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TECHNICAL REPORT 87-19

INTERPRETATION OF HYDRAULIC TESTING IN CRYSTALLINE ROCK AT THE LEUGGERN BOREHOLE

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MARCH, 1989

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ZUSAMMENFASSUNG

Der vorliegende Bericht präsentiert die Resultate der hydrogeologischen Auswertung aller auswertbaren Einfachpacker-, Doppelpacker- und H-Log-Versuche, die in den kristallinen Gesteinen der Bohrung Leuggern durchgeführt worden sind. Der Anhang enthält eine Anzahl Figuren, in denen die Auswertung für jeden einzelnen Versuchsabschnitt zusammengefasst ist. Der Versuch im Muschelkalk zwischen 74.95 und 117.85 m wird in SCHMASSMANN (1985) diskutiert. Der im Bericht besprochene Versuch 217.9S umfasst 14.51 m Buntsandstein und reicht 4.79 m in das Dach des Kristallinuntergrundes. Die Versuchs- und Interpretationsmethoden werden dargestellt. Die Auswertung der Daten erfolgte mit dem Graph Theoretic Field Model (GFTM) von INTERA. Dieses Modell erlaubt, die Bohrlochgeschichte und die thermisch bedingten Druckeffekte in den Simulationsrechnungen zu berücksichtigen.

Der Formationswasserdruck (und die ihm entsprechende Druckspiegelhöhe) konnte für 12 Testabschnitte, in denen die Versuche kurz nach dem Durchteufen durchgeführt wurden und die Gesteinsformationen mittlere bis hohe hydraulische Durchlässigkeit aufwiesen, ermittelt werden. Die berechneten äquivalenten Süsswasser-Druckspiegelhöhen liegen zwischen 363 m ü.M. (knapp unterhalb der Kristallinoberfläche) und 356 m ü.M. (am Bohrlochende).

Für 81 Intervalle, die den gesamten im Kristallin gelegenen Bohrabschnitt abdecken, wurde die hydraulische Durchlässigkeit abgeschätzt. Die in den Simulationsrechnungen erhaltenen hydraulischen Durchlässigkeitsbeiwerte liegen zwischen $2.0 \cdot 10^{-14}$ und $1.0 \cdot 10^{-6}$ m/s. Für sechs Abschnitte (208-267 m, 440-485 m, 506-566 m, 679-704 m, 818-851 m und 1584-1632 m) wurden hohe hydraulische Durchlässigkeitsbeiwerte (grösser als $1 \cdot 10^{-8}$ m/s) erhalten.

Der Basiswert des spezifischen Speicherkoeffizienten wurde für das Kristallin auf $2.2 \cdot 10^{-7}$ m^{-1} geschätzt. Um die mit der spezi-

fischen Speicherkapazität zusammenhängende Unsicherheit in der Bestimmung des besten Schätzwertes des Durchlässigkeitsbeiwertes abzuklären, wurde bei der Auswertung einzelner Tests eine Sensitivitätsanalyse durchgeführt. Dabei wurde der Basiswert des spezifischen Speicherkoeffizienten um eine bis zwei Grössenordnungen variiert.

Die gemessenen Temperaturen im Bohrloch steigen von ungefähr 19°C an der Kristallinoberfläche auf ungefähr 66°C am Bohrlochende an. Die Temperatur nimmt mit der Tiefe annähernd linear mit einem Gradienten von ungefähr 3.4°C/100 m zu.

RESUME

Ce rapport présente les résultats des interprétations des tests hydrogéologiques effectués dans le cristallin au forage de Leuggern. Il s'agit de tests à obturateur simple, double, ou de séries continues de tests à obturateur double (H-log). La séquence des pressions observées et simulées est illustrée pour chacun des tests par une figure en appendice. A part le cristallin, le Muschelkalk a été testé entre 74.95 et 117.85 m; les résultats sont présentés dans le rapport Schmassmann (1985). Le forage a atteint une profondeur vraie de 1632 m. Le premier test décrit dans ce rapport, 217.9S, comprend le toit du cristallin sur 4.79 m et la base du Buntsandstein sur 14.51 m.

Le présent rapport donne une description succinte des techniques de test, et traite de leur interprétation de manière plus approfondie. Les données ont été analysées au moyen du code GTFM de INTERA (Graph Theoretic Field Model), qui permet la simulation des pressions mesurées en tenant compte de l'histoire des pressions dans le forage et des effets thermiques.

On a déterminé la pression non-perturbée de la formation pour 12 intervalles de test, puis calculé le potentiel correspondant à une colonne d'eau douce. Il s'agit de tests effectués tout de suite après le forage de zones aquifères dont la conductivité hydraulique est moyenne à élevée. Le potentiel hydraulique calculé pour une colonne d'eau douce atteint environ 363 m.s.m près du toit du cristallin et environ 356 m.s.m au fond du forage.

La conductivité hydraulique a été déterminée pour 81 intervalles de test, qui recouvrent la totalité du forage de Leuggern en milieu cristallin. Les valeurs se situent entre 2.0E-14 ms^{-1} et 1.0E-06 ms^{-1}. Six zones sont caractérisées par une conductivité hydraulique supérieure à 1.0E-08 ms^{-1}. Elles sont comprises entre les profondeurs vraies suivantes: 208 - 267 m, 440 - 485 m, 506 - 566 m, 679 - 704 m, 818 - 851 m et 1584 - 1632 m.

Le coefficient d'emmagasinement spécifique des roches cristallines a été estimé à $2.2E-07m^{-1}$. Un calcul d'erreur a été effectué avec les données de quelques tests, afin de déterminer la sensibilité des valeurs de conductivité hydraulique au choix de la valeur du coefficient d'emmagasinement spécifique. Pour cela, on a fait varier cette dernière d'un ou deux ordres de grandeur.

Les températures mesurées dans le forage à l'aide du dispositif de test se situent entre 19°C environ au toit du cristallin et 60°C environ au fond du forage. L'accroissement de température avec la profondeur est à peu près linéaire et vaut environ 3.4°C/100 m.

SUMMARY

This report presents the results of hydrogeologic interpretations of all analyzable single packer, double packer, and H-log tests conducted in the crystalline rock in the Leuggern borehole. Testing of the Muschelkalk at 74.95 to 117.85 m depth is discussed by Schmassmann (1985). Test 217.9S, which is discussed in this report, contains 14.51 m of Buntsandstein and 4.79 m into the top of the crystalline. A discussion of the testing and interpretation methods is presented. Data analysis was performed using the INTERA Graph Theoretic Field Model (GTFM) which permits borehole pressure history and thermally-induced pressure effects to be incorporated into the simulations.

Formation pressures (and corresponding equivalent freshwater heads) were determined for 12 test intervals where testing was performed soon after drilling and the formation had an intermediate to high hydraulic conductivity. The calculated equivalent freshwater heads were between about 363 m ASL near the top of the crystalline to about 356 m ASL at the bottom of the borehole.

Hydraulic conductivities were estimated for 81 intervals, covering the entire crystalline rock portion of the Leuggern borehole. Interpreted hydraulic conductivities ranged from 2.0E-14 to 1.0E-06 ms^{-1}. Zones of high hydraulic conductivity (greater than 1.0E-08 ms^{-1}) were obtained for six zones corresponding to the following vertical depths: 208 - 267 m, 440 - 485 m, 506 - 566 m, 679 - 704 m, 818 - 851 m, and 1584 - 1632 m.

A base case specific storage of 2.2E-07 m^{-1} was estimated for the crystalline rock. A sensitivity analysis was conducted for some tests to determine the uncertainty in the best estimate of hydraulic conductivity related to the choice of

specific storage. In these cases, specific storage was varied by 1 to 2 orders of magnitude from the base case value.

The measured temperature in the borehole ranged from about 19°C at the top of the crystalline rock to about 66°C at the bottom of the borehole. The temperature increases approximately linearly with depth at a gradient of approximately 3.4°C/100 m.

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1. INTRODUCTION

Nagra, the National Cooperative for the Storage of Radioactive Waste, is conducting research and investigations into the geologic and hydrogeologic characteristics of crystalline rock in Northern Switzerland. The purpose of this research is to assess the feasibility of using this rock type as a repository for radioactive waste. The investigation program includes: a proposal of 12 deep boreholes, regional geophysical reconnaissance of petrographic and structural conditions, a hydrogeological program to determine ground-water flow characteristics in the deep sub-surface, and neotectonic studies to detect and measure crustal movements (Nold and Thury, 1984).

To date, Nagra has completed six boreholes (Boettstein, Weiach, Riniken, Schafisheim, Kaisten, and Leuggern) of the planned 12 borehole program. The location of these boreholes is shown in Figure 1.1. This report addresses the hydrogeologic aspects of the investigations completed in the Leuggern borehole and in particular, provides analysis and interpretation of borehole hydraulic tests completed to date in the crystalline rock portion of the borehole. Hydraulic tests conducted in the Muschelkalk are described by Schmassmann (1985). The uppermost crystalline interval includes also the lowest part of the Buntsandstein.

Gartner Lee AG (GLAG) were responsible for the completion of the field components of the hydraulic testing program for the Leuggern borehole. The data base for the interpretation of individual hydraulic tests is contained in GLAG field reports and data printouts for each interval. Additional data, such as Nagra quarterly borehole reports and geologic and geophysical logs, have also been utilized.

1.1 Objectives and Scope

The objectives of this interpretive report include the following components:

- Analysis and interpretation of the hydraulic tests completed in the crystalline rock portion of the Leuggern borehole to derive the representative formation parameters: hydraulic conductivity, specific storage, formation pressure, equivalent freshwater head and temperature.
- A compilation and discussion of the interpreted formation parameters.

This report documents work completed by INTERA Technologies, Inc., under contract to Nagra. Contained within are brief descriptions of the borehole hydraulic test equipment, testing methods and analytical techniques, as well as, discussions of the hydraulic test results and interpretations. This report contains the results and hydrogeologic interpretations of all analyzable tests in the crystalline portion of the Leuggern borehole. Some tests did not produce data suitable for analysis as a result of equipment malfunctions (e.g., packer failure). A total of 83 hydraulic tests were analyzed for 81 separate test intervals including 62 H-log tests, 14 single packer tests, and 7 double packer tests.

Complete test descriptions and interpretations for the Leuggern borehole are given in Belanger et al. (1988). This report briefly discusses the Leuggern borehole and the test interpretation results and presents, in detail, in the form of appendices, the analysis approach and the hydrogeologic parameters for each interval.

2 LEUGGERN BOREHOLE DESCRIPTION

The Leuggern borehole is located at coordinates 657' (633.9/271'-207.9) with a reference ground surface elevation of 358.80 m ASL. This location is southwest of the confluence of the Rhine and Aare Rivers in the Table Jura near the southern border of the Black Forest Massif.

Drilling of the borehole began on 9 June, 1984 and finished on 19 February, 1985 at a total depth along the borehole of 1688.90 m. The rig floor elevation was set at 362.37 m ASL (i.e., 3.57 m above ground surface) which results in a top of annulus at about 3.0 m above ground, and an annulus valve at 1.42 m above ground. The borehole was drilled using a wire-line coring technique at a rate of about 1 mh^{-1} with deionized water as the drilling fluid in the crystalline rock portion. The borehole was set vertically but it deviates to the east along its length and the true total vertical depth of the borehole below surface is 1631.63 m. The inclination in the borehole is about 13° and 22° east, away from vertical, at 845 and 1689 m apparent depth, respectively, with major deviations initiated at the Buntsandstein/Crystalline (gneiss) contact at 223 m and at the gneiss/granite contact at 1387 m.

In this report, depths below ground surface are referred to as either apparent depths or true vertical depths. The depth measured along the borehole length is referred to as the apparent depth. In general, all depths reported during drilling and testing (i.e., drilling logs, testing field notes, geological and geophysical logs) are apparent depths. True vertical depths are needed for comparative analysis of formation pressures and equivalent freshwater heads. True vertical depths used in this report have been calculated based on the results of a Schlumberger GCT-Gyro Survey. This borehole deviation survey measured apparent and true vertical depths at approximate 10 m intervals going down and then back up the borehole. The true vertical depth, for an apparent depth not measured in the survey, is derived from a linear approximation of the true vertical depths corresponding to the four nearest (two above and two below) measured apparent depths from the gyro survey.

The geology intersected by the Leuggern borehole (Figure 2.1) is described in detail in Geotest (1985) and only a brief description will be given here. The depths given in this section are apparent depths unless stated otherwise. The borehole intersects a thin layer of Quaternary sands and gravels from ground surface to a depth of 48.50 m below surface. The surficial deposits are underlain by Triassic sediments consisting of the Muschelkalk and Buntsandstein Groups. The Muschelkalk Group (Upper, Middle, and Lower) is primarily composed of carbonates (dolomite and limestone) and evaporites (anhydrite and gypsum) with minor clay and siltstone layers. The Buntsandstein, found between 207.18 and 222.76 m depth, underlies the Muschelkalk Group and is composed of fine to coarse-grained sandstone and siltstone. The base of the Buntsandstein lies uncomformably on crystalline rock at a depth of 222.76 m. The crystalline basement consists of biotite-gneiss to a depth of about 1387.30 m and granite and biotite-granite from 1387.30 to 1688.90 m.

The Leuggern borehole contains various diameter casings to various depths (Figure 2.1). A surface casing of 0.473 m diameter was placed across the Quaternary deposits and cemented into the top of the Muschelkalk at a depth of 53.5 m. A second casing of 0.340 m diameter was installed to the bottom of the Muschelkalk at a depth 208.2 m. The top of the crystalline rock was isolated by a third casing of 0.245 m diameter to a depth of 267.3 m. A final casing of 0.168 m diameter was cemented to a depth of 557.5 m in the crystalline rock.

