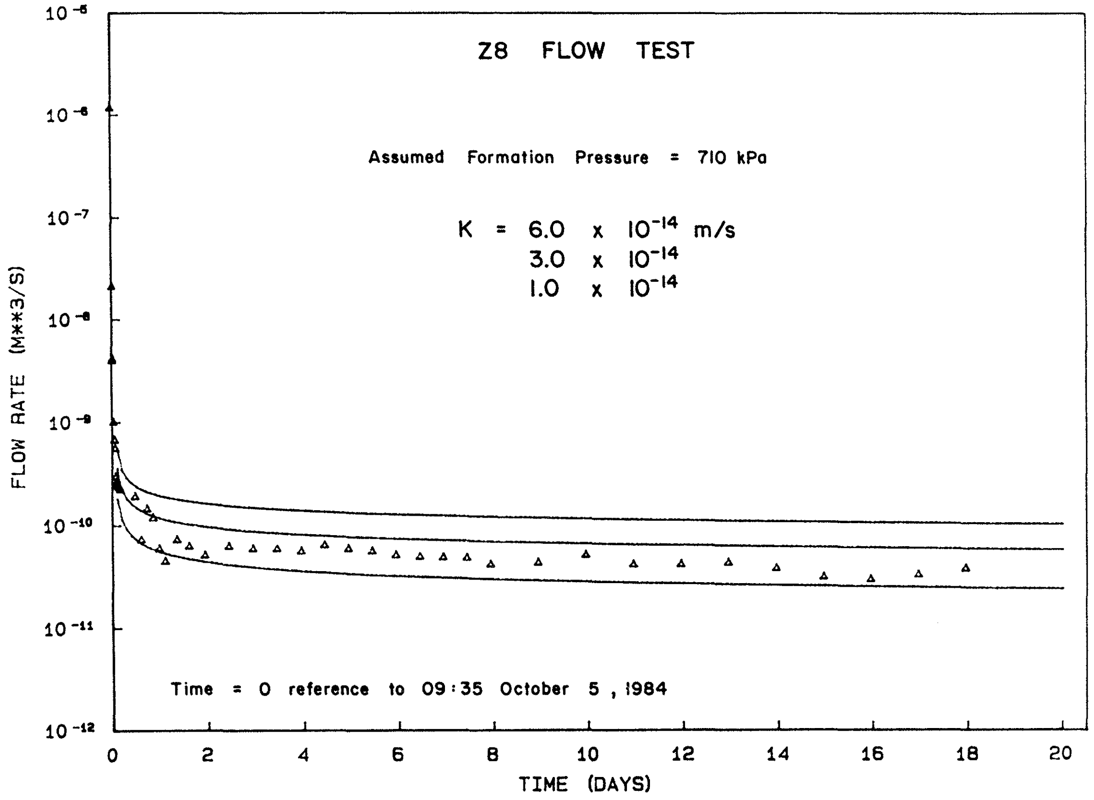

Figure B-5a Measured flow data (Δ) and GTFM simulations for various hydraulic conductivities for flow test of interval Z8 for reference pressure D_o of 710 kPa