Geotest (1985) reports 9 major fracture zones in the crystalline portion of the borehole. These fracture zones were identified by correlation of core logs and geophysical logs (e.g., spinner flowmeter, temperature, caliper, electrical conductivity). The apparent and approximate true vertical depths of the 9 fracture zones are identified by Geotest as follows:

(apparent depth)	(true vertical depth)
• 235 m - 267 m	235 m - 267 m
• 440 m - 460 m	439 m - 459 m
• 546 m - 553 m	544 m - 551 m
• 704 m - 706 m	699 m - 701 m
• 824 m - 828 m	815 m - 819 m
• 840 m - 843.5 m	832 m - 835.3 m
• 914 m - 918 m	904 m - 908 m
• 1197 m - 1200 m	1175 m - 1186 m
• 1301 m - 1303 m	1272 m - 1274 m
• 1648.4 m - 1649.4 m	1594 m - 1595 m

Each of these fracture zones are described in detail by Geotest (1985).

Major drilling fluid losses of more than 1 m^3h^{-1} were encountered at the following apparent depths:

735 m - 745 m
805 m - 812 m
911 m - 917 m
1309 m - 1315 m
1649 m - 1688.9 m

Information regarding the fluid losses are presented in detail in Nagra (1985, Beilage 4.10).

3. FIELD TESTING METHODS

3.1 Equipment Description

Hydraulic testing equipment used in the Leuggern borehole was provided and operated by Lynes GmbH. The surface data collection equipment was operated by Gartner Lee AG (GLAG). The downhole equipment known as the Lynes Hydrologic Test Tool (HTT), is described in detail in Leech et al. (1985) and only a brief description will be provided here.

The hydraulic testing equipment consists of the following major components:

- Hydraulically inflatable packers (single or double configurations) used to isolate the test interval from the rest of the borehole.
- J-Slot controlled mandrel used to inflate the packers and open the test interval to the tubing string.
- Shut-in tool used to isolate (i.e., shut-in) the test interval from the tubing string.
- Multiple sensor (Triple CWL Carrier) used to measure downhole pressures and temperatures. Sensors consist of three pressure transducers to measure pressure below the bottom packer (P1), in the test interval (P2) and above the top packer (P3). Temperature transducers (T1, T2, T3) measure the operational temperature of the respective pressure transducers within the sensor carrier. The sensors are located above the top packer and J-slot-controlled mandrel, i.e., approximately 4.7 m above the top of the test-interval. P1 and T1 sensors are located 0.25 m below P2 and T2 sensors, and P3 and T3 sensors are located 0.25 m above P2 and T2 sensors.
- Conductor cable to transmit pressure and temperature signals to surface.
- Surface data collection equipment.

The simplified operation of the HTT is as follows. The packers and HTT are lowered to the test interval on the tubing string. The J-slot mandrel is open between the tubing string and the packers. The tubing string is pressurized at the surface to inflate the packers. This inflation pressure is sealed in the packers by a movement of the mandrel assembly and the pressure in the tubing string is bled to the borehole annulus (equalization) above the top packer. The shut-in valve is then closed and the test interval is isolated from the tubing string. In this position the tubing string can be swabbed or pressurized without influencing the pressure in the test interval. To perform a slug test, the shut-in tool is opened causing an overpressure or underpressure on the test interval. To perform a pulse test, the shut-in valve is opened and then quickly closed. Section 3.2 gives a more detailed description of slug and pulse test methods.

With careful handling and frequent maintenance, the operation of the test equipment is generally trouble-free. The most frequent cause of abandoned tests is packer rupture or packer leakage. The equipment is known to be non-rigid or compliant, due primarily to the use of flexible rubber packers (see Grisak et al., 1985; pp. 54-60 and 169-171). Packer readjustment or deformation during testing can affect the hydraulic test results, primarily in zones of lower hydraulic conductivity; however; testing methods that incorporate a compliance or waiting period after packer inflation are considered to greatly reduce compliance effects.

Non-Darcy flow conditions can have an effect on hydraulic testing results in two different manners. High flow rates through large aperture fractures in the formation or through the apertures in the Lynes HTT could result in turbulent flow conditions. This would cause a non-linear relationship between flow rate and measured pressure change in the test interval. The measured pressure response could be erroneously interpreted as a conventional formation response unless the non-Darcy flow condition is identified. High flow rates during hydraulic testing may be obtained while conducting slug or pump tests in test intervals with high hydraulic conductivity.

The reported accuracy of the pressure transducers at full scale of 41370 kPa is ±0.05 percent with a resolution of 0.005 percent. This corresponds to an accuracy of 20 kPa or 2 m of water at full scale. The temperature transducers have a reported accuracy of about ±1°C with a resolution of 0.1°C. The accuracy of pressure and temperature transducers can be monitored through calibration.

3.2 Testing Methods

Hydraulic testing methods are described in detail in Grisak et al. (1985) and Leech et al. (1985) and only brief accounts of the various methods will be given here.

Several different test configurations are used during drilling and hydraulic testing according to the purpose and the time allocated for each interval. All of the hydraulic tests are configured in terms of either single packer tests or double packer tests. Hydrogeological reconnaissance (H-log) tests are carried out in a double packer configuration.

Single packer tests are typically used during drilling to isolate the bottom section of the borehole, thus only one packer is required. Their primary use is to determine accurate formation pressures in permeable intervals immediately after drilling, but single packer tests are also used for geochemical sampling and pump testing as well as hydraulic testing of large portions of the borehole. Single packer tests conducted during drilling are typically short in duration in order not to delay the drilling.

Double packer tests use an upper and lower packer to isolate specific intervals within the borehole. These tests are typically completed after drilling in order to assess or re-assess intervals of importance. Double packer tests are used primarily for geochemical sampling or conducting pump tests.

H-log tests provide for reconnaissance level testing. In this test type, double packers are used to test the borehole in 12.5 m or 25 m interval lengths. H-log tests were used primarily to determine the hydraulic conductivity of each test interval. The duration of the tests are often too short to accurately determine an undisturbed formation pressure.

The three test types (single packer, double packer and H-Log tests) typically use one or more of the following hydraulic test methodologies at each test interval:

- Slug tests;
- Pulse tests;
- Drill-stem tests (DST); and
- Pump tests.

These tests are used primarily to estimate the hydraulic conductivity of the interval and in some cases to estimate the formation pressure. In a slug test, a volume of water is quickly introduced to (slug injection test) or removed from (slug withdrawal test) the test interval. The rate of water level recovery back to equilibrium provides an indication of the hydraulic conductivity of the interval. In the Leuggern borehole, using the HTT equipment, slug withdrawal tests were completed by removing fluid from the tubing string (i.e., lowering the water level) with the shut-in valve closed, then opening the valve and allowing fluid in the test interval to flow to the tubing string. The pressure in the test interval was monitored by the pressure transducers in the sensor carrier. Pressures above and below the test interval were also monitored. For slug injection tests, the tubing string was pressurized (i.e., by raising the water level in the tubing) and then, by opening the shut-in valve, the tubing fluid was allowed to flow to the formation, creating an overpressure on the test zone. Slug tests are generally applicable to test intervals with hydraulic conductivities greater than 1.0E-10 ms^{-1}.

A pulse test is completed in a manner similar to the slug test. In a pulse injection test, the fluid in the tubing and test interval is pressurized with a pump while the interval is open to the tubing, and then the shut-in valve is closed. For pulse withdrawal tests, the water level is lowered in the tubing while the shut-in valve is closed and then the shut-in valve is opened and quickly closed to allow the pressure change to be transmitted to the interval. The pulses are not instantaneous and generally take 0.5 to 1 minute to apply. In very low permeability settings (i.e., less than about 1.0E-11 ms^{-1}) pressure recovery in the test zone is attributed primarily to the compressibility of the formation and the compressibility of the fluid in the borehole and in the formation. At higher permeabilities, the effects of specific storage contribute to the dissipation of the pressure transient but the effects become less important than Darcy flow. Pulse tests are generally applicable to test intervals with hydraulic conductivities in the range 1.0E-14 to 1.0E-08 ms^{-1}.

A drill-stem test is a testing technique used extensively in the petroleum industry to assess formation permeability. The method is essentially a combination of the slug and pulse tests described above. In a DST, the test interval is first underpressured as in a slug withdrawal test. After a period of monitoring the flow recovery (referred to as the DST flow period), the shut-in valve is closed to isolate the test zone and induce a more rapid pressure recovery, as in a pulse withdrawal test (referred to as the DST shut-in or build-up period). DST's are generally applicable to test intervals with hydraulic conductivities greater than 1.0E-10 ms^{-1}.

In a pumping test a permeable interval is isolated using either double packers or, if the interval is at the bottom of the borehole, a single packer. The test interval is pumped using a submersible pump placed within the tubing string. The pressure response of the test interval is monitored for the duration of the pumping. After the pumping period, the pressure recovery back to equilibrium can also be monitored. The drawdown and recovery data from the pumping tests are used to estimate the formation hydraulic conductivity. Pump tests are generally applicable to test intervals with hydraulic conductivities greater than 1.0E-09 ms^{-1}, depending on the interval length and the pumping equipment.

4. INTERPRETATION METHODS

The purpose of this section is to provide a description of the methods used to interpret the hydraulic tests in the Leuggern borehole. The interested reader is directed to Grisak et al. (1985) for detailed information on the theoretical development of hydraulic test analysis.

4.1 Definition of Formation and Fluid Properties

The hydraulic test interpretation methods for the Leuggern borehole require the definition or estimation of the physical properties of the rock formation and the formation and borehole fluids. A number of these physical properties are required as basic input parameters to solve the flow equations which describe the testing response and yet have not been specifically determined by measurements in the field at the borehole. These parameters, such as the fluid density, compressibility, viscosity, thermal expansion, formation compressibility and porosity, must be estimated based on the best available information and, in some cases, corrected for borehole conditions such as temperature and pressure. Other physical properties such as hydraulic conductivity, hydraulic head and specific storage are dependent on accurately simulating, with mathematical models, the pressure response in the formation during testing, combined with the application of the basic parameters. For example, in the interpretation of the hydraulic tests at Leuggern, hydraulic conductivity, formation pressure and rock compressibility were treated as uncertain variables and were allowed to change within a reasonable range in order to model the field response of a hydraulic test. On suitably modeling the field response, the formation pressure and rock compressibility were used in the calculation of hydraulic head and specific storage, respectively.

This section provides a definition of properties related to the hydraulic system under study and a discussion of the reasonable property values for the rock formation and borehole and formation fluids that are used in hydraulic test interpretations. In addition, a brief discussion of the methods and sources of information that are used to determine each parameter is provided.

4.1.1 Formation Compressibility

The reader is referred to Section 4.2.3 of Grisak et al. (1985) for a more complete discussion of formation compressibility. The following discussion provides an overview of the approach taken in the borehole test interpretation. The formation compressibility (C_R) can be defined as the change in volume of the formation under an applied stress, and can be written as follows:

$$C_R = - \frac{dV_T/V_T}{d\sigma_e} = \frac{d\epsilon}{d\sigma_e} \qquad (4.1\text{-}1)$$

where V_T = total volume of the rock, L^3;
dV_T = change in total volume, L^3;
$d\sigma_e$ = change in effective stress, $ML^{-1}t^{-2}$;
$d\epsilon$ = change in strain, dimensionless.

The total volume of the formation is the sum of the volume of the solids (V_s) plus the volume of the voids (V_v). The compressibility of the solids is generally considered to be negligible and therefore the change in volume of the solids is essentially zero and the total change in volume of the formation is equal to the change in volume of the voids and the pore fluid. Both the medium and the pore fluid are assumed to be compressible.

For the case of three-dimensional loading with equal stress in all directions, the formation compressibility can be written as:

$$C_R = \frac{3\ (1-2\mu)}{E} \tag{4.1-2}$$

where E = Young's modulus or modulus of elasticity, $ML^{-1}t^{-2}$;

μ = Poisson's ratio.

Young's modulus is the ratio of stress to one-dimensional strain. Poisson's ratio defines the ratio of the strain in directions normal to the applied stress to the strain in the direction of the applied stress.

Using Equation 4.1-2, the formation compressibility can be defined based solely on Poisson's ratio and Young's modulus. For the hydraulic testing in the Leuggern borehole, a suitable value of formation compressibility was determined based on a literature review of Young's modulus and Poisson's ratio. Touloukian et al. (1981) provide values of Young's modulus and Poisson's ratio for uniaxial compressive loading for various types of granitic rock. Young's modulus values range from 5.52 to 64.10 GPa and Poisson's ratio values range from 0.03 to 0.48 for the same rock sample and at various values of upper stress. Using these values for Young's modulus and Poisson's ratio, the formation compressibility can range from about 2.0E-12 to 5.0E-10 Pa^{-1}. The rock property values given in Touloukian et al. (1981) are based on laboratory testing of rock cores and therefore the calculated range of formation compressibilities given above may not be representative of natural systems where the rock formations may contain fractures. The presence of a fracture or a fracture set in a test interval, for example, will increase the rock compressibility depending on the fracture density. In highly fractured rock the formation compressibility is likely to be increased over that for unfractured rock by an order of magnitude or more. Given that the Leuggern borehole is completed in bedrock which contains fractures at some depths, a reasonable range of compressibility may extend as high as 2.0E-08 Pa^{-1}.

Based on the discussions above, the range of values for formation compressibility used in the Leuggern borehole hydraulic test analyses were set at 2.0E-12 to 2.0E-08 Pa^{-1}. The initial estimate of formation compressibility for each hydraulic test interval was chosen based on a qualitative assessment of the degree of fracturing. Highly fractured (or kakiritized) intervals were given formation compressibilities in the range of 2.0E-10 to 2.0E-08 Pa^{-1} while in test intervals with few fractures, a compressibility in the range of 2.0E-12 to 2.0E-10 Pa^{-1} was chosen.