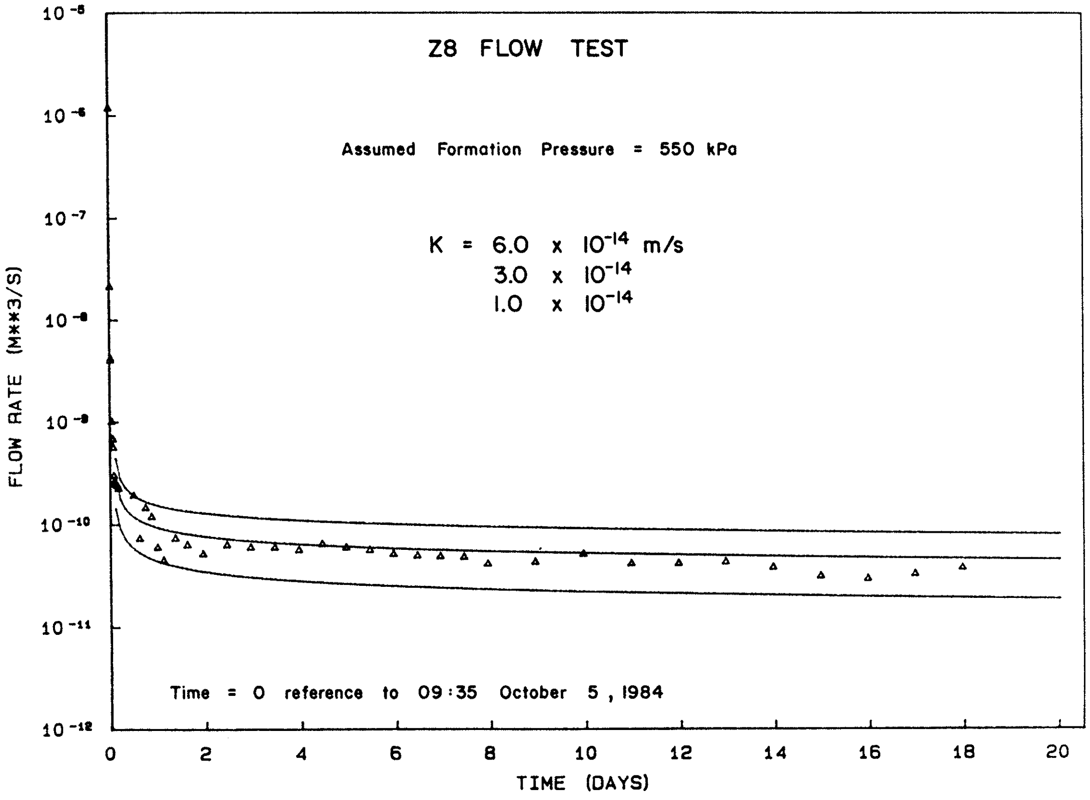

Figure B-5b Measured flow data (Δ) and GTFM simulations for various hydraulic conductivities for flow test of interval Z8 for reference pressure D_0 of 550 kPa