4.1.2 Porosity

Porosity is a measure of the interstitial space in a porous or fractured rock. It is defined as the ratio of the volume of the voids to the total volume of the rock. Porosity may be classified into primary or secondary porosity. Primary porosity results from the original formation of the rock and includes all pore space between grains in a sedimentary rock and within the crystal structure for crystalline material. Secondary porosity is developed after the formation of the rock mass by such mechanisms as solution weathering and fracturing. The total porosity includes both primary and secondary porosities. In the case of a fractured rock the total porosity is the sum of the matrix porosity (i.e., primary) and the fracture porosity (i.e., secondary).

The effective porosity or interconnected porosity is used to describe the pore space that is available to ground-water flow. The pore space that is considered the effective porosity can usually be related to the permeability of the formation. For relatively impermeable crystalline rocks, where hydraulic conductivity is less than about 1.0E-12 ms^{-1}, the effective porosity would probably be the matrix void space. In more permeable systems, where discrete fractures or fracture sets are evident, the effective porosity would be more closely described by the fracture porosity.

Van Golf-Racht (1982) reports a range of secondary porosity for rocks showing isolated fissures of between 0.001 and 0.01 percent, and for rocks with fissure networks of 0.01 to 2 percent. Carlsen and Platz (1984) report porosities for artificially cracked crystalline rock cores of between 0.77 and 0.39 percent. After a period of weathering the porosity of these cores dropped to 0.12 percent, resulting from the accumulation of weathering by-products in the interstices.

While it is difficult to determine a representative effective porosity over the permeability range for the biotite gneiss and granites of the crystalline portion of the Leuggern borehole, a porosity value of 0.5 percent is considered to be a reasonable estimate for use in hydraulic test analyses. This value appears to be reasonable for the matrix (primary) porosity and, when discrete fractures or a fracture set is evident, for the fracture (secondary) porosity. The porosity value of 0.5 percent was used for all test analyses in the crystalline portion of the Leuggern borehole.

4.1.3 Fluid Compressibility

For a fluid such as water, the compressibility (C_w) in terms of a volume change is defined as:

$$C_w = - \frac{dV_w/V_w}{dp} \qquad (4.1\text{-}3)$$

where V_w = volume of water, L^3;

dV_w = change in volume of water, L^3;

dp = change in fluid pressure, $ML^{-1}t^{-2}$.

For a given mass of water the compressibility can also be written in terms of a density change as follows:

$$C_w = \frac{d\rho/\rho}{dp} \tag{4.1-4}$$

where ρ = fluid density, ML^{-3};
$d\rho$ = change in fluid density, ML^{-3}.

Water changes volume or density in a linear fashion with changes in pressure. Because fluid density is temperature dependent, the compressibility is also influenced by the fluid temperature.

For the purposes of hydraulic test analysis, a value of fluid compressibility (C_w) was taken from Figure 4.1 which illustrates the variation of fluid compressibility with changes in pressure and temperature. To provide a fluid compressibility typical of a Leuggern test interval, values were chosen from Figure 4.1 using an in-situ pressure and formation fluid temperature which were estimated based on the field data. [Note: the fluid property curves for compressibility, density, viscosity, and thermal expansion as shown in Figures 4.1, 4.2, 4.3, and 4.4, respectively, are based on tabulated data for pure-water presented in Dorsey (1968).]

In a discussion of fluid compressibility in hydraulic testing it is also worthwhile to consider the interpretation of the test system compressibility and the observed compressibility. The test system compressibility (C_{TS}) includes the compressibility of water and the deformation of components of the hydraulic testing equipment. The system deformation, which is due to a certain amount of non-rigidity or compliance in the equipment resulting from packer deformation or readjustment, entrapped air in the equipment or machined tolerances on the seating and positioning of various steel components and O-ring or other seals, should be considered if the information is available. System compliance enhances the compressibility within the test interval.

Most of the system compressibility for the Lynes equipment used in the testing of the Leuggern borehole is represented by the packer compliance. The packer compliance or packer readjustment is a continuing process throughout a hydraulic test in response to the pressure differential between the test interval, the packer pressure and the pressure above and below the test interval. A discussion of packer compliance effects with respect to hydraulic tests is provided in Grisak et al. (1985).

While it is recognized that the test system compressibility may be greater than the compressibility of fluid only in the test zone, there has not been sufficient evaluation of the Lynes test equipment to estimate a value of C_{TS} a priori. In laboratory and field testing using other systems (Neuzil, 1982; Forster and Gale, 1980, 1981; and Hsieh et al., 1983) the test system compressibility was found to be between a factor of 2 to 6 greater than the compressibility of water. None of these systems, however, are comparable to the Lynes system to allow a direct extrapolation to tests completed in the Leuggern borehole. In fact, the Lynes system is considered to be more rigid than these systems and therefore, in our opinion, the system compressibility is probably a factor of 2 or 3 greater than water.

Another method of estimating the system compressibility is to measure the test interval pressure change after an instantaneous injection of a known volume of water and calculate an observed compressibility, as described by Neuzil (1982). This type of testing requires a very tight formation such that only a small fraction of the water pumped into the test interval flows out into the formation during pressurization of the interval. Alternatively, the test zone compressibility could be derived by pressurizing a representative test interval in blank casing using a test tool assembly identical to the borehole testing equipment. While these methods may provide a more appropriate measurement of system compressibility, it can not be used in the hydraulic testing in the Leuggern borehole because the injected volume was not measured during the testing phase.

4.1.4 Fluid Density

The fluid density is defined as the mass per unit volume of fluid and is a function of temperature and pressure, dissolved and suspended solids, and dissolved free gas. For use in hydraulic test analysis the fluid density must represent in-situ conditions and therefore must be corrected for temperature and pressure. The variation of fluid density with changes in temperature and pressure is given in Figure 4.2. To determine an appropriate fluid density for use in the hydraulic test analysis a pure-water density was assumed and corrected for temperature, pressure and salinity. The formation temperature was selected based on measured temperatures of the borehole fluid as reported in the interval reports. The in-situ pressure was derived from the measured pressure at the end of the shut-in period of the hydraulic testing sequence. The corrected fluid density is estimated based on Figure 4.2.

4.1.5 Fluid Viscosity

The internal resistance of a fluid to motion is known as its viscosity. Viscosity is greatly influenced by temperature while changes in pressure have only a negligible effect. The variation of viscosity with changes in temperature is given in Figure 4.3.

The viscosity of the fluid in the test zone and formation must be corrected for temperature for use in hydraulic test analysis. The average temperature is estimated based on the measured temperature transducer response during the interval testing. The viscosity is estimated based on a comparison to Figure 4.3.

4.1.6 Fluid Thermal Expansion Coefficient

Pressure changes within a shut-in test zone can occur as a result of temperature changes of the shut-in borehole fluid. If the borehole fluid is at a different temperature from the formation fluid, due to mixing within the borehole or the introduction of drilling fluids, expansion or contraction of the fluid will result in a fluid volume change which will result in a corresponding pressure change. The magnitude of pressure change is a function of the thermal expansion coefficient which is temperature dependent and, to a lesser extent, pressure dependent. At constant pressure, the thermal expansion of pure water can be expressed as follows:

$$\beta = \frac{1}{V} \left(\frac{\Delta V}{\Delta T} \right)_P \qquad (4.1.5)$$

where β = thermal expansion coefficient, $°C^{-1}$;
V = volume of water, L^3;
ΔV = change in volume of water, L^3;
ΔT = change in temperature of water, °C.

For pure water, the variation of the thermal expansion coefficient with temperature and pressure is given in Figure 4.4. For temperature variations from 0 to 100°C, the thermal expansion coefficient varies from -3.9E-05 to 7.5E-04$°C^{-1}$.

In the analysis of the Leuggern hydraulic tests, the thermal expansion coefficient was estimated by correcting the freshwater coefficient for borehole temperature and pressure at the test zone. The thermal expansion coefficient was only required when the borehole fluid underwent a significant (i.e., greater than 0.2 to 0.3°C) temperature change during pulse tests and build-up periods of drill stem tests. The borehole temperature was estimated from the responses of the temperature transducers. The pressure was estimated based on the average shut-in pressure response in the hydraulic test sequence. The average temperature and pressure were then applied to Figure 4.4 to determine the corrected thermal expansion coefficient of the test interval fluid.

4.1.7 Formation Pressure and Annulus Pressure

The formation fluid pressure is the undisturbed static pressure of the formation beyond the influences of the borehole. When analyzing hydraulic test data to determine hydraulic conductivity, a formation pressure representative of undisturbed conditions must be estimated as an initial condition for the analysis method. Several different approaches were used to define undisturbed fluid pressure within the test interval, including the Horner method of analysis. A detailed description of the approaches for selecting the initial value of formation pressure is given in Section 4.3.

The effect that borehole pressure (i.e., annulus pressure) exerts in a test interval prior to testing can be important for test interpretation purposes. Annulus pressure was considered when simulating the pressure history of the test interval prior to testing. When the annulus pressure differs from the formation pressure and the test interval is exposed to annulus pressure for a significant period of time, the result is a pressure disturbance or transient around the borehole. The annulus pressure is estimated at the center of the test interval from the P3 transducer during the installation of the test tool, and prior to the start of testing. At Leuggern, the annulus pressure often corresponds to overflow conditions at the top of the borehole casing and therefore, in this instance, would be less than the static fluid pressure of the formation.

4.1.8 Hydraulic Head and Equivalent Freshwater Head

The concept of a hydraulic potential, developed by Hubbert (1940), was derived on the basis of energy relationships for a homogeneous fluid. The fluid potential (ϕ) in a porous medium is defined as follows:

$$\phi = gh \tag{4.1-6}$$

where g = gravitational acceleration, Lt^{-2};
h = hydraulic head; L.

For situations dealing with homogeneous fluids (i.e., constant properties spatially and temporally), the hydraulic head (h) is related to pressure by the following equation:

$$h = Z + \frac{p}{\rho g} \tag{4.1-7}$$

where Z = elevation head (distance from the measuring point to a reference datum), L;
p = pressure, $ML^{-1}t^{-2}$;
ρ = fluid density, ML^{-3};
g = gravitational acceleration; Lt^{-2}.

If the fluid density is assumed equal to the density of fresh water, then the hydraulic head calculated from equation 4.1-7 is referred to as the equivalent freshwater head.

Equivalent freshwater head can be calculated from formation pressure and is useful in the comparison of formation pressures from intervals at the same depth with similar salinity.

To calculate the equivalent freshwater head at the center of an interval, the formation pressure at the center of the interval must first be calculated as follows:

$$p_{fc} = p_{ft} + \rho g d_{ct} \tag{4.1-8}$$

where p_{fc} = formation pressure at the center of the interval; $ML^{-1}t^{-2}$;

p_{ft} = formation pressure at transducer depth; $ML^{-1}t^{-2}$;

ρ = average fluid column density; ML^{-3};

g = gravitational acceleration Lt^{-2};

d_{ct} = true vertical distance between the transducer and the center of the interval, L.

Equivalent freshwater head is then calculated by:

$$H = \left(\frac{p_{fc} - p_{atm}}{\rho_f g}\right) - d_c + Z \tag{4.1-9}$$

where H = equivalent freshwater head (m ASL), L;

ρ_f = reference density of fresh water, ML^{-3};

p_{atm} = barometric pressure, $ML^{-1}t^{-2}$;

d_c = true vertical depth to the center of the interval, L;

Z = datum elevation (m ASL), L.

For all Leuggern borehole calculations, the gravitational acceleration was assumed to be 9.8065 ms^{-2}.

Chapter 6 summarizes the equivalent freshwater head values obtained for the borehole which correspond to the interpreted static formation pressures. Below we present an example calculation of freshwater head for interval 676.8H.

Test 676.8H

Using 4.1-8, where

P_{ft} = 6570 kPa

ρ = 0.997 gcm^{-3}

g = 9.8065 ms^{-2}

d_{ct} = 18.03 m

$$P_{fc} = 6570 + [(0.997)(9.8065)(18.03)]$$

$$= 6746.28 \text{ kPa}$$

Using 4.1-9, where

P_{fc} = 6746.28 kPa

P_{atm} = 102.0 kPa

ρ_f = 1000 kgm^{-3}

g = 9.8065 ms^{-2}

d_c = 672.51 m

Z = 358.8 m ASL

$$H = \left[\frac{6746.28 - 102.0}{9.8065}\right] - 672.51 + 358.8$$

$$= 363.8 \text{ m ASL}$$

4.1.9 Hydraulic Conductivity

The basis of ground-water flow lies in the development of Darcy's Law which relates the rate of ground-water flow to a hydraulic gradient.

$$v = - K \frac{dh}{dl} \qquad (4.1\text{-}10)$$

where v = specific discharge, Lt^{-1};
K = hydraulic conductivity, Lt^{-1};
h = hydraulic head, L;
l = distance between head measurements, L;
dh/dl = hydraulic gradient, LL^{-1}.

In equation 4.1-10, K is a constant of proportionality and is a function of both the medium and the fluid. The hydraulic conductivity can be defined in terms of medium and fluid properties as:

$$K = \frac{k\rho g}{\mu} \qquad (4.1\text{-}11)$$

where k = intrinsic permeability, L^2;
ρ = fluid density, ML^{-3};
μ = fluid viscosity, $ML^{-1}t^{-1}$;
g = gravitational acceleration, Lt^{-2}.

For the case of a porous medium, the intrinsic permeability is a property of the medium alone, being a function of the grain size, sphericity and roundness of the grains, the nature of their packing and degree of cementation and fracturization.