APPENDIX C

Plots of GTFM Simulations for Pressure Recovery Data

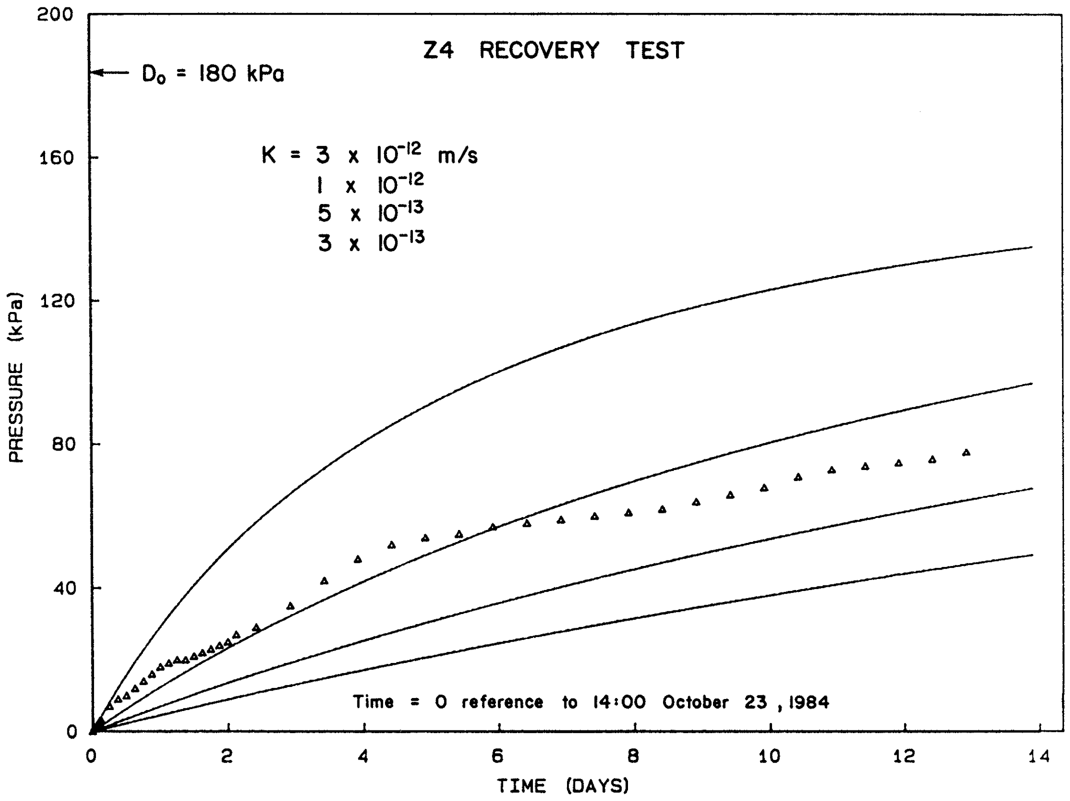

Figure C-1 Measured pressure recovery data (Δ) and GTFM simulations for various hydraulic conductivities for interval Z4

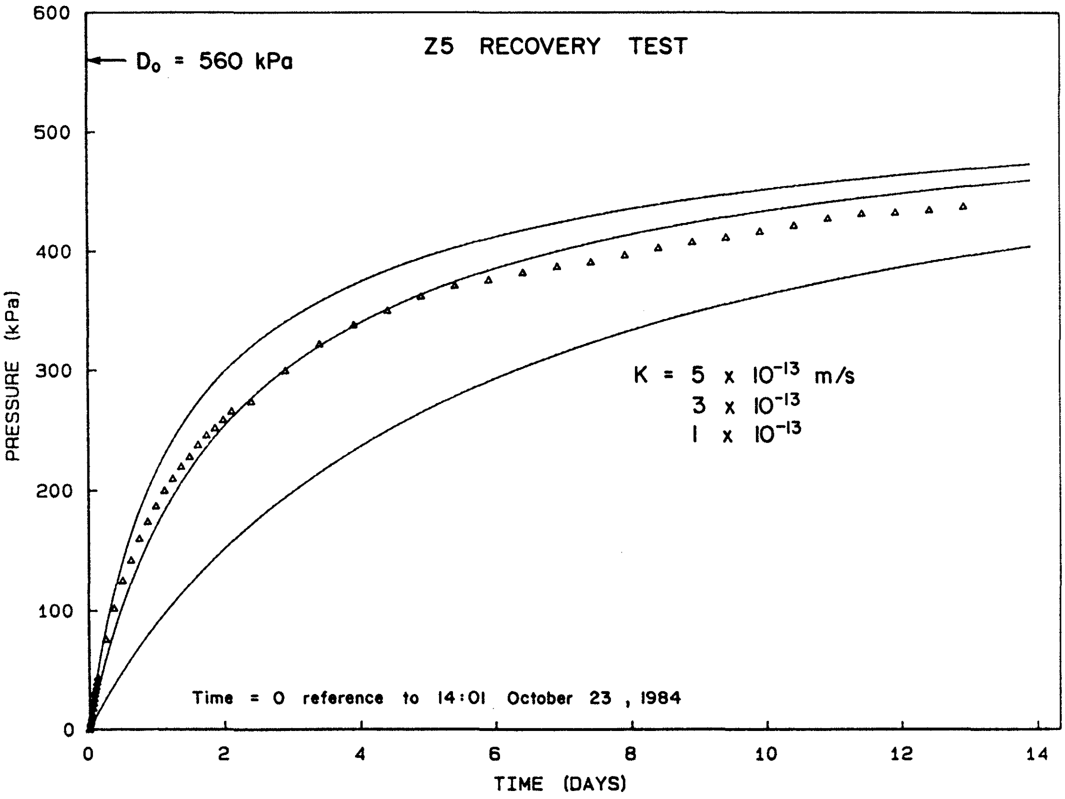

Figure C-2 Measured pressure recovery data (△) and GTFM simulations for various hydraulic conductivities for interval Z5

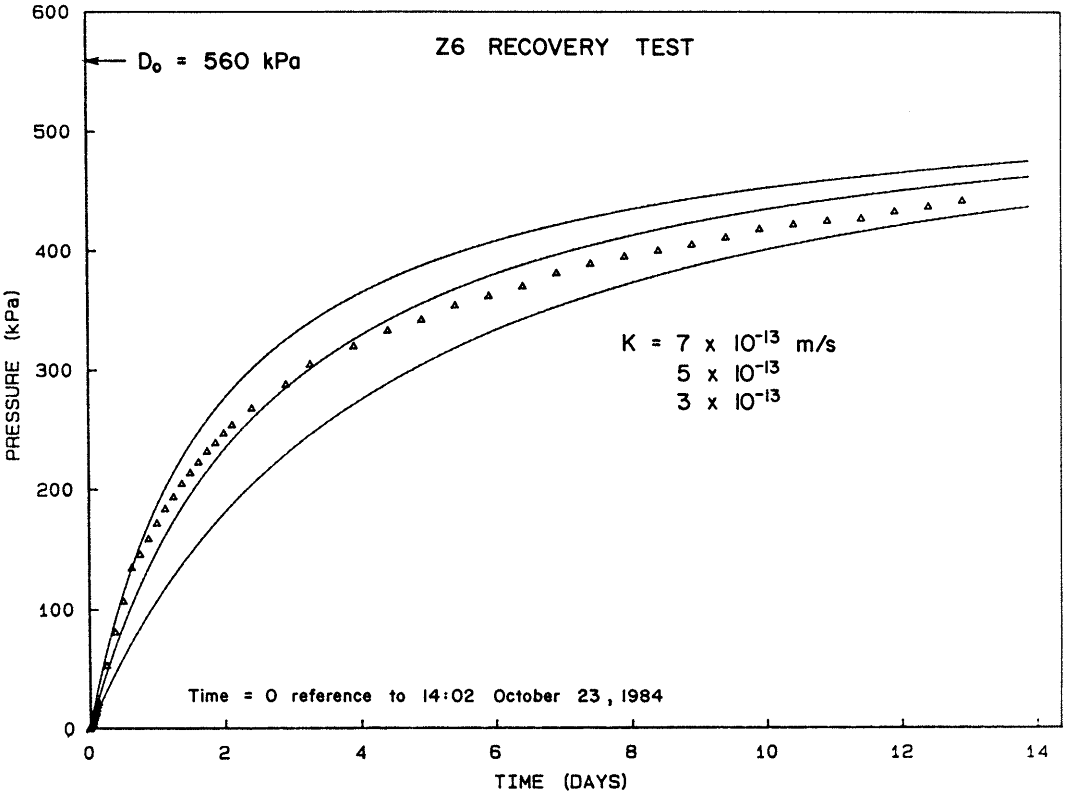

Figure C-3 Measured pressure recovery data (Δ) and GTFM simulations for various hydraulic conductivities for interval Z6