For the case of a fractured rock system, the hydraulic conductivity may be conceptualized by idealizing the fracture as a parallel plate model (Snow, 1969). Applying the Navier-Stokes equation for single phase, non-turbulent flow of a viscous incompressible fluid the hydraulic conductivity of the fracture, K_f, becomes:

$$K_f = \frac{\rho g}{12\mu}(2b)^2 \qquad (4.1\text{-}12)$$

where the fracture aperture is 2b. As in a porous medium, the fracture hydraulic conductivity is dependent on the properties of the fluid but is also dependent on the fracture aperture. Flow through fractures is governed by the hydraulic gradient and aperture of the fracture and its surface roughness, providing the flow remains laminar. For a single set of parallel plates the rate of flow (Q) can be described by:

$$Q = \frac{(2b)^3 \rho g}{12\mu} \frac{dh}{dl} \tag{4.1-13}$$

For a series of fractures with a spacing of n per unit length the effective hydraulic conductivity of the fractures is:

$$K_f = \frac{(2b)^3 n\rho g}{12\mu} \tag{4.1-14}$$

For the Leuggern borehole, Nagra chose a porous media approach for interpreting hydraulic testing results to determine hydraulic conductivity. This approach implies that ground-water flow within the fractured test interval can be approximated by a porous-media equivalent. In this case, the hydraulic conductivity determined from the test interpretation is an equivalent rock mass hydraulic conductivity (K_{erm}) applied to the entire test interval. This results from the interpretation of a pressure-time record that represents the response of the isolated test interval. The K_{erm} is an average for the test interval and it is recognized that higher or lower hydraulic conductivities may be contained within the interval in the form of fractures, fracture sets or separate permeable lithographic units.

4.1.10 Specific Storage

The specific storage of a saturated geologic medium is defined as the volume of water that a unit volume of the medium releases from storage under a unit decline in hydraulic head. This volume of water released from storage is dependent upon the compressibility of the fluid and the medium. Specific storage S_s can be expressed:

$$S_s = g\rho \; (C_R + \theta \; C_W) \qquad (4.1\text{-}15)$$

where ρ = fluid density, ML^{-3};
g = gravitational acceleration, Lt^{-2};
C_R = rock or formation compressibility, $M^{-1}Lt^2$;
θ = effective porosity, dimensionless;
C_W = fluid compressibility, $M^{-1}Lt^2$.

The mathematical representation of the specific storage is dependent on the definition of the fluid and medium compressibilities. A detailed review of the various conventions for defining the formation compressibility is given by Narasimhan and Kanehiro (1980), and has been reviewed in Section 4.1.1. The expression for specific storage noted above is based on a formation compressibility definition utilizing a normalization with respect to the bulk volume of the sample being tested. This definition is consistent with the standard hydrologic approach.

The storage coefficient is equal to the product of the specific storage and the formation thickness. During hydraulic testing, the full test interval length is usually chosen as the formation thickness because the portion of the test interval length most actively contributing to the pressure recovery is unknown.

As indicated by equation 4.1-15, specific storage is a function of the formation fluid density and compressibility, the rock compressibility and the formation porosity. Of these parameters, rock compressibility and formation porosity are the least certain for any test interval. As discussed previously, a porosity of 0.5 percent was assumed for the crystalline rock and compressibility was calculated from literature values of Young's modulus and Poisson's ratio that were considered to be representative of crystalline rock.

When specific storage was varied to determine the sensitivity of the interpreted hydraulic conductivity to this parameter, the variation was achieved by adjusting rock compressibility within the following ranges: a rock compressibility of 2.0E-08 Pa^{-1} for highly fractured, fissured, or kakiritized rock, to 2.0E-12 Pa^{-1} for an unfractured granite (see Sections 4.1.1 and 4.1.2). The most commonly used value for the biotite-gneiss and granite prevalent at Leuggern was a compressibility of 2.0E-11 Pa^{-1}. This results in a base case specific storage of 2.2E-07 m^{-1}.

Some authors, such as Black (1985) and Barker and Black (1983), propose a much wider range of values, from 5.0E-13 to 2.0E-08 m^{-1}, for specific storage using a concept based on fissured porous media. While the concept is applicable to hydraulic tests in granite, it assumes the rock is essentially non-porous and incompressible with all of the storage contained within the fractures and requires a detailed knowledge of matrix properties and fracture properties (i.e., frequency, porosity, etc). Laboratory measurements on cores indicate that rock, even granite, is both porous and compressible and therefore matrix contributions may be significant especially at low hydraulic conductivities (i.e., 1.0E-13 to 1.0E-9 ms^{-1}). For the Leuggern hydraulic testing program, Nagra required that a porous media approach be used throughout. Therefore, the specific storage values based on the measured rock properties discussed above (porosity and compressibility) are considered to be defendable and representative for the test interpretations.

The specific storage of the formation selected for the interpretation of a hydraulic test can have a significant effect on determining the best estimate of hydraulic conductivity for a test interval. In general, when simulating a pulse test, an increase in formation specific storage results in a corresponding increase in the rate of pressure recovery within the test interval. These effects become more pronounced at lower hydraulic conductivities. For example, at a hydraulic conductivity of 1.0E-12 ms^{-1} or less, the uncertainty in the estimate of hydraulic conductivity associated with a variation in S_s over two orders of magnitude (e.g., 2.0E-06 to 2.0E-08 m^{-1}) is close to one order of magnitude. The choice of formation specific storage for interpretation of tests in crystalline rock is discussed below.

Several sensitivity studies were performed in an attempt to quantify the effect of specific storage on the interpreted hydraulic conductivity. A general conclusion is that at higher hydraulic conductivities (e.g., 1.0E-06 to 1.0E-08 ms^{-1}) the interpreted hydraulic conductivity is relatively insensitive to variations in specific storage, while at lower hydraulic conductivities (e.g., 1.0E-11 to 1.0E-12 ms^{-1}) the interpreted hydraulic conductivity varies by as much as one order of magnitude when specific storage is varied by two orders of magnitude. The specific storage used in each of the analyses described in this report was usually assumed to be the base case value unless a sensitivity analysis was judged to be warranted in improving the fit between the measured and simulated pressure responses.

4.2 Hydraulic Test Interpretation Methods

4.2.1 Analytical Solutions

The pressure response during hydraulic tests varies with time depending on the hydraulic properties of the formation being tested. Under ideal test conditions, hydraulic tests can typically be analyzed using analytical solutions of the transient radial flow equation. Each test type (i.e., slug, pulse, drill stem or pump test) has had an appropriate analytical solution developed, which allows for the determination of transmissivity and in some cases formation pressure. The various test types and the literature references that provide the analytical solutions are listed as follows:

- Slug injection or withdrawal test - Cooper et al. (1967)
- Pulse injection or withdrawal test - Cooper et al. (1967)
  - Bredehoeft and Papadopulos (1980)
- Pulse test - Fractured Media approach - Wang et al. (1978)
  - Barker and Black (1983)
- Drill stem test - Matthews and Russell (1967)
  - Earlougher (1977)
- Pumping or Injection test - Theis (1935)
- Constant Drawdown Flow test - Jacob and Lohman (1952)

The reader interested in more details on the analytical solutions for individual hydraulic testing techniques is directed to the original references. A review of the theoretical aspects of borehole hydraulic testing methods is provided in Grisak et al. (1985). The analytical solutions generally use the confined porous media approach (except for the pulse test fractured media approach) for conceptualization of the flow regime during hydraulic testing of rock. For fractured rock, if the fracture geometry is known and meets the conditions of a fracture flow model, such as the analytical solutions published by Wang et al. (1978), then a fractured-medium approach can be taken to interpret the pressure-time data. For the Leuggern borehole, this type of understanding of the fracture system was not possible. Moreover, the physical conditions of fracturing assumed in the fracture flow models, such as the existence of either a single fracture or a number of identical contributing fractures within the test interval, most likely does not describe the fracture geometry at Leuggern. Therefore, an equivalent porous-media-based analysis method was chosen as an adequate, and in many cases preferable, approach to interpreting the Nagra borehole tests. For the interested reader, Grisak et al. (1985) provides a discussion of the results from a comparison of test interpretations using fractured-media versus porous-media-based computer models.

Using a porous-media conceptualization the following simplifying assumptions are adopted:

(1) The aquifer (test interval) is confined, infinite in areal extent and constant in thickness;
(2) The aquifer is homogeneous;
(3) Areal flow in the aquifer is negligible;
(4) Initially, constant head exists across the aquifer;
(5) No vertical component of flow exists in the aquifer.

These assumptions have been universally applied in groundwater problems in porous media to simplify the flow regime in a manner that is conducive to analysis. A discussion of the validity of these assumptions as applied to hydraulic testing is given in Grisak et al. (1985).

The analytical solutions can be solved using a representative range of parameters to obtain a series of type curves. The type curves can be compared graphically to the field data to determine the hydraulic parameters. A discussion of this method is provided in numerous references treating ground water resource evaluation, one of which is Freeze and Cherry (1979).

Type curves can provide an estimate of the hydraulic parameters, but in many cases, because of the quality of the data or the non-representativeness of an analytic solution, the fit to the type curves is poor and the field data can be matched to various parts of several curves. This non-uniqueness of fit in the use of type curves can result in considerable uncertainty in the estimation of the formation parameters. It is also necessary to extrapolate between curves if an accurate match can not be obtained with the existing curves. Herein lies the advantage of implementing the analytic solutions in the form of computer models. In the computer implementation, the analytical solution is solved numerically using appropriate ranges of formation parameter values. Each computer simulation is compared to the field data until a best fit curve is found. The formation parameters for the field data are the same as those for the best-fit curve. The advantages of the computer implementation method are therefore: (1) sensitivity analyses can be conducted to assess the effects of parameter value variation on the simulated pressure or head responses; (2) the formation parameters can be more easily varied to determine a more accurate best-fit curve; and (3) errors due to extrapolation and matching to the wrong curve are reduced.

4.2.2 Practical Considerations in Interpreting Hydraulic Tests

In most cases, analytical solution methods for interpretation are best applied when all or most of the theoretical assumptions (i.e., confined, infinite, homogeneous aquifer with constant thickness and initially constant head) can be achieved. For deep borehole testing, non-ideal conditions often exist during the testing procedure, which may reduce the ability of the analytical methods to represent the testing results.

The purpose of this section is to identify and evaluate the processes and factors which are important in the analysis and interpretation of borehole hydraulic tests. The factors which are of particular importance in evaluating low hydraulic conductivity formations include borehole pressure history, formation pressure and hydraulic head, thermally-induced pressure responses, borehole/formation skin effects and non-homogeneous medium. A discussion of these factors is necessary to provide a basis for the development of the analysis technique - the Graph Theoretic Field Model (GTFM) described in Section 4.3 and used throughout the analysis of the Leuggern hydraulic tests.

The following discussion is based on concepts presented by Grisak et al. (1985).

4.2.2.1 Borehole Pressure History

During the drilling of the test interval, an overpressure may occur in the borehole (known as the drilling overpressure) during the circulation of the drilling fluid for the removal of cuttings from the borehole. The pressure within the borehole at the drill bit during drilling is estimated to be the sum of the annulus pressure (corresponding to borehole overflow conditions) and the drilling overpressure. The drilling period is usually followed by an open borehole period where the test interval is exposed only to annulus pressure. These pre-test borehole pressures will, in general, be different from the in-situ formation pressure. The pre-test borehole pressure history may be further influenced by pressure differentials imposed on the interval during previous tests. These pressure differences result in the development of a pressure disturbance surrounding the borehole that is different in magnitude from the formation pressure. The net effect of the pressure disturbance developed during the drilling and the open borehole periods is the development of testing conditions that do not meet the constant head assumption involved in data analysis methods using analytical solutions. The pressure recovery in the interval will not be simply related to the recovery to static formation pressure from the pressure differential imposed at the start of the test. The pressure transient developed during drilling and prior to testing can strongly affect the pressure recovery curve. The analysis of packer tests using analytical solution methods could, therefore, yield incorrect hydraulic conductivity estimates under conditions where a pressure transient exists in the vicinity of the borehole rather than static formation pressure. Grisak et al. (1985) and Pickens et al. (1987) discuss several examples of the variation in hydraulic test response dependent on the magnitude and duration of the annular pressure history for pulse and slug tests.

The determination of the magnitude of the pressures during history events represents the largest uncertainty associated with incorporating the pressure history into the analysis of the hydraulic tests. The drilling overpressure, for example, is difficult to determine in terms of the magnitude of pressure imposed on the formation. The drilling overpressure at the mud pump (i.e., at surface) is measured and recorded, but due to head losses in the tubing string, drill bit and borehole annulus and turbulent flow at the bit, the actual pressures imposed on the formation can only be approximated. Calculation of frictional losses through the drill pipe and at the bit for a tri-cone assembly (e.g., Myers and Funk, 1967; Sutko and Myers, 1971; Exploration Logging, Inc., 1983) have indicated that a 50 percent loss of applied pressure (from the mud pump) would be a reasonable approximation of the overpressure felt by the formation during drilling. Similar data for core drilling are not available, however, it is assumed that it would be somewhat similar in magnitude. Therefore, the pressure on the formation during the drilling period is simulated with the annulus pressure plus half of the drilling overpressure measured at the mud pump. A second uncertainty associated with the drilling period is the length of time that the interval is exposed to the drilling pressure. The top of the interval is open to the drilling pressure for the entire drilling period while the bottom of the interval is open for only a short time. For simulation purposes, the entire test interval is considered to be exposed to the drilling pressure for half of the drilling period. It should be noted that drilling overpressures are quickly dissipated in an open borehole. For example, if a drilling overpressure is imposed upon a test interval followed by an open borehole period at annulus pressure, the overpressure, depending on the magnitude and duration, would be dissipated in a relatively short period of time. Therefore, drilling overpressures may only have a significant impact on the borehole history if the hydraulic testing is conducted shortly after the imposition of the overpressure. More detail on the dissipation of drilling period effects is provided below.

The annulus pressure has less uncertainty associated with its measurement because the fluid level in the Leuggern borehole is near the surface or overflowing under static conditions and therefore the annulus pressure is generally taken as the pressure associated with the height of the fluid column from the transducer depth to the top of the casing or casing overflow valve.

The annulus pressure may be uncertain if the casing outflow elevation or the borehole fluid density change during the borehole pressure history period. The outflow elevation may vary by about 1.5 to 2.0 m depending on the configuration of the overflow valve with respect to the top of the tubing string and the drill rig floor elevation.

The borehole fluid throughout drilling and testing in the crystalline rock was distilled water and therefore the fluid initially has a density of approximately 1000 kgm^{-3}. However, formation inflow into the borehole would result in mixing of the formation and borehole fluids resulting in an increase in fluid density and annulus pressure. During the drilling program, the borehole may contain suspended solids (i.e., rock flour) which will also increase the fluid density and annulus pressure. With the annulus pressure changing with time, the pressure measured at transducer P3 of the Lynes Hydrologic test tool prior to the start of testing may not be entirely representative of the pressure history at the test interval.

The borehole pressure history may also include the differential pressure between annulus pressure and test interval pressure, or pressure disturbances imposed on the interval during previous test sequences that included at least a part of the interval. However, in most cases these influences on the pressure history can be incorporated into the analysis at least in a simplified form.

Sensitivity analyses were performed to assess the effects of an uncertain drilling overpressure period on the simulated pressure response and thus on the interpreted hydraulic conductivity. The results are discussed below in terms of the length of open borehole period separating the drilling from testing sequence, during which the drilling disturbance would dissipate. GTFM simulations were run with a 3-day drilling disturbance at overpressures ranging from 0 to 2000 kPa above annulus pressure. The duration of an open borehole period at annulus pressure following the pressure disturbance and prior to testing was varied from 1 to 30 days. Testing consisted of either a slug injection test (with K = 1.0E-07 ms^{-1}) or a pulse injection test (with K = 1.0E-12 ms^{-1}). Test interval parameters used in the sensitivity runs are considered representative of the Leuggern borehole. They include a specific storage of 2.2E-07 m^{-1}, a test interval length of 22.68 m, and a formation pressure equal to annulus pressure at 5000 kPa.

Table 4.1 presents a summary of the sensitivity results. Drilling overpressure of 2000 kPa applied over 3 days will dissipate to less than one percent of the original overpressure after about 13 days of open borehole conditions at a formation hydraulic conductivity of 1.0E-07 ms^{-1}. At this point, the drilling pressure would have no effect on the test response. For a hydraulic conductivity of 1.0E-12 ms^{-1}, this same pressure disturbance would dissipate after about 22 days of open borehole immediately preceding testing. Table 4.1 allows an estimate of the significance of the drilling pressure on the pressure response for a slug and pulse test. Although certain guidelines are used in estimating drilling overpressure, there are several instances, such as test 912.5S which is discussed below, in which the magnitude of the drilling overpressure appears to be very significant and some uncertainty exists as to the modeled drilling pressure. These sensitivity analyses allow a basis for evaluating the effect of the history pressure on the test interval pressure response.

4.2.2.2 Formation Pressure

One of Nagra's objectives in hydraulic testing is to determine static formation pressure at the test interval. For the case where the test zone has been subjected to very little or no borehole history and thermal effects are not significant, this pressure can be measured by a transducer at the test interval either during the static recovery period at the beginning of a test sequence (sometimes referred to as the P_{stat} period) or by allowing a pressure test to recover completely to a steady pressure (i.e., observing a stabilized pressure for several hours). In the instance of a complete recovery, the formation pressure can simply be taken from the data record. If the conditions are such that a test interval may be recovering to a static formation pressure but the test is terminated before a complete recovery, then the approach can be taken to determine formation pressure (P_f) by matching the partial recovery curve with simulated pressures using a reasonably unique set of K, S_s and P_f. This constitutes a simple calibration of formation pressure.

If a significant pressure disturbance exists around the borehole at the test interval, then a stable recovery pressure can be biased by borehole history and, in the case of a shut-in test, by changes in fluid temperature within the test zone. In cases with significant pressure histories and/or thermal effects, the recovery to a static formation pressure can take as long as several months. When pressure recovery in a test interval is influenced by a pressure disturbance around the borehole and/or thermal effects, if the analysis technique can simulate these effects accurately, then it is possible to determine a formation pressure from such a test response. Simulated pressures with history and thermal effects considered are fit to the portion of the pressure response that has been measured and, providing that the fit is reasonably unique in P_f, this value of formation pressure, which has been used in simulating the pressure response, can be taken as P_f for the isolated zone. This approach constitutes a more sophisticated calibration and is discussed further in Section 4.3. In most instances where pressure recovery is influenced significantly by history and thermal effects, the model of these effects is too uncertain to yield a unique formation pressure and the influence of these effects on the pressure recovery prevents the determination of a unique P_f.

4.2.2.3 Thermally-Induced Borehole Pressure Response

During and subsequent to drilling a test interval, a temperature profile can develop into the formation in response to the differential temperatures between the borehole fluid and the rock. The net effect of the development of such a profile is a variation in the borehole fluid temperature during the hydraulic testing period as the borehole fluid equilibrates with the formation temperature. These temperature variations may result in significant pressure changes during pulse testing (i.e., under shut-in conditions where the thermally-induced changes in fluid volume are confined between packers), especially in low hydraulic conductivity formations.

Thermally induced pressure effects should be included in the analysis technique if the hydraulic testing technique is a pulse test, if the temperature change in the test interval during any single pulse test is greater than 0.2°C, and if the expected hydraulic conductivity of the interval is less than 1.0E-10 ms^{-1}.

Examples which illustrate the potential importance of thermal effects on the measured pressure response during borehole hydraulic testing are given in Grisak et al. (1985) and Pickens et al. (1987).

Analysis methods (e.g., GTFM) have been developed and utilized to account for thermally-induced pressure effects and borehole history effects to allow for more accurate formation pressure and hydraulic conductivity estimates to be determined from the test data.

4.2.2.4 Non-Homogeneous Medium

Standard analysis techniques make the assumption that the hydraulic tests are representative of a homogeneous medium of infinite extent. However, in crystalline rock it is possible that the formation is heterogeneous and that hydrogeologic boundaries may exist within close proximity of the borehole.

Heterogeneities in crystalline rock may include fault or shear zones, lithologic changes (i.e., increases in schistoscity or gneissoscity), kakiritization, or changes in the fracture frequency and distribution. In the crystalline rock at Leuggern, fractures and kakirite zones are the most dominant hydrogeologic features and may have a significant control on rock hydraulic conductivity and ground-water flow. Unfortunately, in deep borehole testing, fracture characteristics such as frequency, length, aperture size and orientation are rarely described in sufficient detail in order to be incorporated into an analytical technique. Given the uncertainties associated with fracture characteristics, the homogeneous assumption along the test interval length provides the simplest and possibly the most practical approach to be used in analytical methods. Fractured media approaches and dual porosity models are available for hydraulic test analysis, however, their use is more successful in those cases where the fracture heterogeneities and their response to hydraulic tests are better understood.

The assumption of infinite extent is related to homogeneity in that changes in the formation close to the borehole could represent boundary conditions for the hydraulic tests. Again, fractures may play a controlling part in defining the extent of the tested formation. Test intervals may be bounded by permeable fractures which may represent relatively constant head boundaries or by permeable fractures of limited extent which may be considered as impermeable (no flow) boundaries. Each of these conditions are contrary to the assumption of infinite extent, and if present, the analysis method which assumes homogeneity may not accurately represent the formation response. In order to reduce the uncertainty, hydrogeologic boundaries, if they can be identified, can be included in the hydraulic test analysis. However, in the presence of other possible disturbances, the type of boundary (no flow or constant head boundary) and the distance to the boundary may be difficult to determine. For simulation purposes, external boundary conditions were applied at radial distances sufficiently large to not affect the calculated pressure response in the test interval.

4.2.2.5 Parameter Uncertainty

The physical properties of the formation, estimated from literature values of similar rock types, cannot be considered unique. For example, porosity could vary by about an order of magnitude and rock compressibility by several orders of magnitude and still fall within a reasonable range for the types of rock at Leuggern, considering the uncertainty in the fracturing and structure in the rock. A sensitivity study of the effects of specific storage on the interpreted effective hydraulic conductivity for several test responses at Leuggern has shown that below 1.0E-10 ms^{-1}, uncertainty in specific storage can have an effect on the interpreted hydraulic conductivity. One approach to determine the effect is to simulate the measured pressure-time data using a reasonable range of specific storage. The result is a range of hydraulic conductivities corresponding to a range of specific storage. The hydraulic conductivity corresponding to an intermediate value of storage is then adopted as the base case value with the upper and lower limit on hydraulic conductivity used to qualify this value.

This approach to uncertainty is accomplished using a simulation code such as GTFM where sets of hydraulic parameters can be used in the calculation of pressure-time profiles. By graphically comparing the simulated pressure data with the measured data for a range of hydraulic conductivity with each hydraulic conductivity simulated at different values of specific storage, a range of best-fit hydraulic conductivities can be obtained to quantify the uncertainty.

4.2.3 Analysis Technique - Graph Theoretic Field Model (GTFM)

As has been noted in previous subsections, the use of analytical solutions based on the standard hydraulic testing procedures and equations is invalid under certain conditions and will yield incorrect estimates for the formation parameters. It is essential in the analysis of the hydraulic testing data to incorporate all important parameters and test conditions.

The problem of quantitatively describing borehole pressure history, thermally-induced pressure responses, borehole/formation skin effects and other factors in hydraulic tests was approached by the development and application of a model to meet the following objectives: (1) assist in understanding of the relative importance of various parameters and conditions on the borehole pressure response during hydraulic testing and (2) provide an analytical capability for analysis of hydraulic tests which includes the important phenomena. In order to simulate the system behavior it was first necessary to develop an appropriate mathematical model. Since the task at hand was to simulate system response to special testing conditions which are represented as mathematically complex boundary conditions, a numerical modeling approach was selected.

Prior to development of the numerical model, the modeled system specifications were developed. For the borehole simulation model, the conceptualization of the actual physical system was simplified by the following assumptions:

- the formation whose response is being simulated is homogeneous (vertically), is confined, has a constant thickness and has a finite radius centered upon the borehole;

- the major influence on the formation behavior is the borehole and conditions imposed in the borehole;

- all flow is radially away from or towards the test interval of the borehole;

- the pressure in the formation is uniform and constant radially at the start of a drilling period or a test sequence; and

- the effects of fluid temperature changes in the formation may be neglected in comparison to any thermally-induced pressure changes in the borehole during testing.

Given the above assumptions, a numerical model of the physical system was developed using a generalized Graph Theoretic Field Model (GTFM) approach. The details of the mathematical model, GTFM, and its development, verification and application is documented in Grisak et al. (1985) and Pickens et al. (1987). The interested reader is directed to the original references for more details on the approach and test cases. The following paragraphs provide an overview of the approach and capabilities of the model.

GTFM constitutes a generalized methodology for modeling the behavior of field or continuum type problems. GTFM is based upon linear graph theory, continuum mechanics and a spatial discretization procedure. Savage and Kesavan (1979) present generalized descriptions of the methodology. The GTFM methodology, as applied to the physical system under consideration, results in an identical set of algebraic equations as would be derived using finite-element or finite-difference methodologies.

The GTFM simulation model is capable of handling the following conditions:

- borehole pressure history;
- isothermal and non-isothermal fluid conditions in the borehole;
- fixed pressure, pumping, pulse test and slug test sequences;
- fixed-pressure or zero-flow outer boundary; and
- borehole/formation skin effects.

There are two physical boundaries in the modeled system: the internal boundary at the borehole and the external boundary at the outside radius of the formation. The boundary condition at the external boundary can be either constant pressure or zero flow. Boundary conditions at the internal boundary are a function of the type of test being simulated. The model was designed to simulate tests consisting of multiple consecutive test sequences, where each test sequence is one of four types: pumping, history, slug or pulse. Pumping sequences correspond to a specified flow boundary condition applied at the borehole. A wellbore storage boundary condition can be incorporated with the specified flow. History sequences are intended to be used for including the effects of pre-test borehole history. A history sequence is modeled as a fixed-pressure boundary condition at the borehole. Slug sequences model the response of the formation to an instantaneous pressure change in an open well or borehole or in an open tubing string connected to a packer-isolated test interval. Pulse sequences model the response of the formation to an instantaneous pressure change in a shut-in test interval. Pulse sequences can be isothermal or non-isothermal. For the latter, the effects of temperature changes in the shut-in section of the borehole are incorporated in the simulation.

Hydraulic testing of a borehole interval usually involves a sequence of tests, each of which affect the measured pressure response of subsequent tests. The model presented here can be used to simulate multiple tests (i.e., test sequences) by using the pressure value at each node of the model grid at the end of a test as the initial condition for the subsequent test.

4.3 Hydraulic Test Interpretation Approach

This section describes the approach used in interpreting the sequences of hydraulic tests conducted in the Leuggern borehole. In general, the interpretation approach consists of estimating the borehole pressure history for the test zone during the drilling phase and between drilling and the start of testing, borehole temperature and the physical properties of the formation, fluid and test interval and then by selecting a range of values for hydraulic conductivity and formation pressure, generate, using GTFM, a series of simulated pressure curves for each hydraulic test. Hydraulic properties are adjusted until a best-fit simulation is obtained. The hydraulic properties used in the simulations are meant to describe the test interval. Once a best-fit case has been established, sensitivity studies can be conducted to determine the influence of the more uncertain parameters on the interpreted hydraulic conductivity.