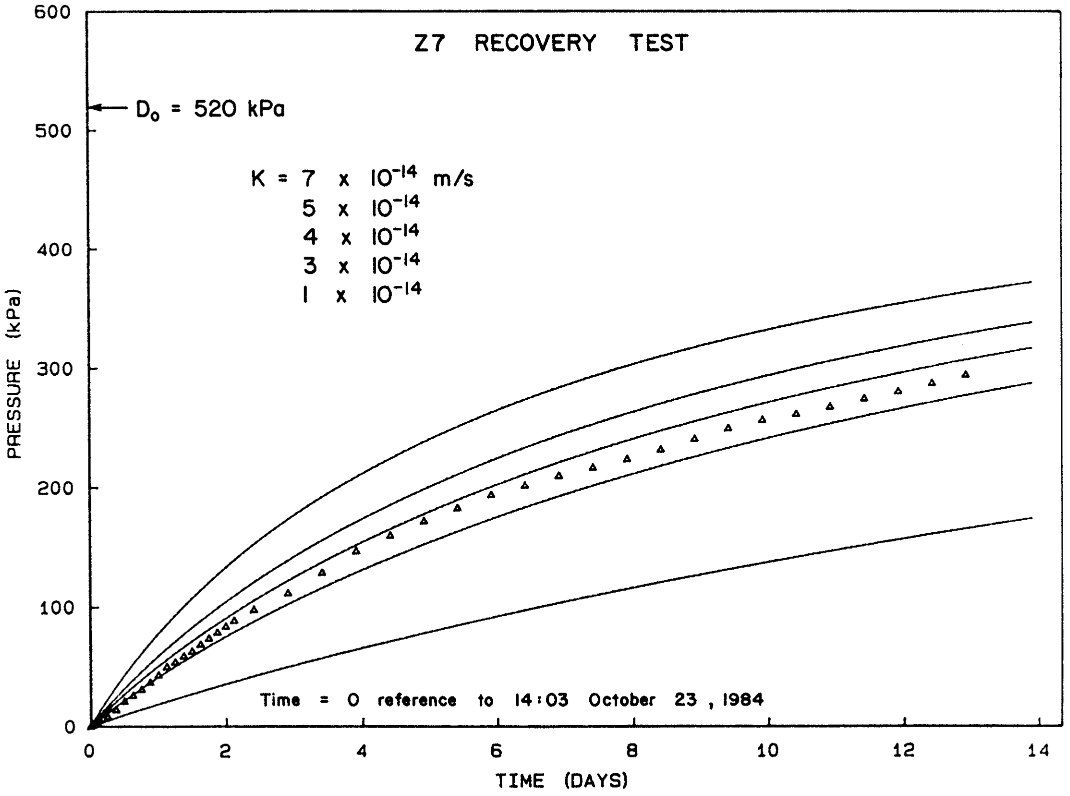

Figure C-4 Measured pressure recovery dta (Δ) and GTFM simulations for various hydraulic conductivities for interval Z7