An example is presented which illustrates the various components of the analysis approach including the determination of the borehole pressure history and the temperature at the test interval, the selection of appropriate parameters, estimation of the formation hydraulic properties and calibration of formation pressure. The interval selected as an example is test 1504.7H which was conducted in the Leuggern borehole at an apparent depth of 1492.24 to 1517.21 m on 8 and 9 March, 1985. This test sequence is appropriate because it represents a complex interpretation involving borehole history effects, a temperature change during testing, hydraulic conductivity determination and sensitivity to parameter uncertainty. The calibration technique to determine formation pressure is not used in this test because of the complicating effects of borehole history and temperature change. Test 444.2S is discussed in terms of deriving a static formation pressure by calibration.

The specifications and characteristics of the formation and the borehole and equipment configuration are given in Table 4.2. All of this information is obtained from borehole geological logs (i.e., rock type, fractures, drilling period, etc.), geophysical surveys (i.e., borehole diameter, true depth) and field hydraulic test reports (i.e., equipment configuration, depth interval, borehole temperature and testing sequences). The testing sequence for 1504.7H, illustrated in Figure 4.5, consisted of a pulse injection test (Pi01) and a slug withdrawal test (Sw01).

4.3.1 Initial Conditions

4.3.1.1 Borehole Pressure History

The borehole pressure history for test 1504.7H consists of three components: a drilling overpressure, an open borehole (i.e. annulus pressure) period and a packer compliance period. The borehole pressure history is illustrated in Figure 4.6. The drilling of the test interval began on 23 January, 1985 at approximately 1100 hrs and continued until 1630 hrs on 25 January, 1985. The middle of the drilling period is estimated at 1345 hrs on 24 January, 1985.

The fluid overpressure at the test zone applied during drilling was estimated to be about 620 kPa above full annulus pressure (P_a) based on the approach to estimating pressure as discussed earlier. The drilling overpressure is included in the borehole pressure history for the period from the middle to the end of the drilling period.

After drilling, the interval was exposed to open borehole or annulus pressure conditions. The annulus pressure was determined from the hydraulic test field reports using the P3 transducer reading (which measures annulus pressure) of 14226 kPa. The annulus pressure was imposed upon the test interval from the end of drilling to the start of testing, a period of about 42 days.

The test interval was isolated between straddle packers during the reconnaissance H-logging phase of testing. Following packer inflation, the test interval was subjected to an equipment compliance period of about 50 minutes where the test interval was shut-in at a pressure of about 20 kPa above annulus pressure and then opened to the tubing string temporarily. Hydraulic testing of the interval began at the end of the compliance period.

The borehole pressure history therefore consisted of about 27 hours of drilling overpressure followed by 42 days at annulus pressure and 0.83 hours of equipment compliance. The length and magnitude of these pressure conditions are input to GTFM in order to define the pressure disturbance surrounding the borehole (i.e., the pressure transient) prior to the start of testing.

4.3.1.2 Temperature Profile

During test 1504.7H, the temperature of the borehole fluid at the transducers decreased from 61.8°C at the start of the testing sequence to about 61.3°C at the end of the testing sequence. This temperature change of 0.5°C was considered in the simulation of the pressure response.

From a review of the temperature data of T1, T2 and T3, the cooling trend illustrated in Figure 4.7 was considered to be representative of the test interval temperatures. A possible explanation for the thermal response is provided in the NTB Appendix for this interval. In order to incorporate the temperature change in the analysis technique, the measured temperature data is simulated using either a polynomial or cubic spline approximation and the approximated (smoothed) temperature response is input to GTFM such that the simulated pressure response is corrected for, in this case, fluid thermal contraction resulting from the temperature decrease with time.

4.3.1.3 Parameter Selection

The list of parameters chosen for the analysis of test 1504.7H are given in Table 4.3. The most representative formation compressibility was estimated to be 2.0E-11 Pa^{-1} based on the discussions in Section 4.1. This value is based on a literature review of values of Young's Modulus and Poisson's Ratio for a granite and a granitic gneiss. The formation compressibility (and corresponding specific storage) reported in the table was used in calculating the most reasonable fit to the pressure data. Since these values are intermediate to the range of values chosen for the sensitivity study, they are considered to be the base case values.

Similarly the effective formation porosity was estimated to be 0.5 percent based on a literature review of reported values for granite and granitic gneiss rocks and singly and multiply fractured rocks.

The fluid compressibility has been estimated by assuming a pure-water compressibility and correcting it for downhole temperature and pressure (see Figure 4.1). In this case, the average fluid temperature in the interval of about 61.5°C and average pressure of about 14300 kPa (i.e., approximate formation pressure) results in a fluid compressibility of 4.32E-10 Pa^{-1}.

In a similar fashion, the fluid density and thermal expansion coefficient are corrected for formation temperature and pressure to result in values of 989 kgm^{-3} and 5.2E-4$°C^{-1}$, respectively.

The specific storage can be calculated using the formation compressibility, porosity, fluid compressibility and fluid density to yield a value of 2.2E-7 m^{-1}. This value is the base case value.

The test interval length is the distance between the straddle packers. The borehole diameter is determined from the drilled diameter or the most recent caliper log through the test interval. In the case where caliper logs are not available the drilled diameter is assumed to be a reasonable estimate.

4.3.1.4 Sequential Test Set-Up and Simulation

Once the borehole pressure history and temperature profile have been determined and the fluid, formation and test interval parameters have been measured or estimated, the hydraulic test sequence can be set-up. The packer tests to be interpreted at each interval must be treated and analyzed in sequence. This is necessary as the pressure disturbance around the borehole is modified by each preceding test.

For pulse tests and slug tests, as conducted at 1504.7H, the initial pressure imparted to the test zone after overpressuring or underpressuring the tubing string is specified in GTFM as the starting pressure in the test interval. For example, test Pi01 in Figure 4.5 has a starting pressure of 16372 kPa, and test Sw01 a starting pressure of 12457 kPa. The pressure record at the start of each test must be carefully examined to determine the true starting pressure. Fluctuation in the pressures at the start of a test can be caused by movement of the shut-in valve, equipment compliance and problems with the injection pump at ground surface. The early time of all tests is examined for the start of a regular pressure response and this starting pressure is specified in the simulation model. The duration of each test is specified while assembling the test sequence and the nature of the transient time stepping through the test must be specified by the analyst. By correctly specifying the initial pressure of each test sequence in GTFM, the simulated hydraulic response can be more readily compared to the measured response for each hydraulic test.

As part of the set-up of a pulse test simulation in GTFM, the analyst needs to specify whether the fluid temperature within the test interval is constant or varying. On specifying a variable fluid temperature, as would be the case for Pi01 of test 1504.7H, the temperature change of the borehole fluid described by the temperature curve for the period of the pulse test is applied to the calculated borehole pressures to correct the rate of pressure change for a temperature change. An indication of the representativeness of the measured temperature change can be seen in the concordance of the simulated pressure curve with the measured data. A simulated pressure curve for a pulse test which does not show the same shape as its measured counterpart possibly indicates that the measured temperatures were not representative of the test interval.

4.3.2 Initial Estimates of Formation Pressure, Hydraulic Conductivity and Specific Storage

Using the GTFM approach to hydraulic test interpretation requires that an initial estimate of formation pressure, hydraulic conductivity and specific storage be specified. The initial estimate of formation pressure can be obtained in three different ways. Tests from Leuggern were grouped according to estimated hydraulic conductivity and likelihood of determining a calibrated formation pressure. Many of the single packer tests were completed in permeable zones and recovery of the test interval to static pressure was obtained. These tests and several of the H-log tests provided initial estimates of formation pressure directly from the recovery portion of the data record. For tests completed in lower permeability zones where recovery to static was not obtained, an initial estimate of formation pressure was obtained by interpolating between the closest calibrated formation pressures above and below the interval, or if the interval could not be bounded by calibrated pressures, then by extrapolating to the P2 transducer location from the nearest calibrated pressure. The third approach to estimating pressure was taken while interpreting tests between 1100 and 1400 m during a preliminary evaluation of results, prior to the work for this report (INTERA, 1986). Since this group of tests was completed in relatively low permeability zones, the interpretations were completed without benefit of known or calibrated formation pressures for reference. Formation pressures were therefore estimated at annulus pressure because of the significant annulus pressure effects during history and the expectation that the pressure transient around the borehole, created by the history period, would strongly influence the test interval pressure recovery.

Test 444.2S is an example of determining an initial estimate of formation pressure for a test which provides a calibrated formation pressure. The final pressures of tests Pi01 and Pw01 are relatively stable at 4395 and 4393 kPa, respectively (see Figure 4.8) which indicates that the true formation pressure is likely bounded by these two values. The pressure stabilized to 4395 kPa for the last 11 hours of test Pi01 and returned to 4393 kPa within 0.7 hours of recovery during test Pw01. The calibrated formation pressure at transducer depth for test 444.2S is 4394 kPa.

For the initial estimate of hydraulic conductivity it is often necessary to choose three or four values which are separated by one order of magnitude in order to provide a wide enough range for the simulated responses to bracket the measured response. The shape of the hydraulic response for various test types can be used as a general indication of the required range of hydraulic conductivity values. For test intervals with hydraulic conductivities less than 1.0E-10 ms^{-1}, slug tests do not show an appreciable pressure recovery while for hydraulic conductivities greater than 1.0E-07 ms^{-1} pulse test recoveries are almost instantaneous. This is combined with an understanding of recovery rates for slug and pulse tests at various formation hydraulic conductivities. A preliminary assessment of hydraulic conductivity for test 1504.7H would be conducted using the Pi01 data which shows close to 90 percent pressure recovery in 6 hours. From previous test interpretations, this rate of recovery would indicate a low hydraulic conductivity on the order of 1.0E-11 ms^{-1}. The initial range of hydraulic conductivity used to attempt to bracket the test response was 3.0E-12 to 3.0E-11 ms^{-1}.

The initial estimate of the formation specific storage is taken as the base case value calculated from the porosity, fluid compressibility and rock compressibility. During the first GTFM simulation, to determine the bounding values of hydraulic conductivity, a single specific storage is specified.

4.3.3 Iterative Approach for Solving for Formation Pressure, Hydraulic Conductivity and Specific Storage

To start the test analysis, the simulated pressure-time curves are generated for an initial value of formation pressure, specific storage and an estimated range of values for hydraulic conductivity which are intended to bracket the data. In this case the hydraulic conductivity is a variable parameter and the rest of the parameters (i.e., formation pressure, specific storage, etc.) are constant. The simulated pressure curves can be compared to the measured field data to determine if the shape of the hydraulic conductivity-dependent curves are similar to the field data and if the final pressures of the simulated curves are similar to the final pressures of the field data. If the shape of the pressure curves does not match the field data (i.e., simulated pressures are too high or too low) the hydraulic conductivity values need to be adjusted to provide a more suitable fit. By using a sufficiently wide range of initial values of hydraulic conductivity it is often possible to bracket the field data and then refine the hydraulic conductivity values to obtain a best-fit thus minimizing the number of iterations.

For those tests in permeable zones which are not influenced significantly by pressure history or thermal effects, the measured pressure approaching complete recovery should match the simulated response. Otherwise, the formation pressure needs to be adjusted to obtain this match. The formation pressure that is used to obtain the most representative simulation is called the calibrated formation pressure. Essentially, for the tests that can be calibrated, GTFM is being used as a technique for solving for static formation pressure in partial test responses where, had the tests been allowed to recover completely, the recovery would have been to the static formation pressure.

Assuming that the borehole history, thermal effect, and formation pressure are accurate, the analyst can vary hydraulic conductivity and specific storage in order to improve the simulated fit. Usually, varying specific storage by one order of magnitude above and below the base case value is reasonable to describe the natural variability in the porosity and rock compressibility of the formation. The formation storage value which provides the best fit to the measured data is reported in the summary table of formation and fluid parameters for each interval.

4.3.4 Sensitivity of Best-Fit Hydraulic Conductivity to Variation in Specific Storage

The iterative approach to determining hydraulic conductivity, as discussed in Section 4.3.3, provides a best-estimate of this parameter based on a base-case value of specific storage determined from the literature. Given the uncertainties in the degree and nature of fracturing of rocks in a test interval and the range of compressibility calculated from stress and strain data in the literature for a particular rock type, it is reasonable to assume that specific storage could vary by as much as two orders of magnitude. To evaluate the effects of this uncertainty on the interpreted hydraulic conductivity, a general sensitivity study was completed on test intervals of hydraulic conductivity equal to 1.0E-07, 1.0E-10 and 1.0E-12 ms^{-1}. It was found that the interpreted hydraulic conductivity is relatively insensitive to specific storage variability for hydraulic conductivities greater than 1.0E-10 ms^{-1}. Test intervals in this range of permeability were assigned an uncertainty of less than half an order of magnitude in hydraulic conductivity. The effect of varying specific storage for hydraulic conductivity less than 1.0E-10 ms^{-1} can be significant and based on the case study of permeabilities in this range which included variation of specific storage over eight orders of magnitude, estimates of sensitivity of the interpreted hydraulic conductivity to specific storage variability were obtained for each of the tests. It was found that, for the most sensitive case, the uncertainty in hydraulic conductivity can be up to one order of magnitude depending on the choice of the specific storage for the interval.

5. EXAMPLE OF APPLICATION OF THE INTERPRETATION METHODOLOGY

This chapter provides an illustration of the application of the interpretation methodology for hydraulic conductivity and specific storage for a selected test zone (813.0H) as discussed in Belanger et al. (1988). Full details on the interpretation of the hydraulic testing in all other test zones are provided in the same report.