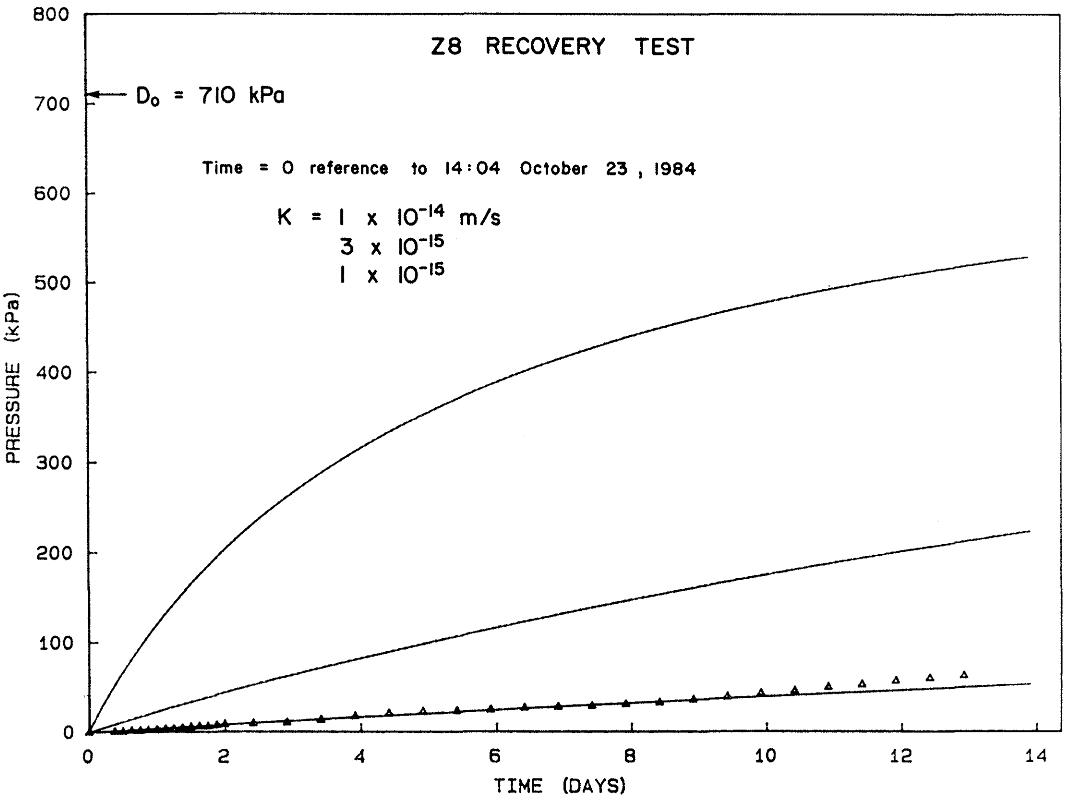

Figure C-5a Measured pressure recovery data (Δ) and GTFM simulations for various hydraulic conductivities for interval Z8, at an assumed reference pressure of 710 kPa

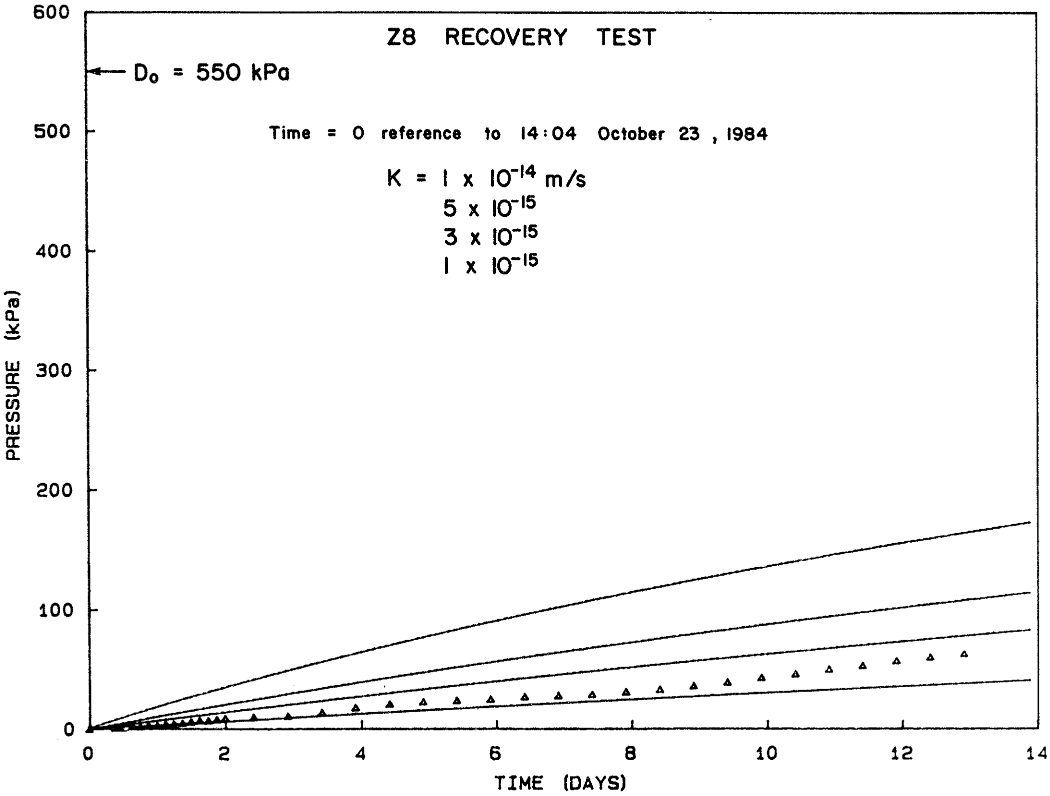

Figure C-5b Measured pressure recovery data (Δ) and GTFM simulations for various hydraulic conductivities for interval Z8, at an assumed reference pressure of 550 kPa