Test 813.0H (800.56 m - 825.53 m)

H-log testing was performed in this interval on 1 November 1984, as a part of H-log sequence #3, in order to determine the hydraulic conductivity of the formation. The pre-test pressure history was simulated with a 31 hour drilling period with a 350 kPa drilling overpressure, a 6.0 day open borehole period at an annulus pressure of 7851 kPa, and a 1 hour packer compliance period as shown in Figure 5.1. A listing of the borehole geology in this interval can be found in Table 5.1 along with drilling and testing dates.

Test 813.0H consisted of a 2.2 hour pulse injection (Pi01) and a 3.1 hour drill-stem test (0.5 hour Sw01 followed by 2.6 hour Pw01). Figure 5.2 shows the pressure response to 813.0H testing and gives starting and ending pressures for each test. The temperature changed by only 0.1°C during testing such that thermal effects were not included in the simulation. A formation pressure at P2 depth was estimated by interpolating between the calibrated values obtained from surrounding single packer tests. The selected value of 7870 kPa (at P2 depth) results in a calculated equivalent freshwater head at the center of the interval of 362.32 m ASL, a head which correlates well with calculated heads from single packer testing of surrounding intervals. Table 5.2 lists the estimated formation and annulus pressures as well as other input parameters used in the GTFM simulation.

Figure 5.3 is a plot of the simulated pressure response for three values of hydraulic conductivity ranging from 1.0E-11 to 1.0E-10 ms^{-1} and a specific storage of 2.2E-07 m^{-1}. The best-fit hydraulic conductivity from Figure 5.3 is 3.0E-11 ms^{-1}, which gives an adequate fit to the observed Pi01 data and a very good fit to the DST sequence. To achieve a better fit of the late time response of Pi01 would require an inconsistently high formation pressure or a hydraulic conductivity of perhaps 2.5E-11 ms^{-1}. However, an improved fit of the late time response can only be achieved by deterioration of the early-time fit. Figure 5.4 shows the simulated response for a specific storage of 2.0E-06 m^{-1} and the same range of hydraulic conductivities, 1.0E-11 to 1.0E-10 ms^{-1}. In this case, the best-fit hydraulic conductivity is about 1.0E-11 ms^{-1}, which provides a better fit to the measured Pi01 response but a poorer fit to the Pw01 response when compared to the best-fit simulation from Figure 5.3. The underestimation of the simulated response to Pw01 shown in Figure 5.4 is similar to results from the surrounding H-log test interpretations. A comparison of Figures 5.3 and 5.4 indicates that by varying the specific storage one order of magnitude the best-fit hydraulic conductivity changes by approximately one half of an order of magnitude. This sensitivity is similar to that found in surrounding intervals of similar hydraulic conductivity.

The best-fit formation parameters for the interval are considered to be a hydraulic conductivity of 1.0E-11 ms^{-1} and a specific storage of 2.0E-06 m^{-1} based on the better Pi01 fit. However, due to the lack of information available to determine a unique specific storage value it must be concluded that this interval has a hydraulic conductivity between 1.0E-11 and 3.0E-11 ms^{-1} and a specific storage between 2.0E-06 and 2.2E-07 m^{-1}.

6. RESULTS

Hydrogeologic interpretations were performed on all analyzable tests in the crystalline portion of the Leuggern borehole. Representative formation pressures were determined from 13 tests for 12 separate test intervals (tests 850.0SI and 850.0SII tested the same interval). Hydraulic conductivities were estimated from 83 tests for 81 separate test intervals (850.0SII and 1125.1HII were retests).

6.1 Formation Pressures and Equivalent Freshwater Heads

Representative formation pressures were determined from the following tests:

217.9S	Buntsandstein/Biotite-gneiss
251.3S	Biotite-gneiss
444.2S	Biotite-gneiss
676.8H	Biotite-gneiss
696.2H	Biotite-gneiss
705.7S	Biotite-gneiss
850.0SI	Biotite-gneiss
850.0SII	Biotite-gneiss
854.7S	Biotite-gneiss
912.5S	Biotite-gneiss
1643.4S	Granite
1665.5S	Granite
1676.4S	Granite

Equivalent freshwater heads were calculated for these intervals from the formation pressures utilizing a freshwater density of 1000 kgm^{-3}. The formation pressures and equivalent freshwater heads are summarized in Table 6.1. The formation pressures are plotted in Figure 6.1 and the equivalent freshwater heads are plotted in Figure 6.2 The calculated equivalent freshwater head is approximately 363 m ASL near the top of the crystalline and 356 m ASL at the bottom of the borehole.

The important factors which may affect the interpretation of the in-situ formation pressure from the measured pressure response during testing include: borehole pressure history, thermally-induced pressure effects, testing procedures, and non-ideal formation conditions. The influence of borehole pressure history and thermal effects has been discussed along with other factors in Section 4.2. In general, the determination of formation pressure is possible in intervals which have a short borehole history period between drilling and testing and which have high hydraulic conductivities.

Test 1676.4S yields a formation pressure and equivalent freshwater head outside of the general trend and must be carefully considered with respect to its representativeness. The test was conducted in a zone of high hydraulic conductivity (1.0E-06 ms^{-1}) and displays a fairly short history period (about 12 days). The 12 day history period should be of minor significance given the very high permeability of this interval. Since the simulation for this test sequence achieved a very good fit of the shut-in recovery pressures, the low formation pressure and corresponding freshwater head are reported with confidence.

6.2 Formation Hydraulic Conductivities, Specific Storages, and Temperatures

Hydraulic conductivities were obtained for test intervals over the complete depth range of the crystalline rock intersected in the Leuggern borehole with the exception of 227.50 to 237.92 m depth. Table 6.2 summarizes the estimated hydraulic conductivity, the estimated specific storage, and the borehole temperature at the end of the testing determined from each analyzable hydraulic test. Hydraulic conductivities are plotted in Figure 6.3.

Interpreted hydraulic conductivities ranged from less than 1.0E-13 to 1.5E-06 ms^{-1}. Zones of high hydraulic conductivity (greater than 1.0E-08 ms^{-1}) were observed at the following true vertical depths:

- 208 - 267 m (217.9S to 251.3S)
- 440 - 485 m (444.2S to 474.6H)
- 506 - 566 m (538.0S)
- 679 - 704 m (696.2H to 705.7S)
- 818 - 851 m (837.8H to 850.0SII)
- 1584 - 1632 m (1643.4S to 1676.4S)

These high K zones appear to correlate with major fracture zones identified by Geotest (1985) which are summarized in Section 2.0 of this report. Successful retests were performed on 3 intervals, 850.0SII, 1125.1HII, and 1149.8HII, in an attempt to substantiate less certain pressure responses observed in the initial tests. A fourth retest, 1603.5HII, was performed after the initial test was aborted.

The hydraulic conductivity of less than 1.0E-13 ms^{-1}, determined for test 1283.8H, was significantly lower than adjacent zones as well as being lower than all other test intervals. The pressure response during 1283.8H was apparently affected by problems with the test tool, although a retest was not performed to confirm this. However, the hydraulic conductivity for this zone, reported as 2.0E-14 ms^{-1} in the Appendix, is still considered to be very low.

The important factors which may affect the testing interpretation for hydraulic conductivity include: borehole pressure history, thermal effects, testing procedures, estimation of formation pressure, estimation of specific storage, and non-ideal formation conditions. Most of these factors have been addressed previously in Sections 4.2 and 4.3. The sum of all factors affecting the measured pressure response is considered to produce some uncertainty in the interpreted hydraulic conductivity values. The amount of uncertainty is related to the formation permeability, with more permeable zones being less affected by such factors as history pressure and thermal effects. For intermediate to low permeability zones, uncertainty may be as much as ± one order of magnitude.

The base case specific storage value of 2.2E-07 m^{-1} was assumed for most test intervals, unless a significant improvement in fit between the measured and simulated pressure responses warranted a different value.

Temperatures measured at the end of testing in each interval were assumed to be representative of the tested interval. The temperatures were used in determining temperature-dependent fluid parameters. However, the temperature transducers were located above the packed-off interval (approximately 5.8 m above the top of the interval) and therefore measure the temperature in the borehole location of the hydrologic test tool (i.e., sensor carrier) and not the temperature in the interval. The measured temperature in the borehole ranged from about 19°C at the top of the crystalline rock to about 66°C at the bottom of the borehole. The temperature increased approximately linearly with depth at a gradient of approximately 3.4°C/100 m.

The measured temperatures should be used with caution since they are not necessarily representative of undisturbed formation conditions. Comparison with other measurements from temperature logging is necessary to develop an in-situ temperature profile.

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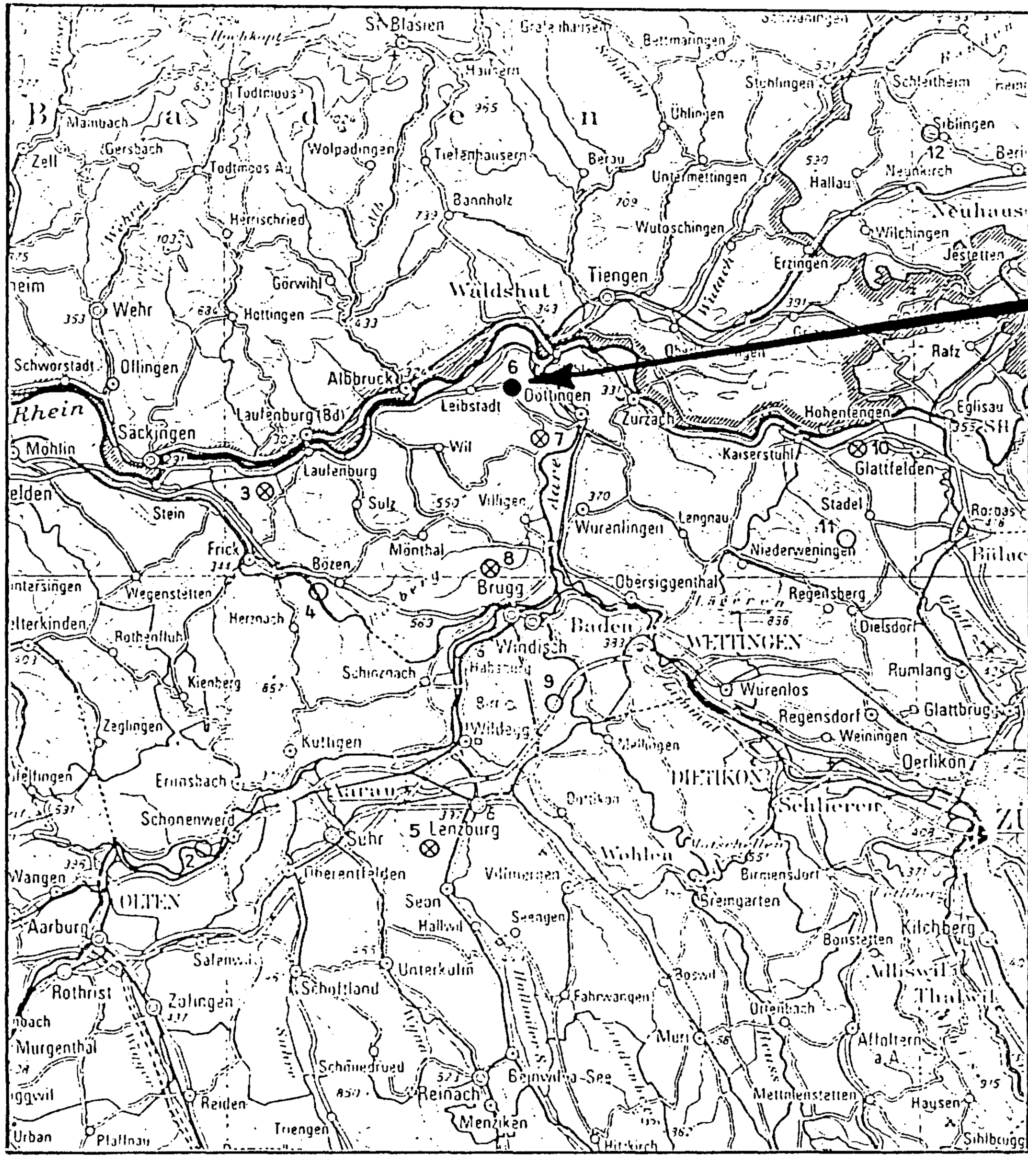


Borehole		Depth
○ 1	HAEGENDORF	ca 2400 m
○ 2	NIEDERGOESGEN	ca 2250 m
⊗ 3	KAISTEN	1306 m
○ 4	HORNUSSEN	ca 1600 m
⊗ 5	SCHAFISHEIM	2006 m
● 6	LEUGGERN	1689 m
⊗ 7	BOETTSTEIN	1501 m
⊗ 8	RIKINEN	1801 m
○ 9	BIRRHARD	ca 2350 m
⊗ 10	WEIACH	2482 m
○ 11	STEINMAUR	ca 2500 m
○ 12	SIBLINGEN	ca 1450 m

LEGEND

○ Borehole

⊗ Borehole Completed

Figure 1.1: Leuggern Borehole Location

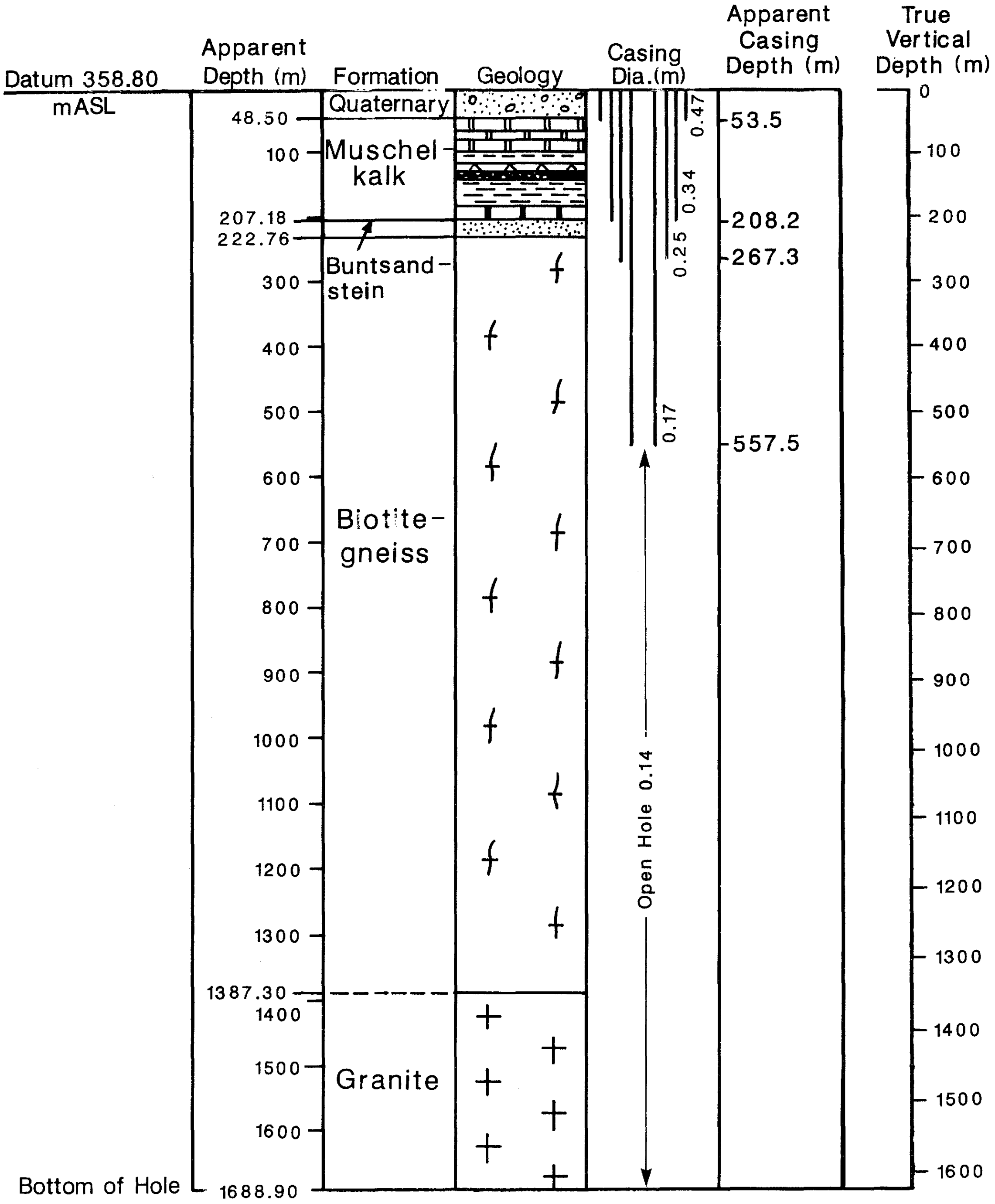


Figure 2.1: Leuggern Borehole Geology

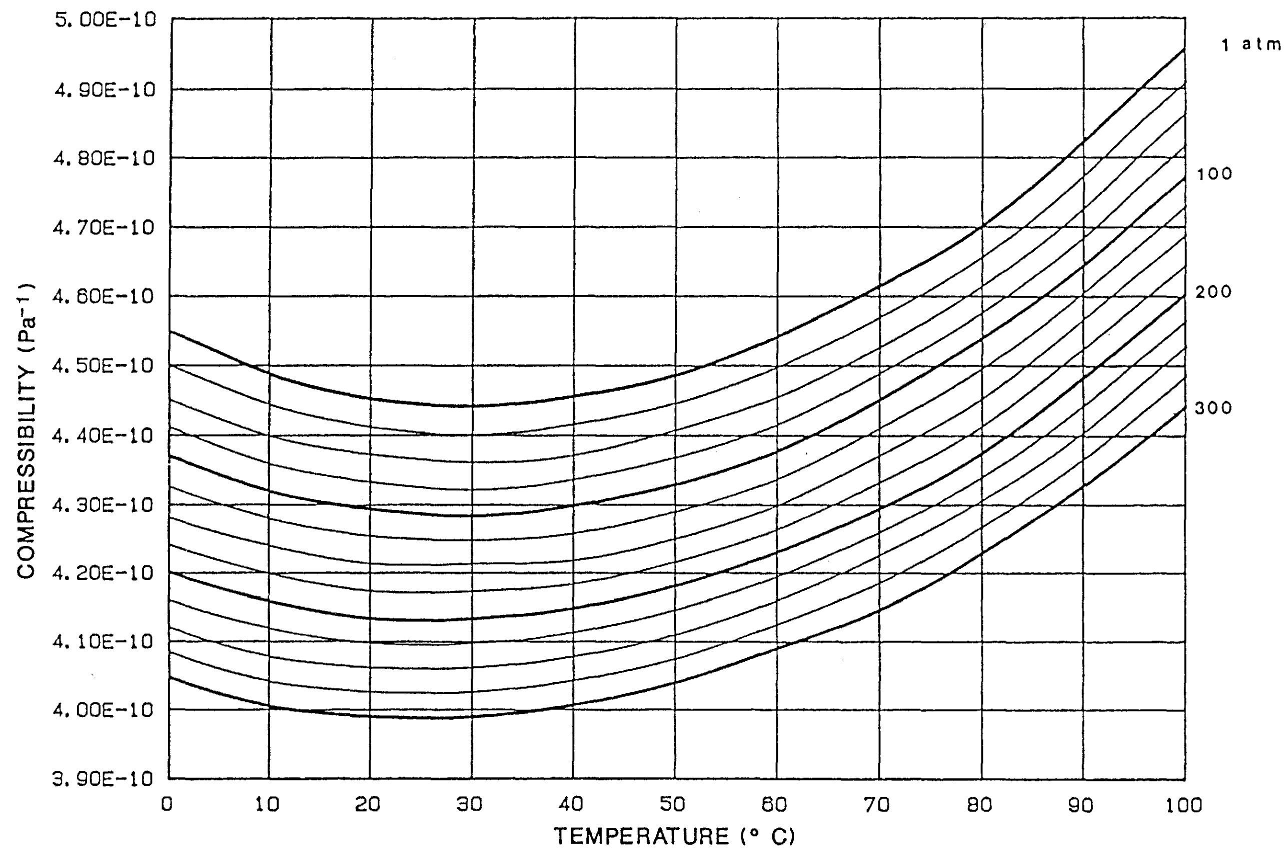


Figure 4.1: Fluid Compressibility: Variation with Temperature and Pressure

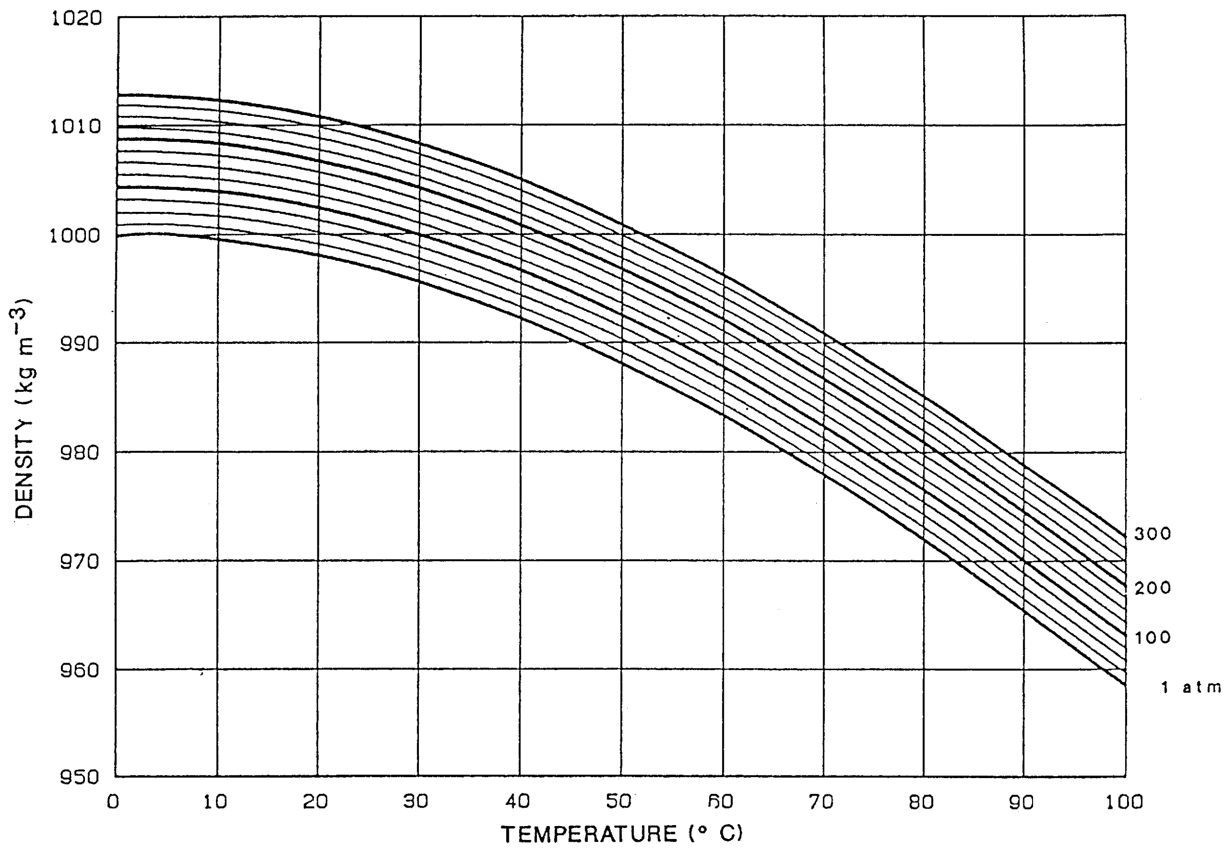


Figure 4.2: Fluid Density: Variation with Temperature and Pressure

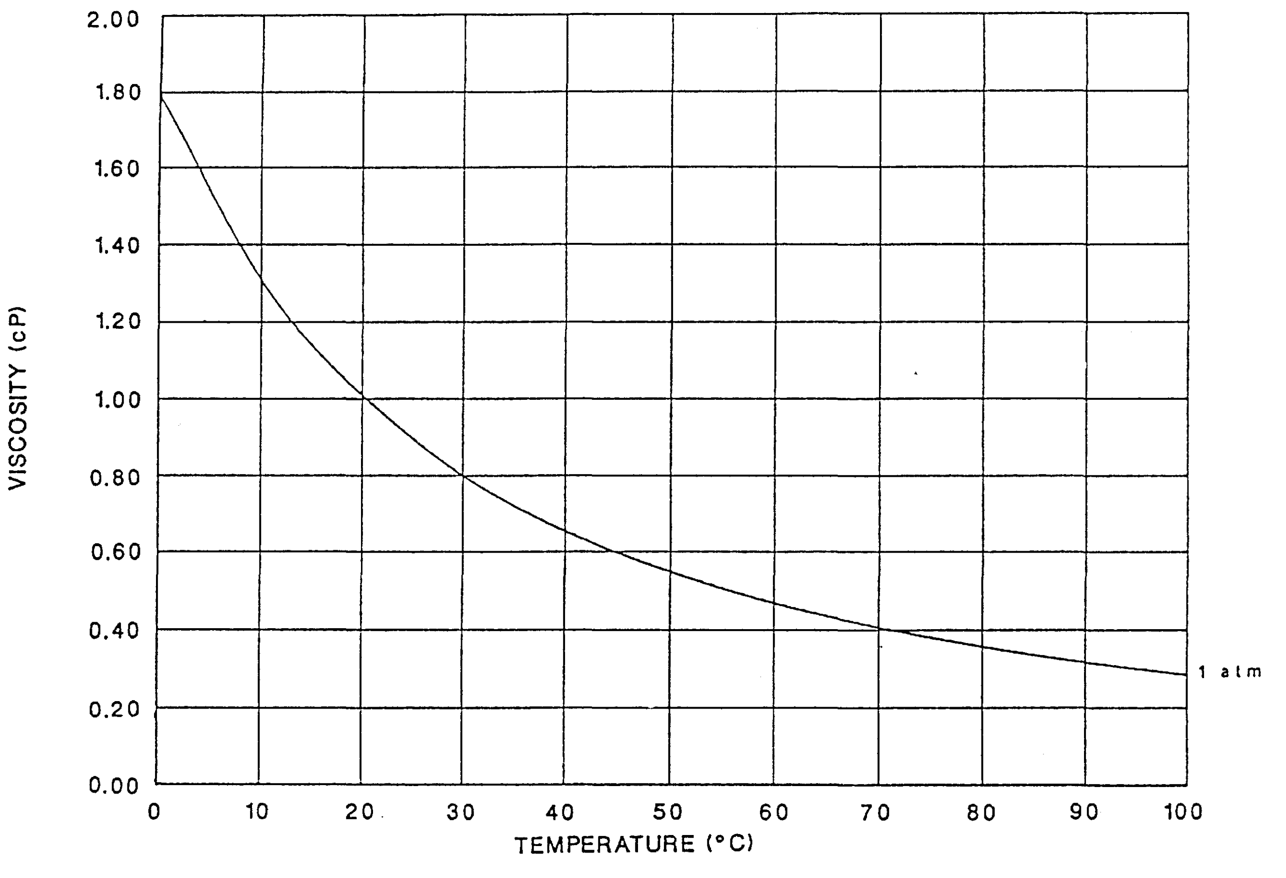


Figure 4.3: Fluid Viscosity: Variation with Temperature

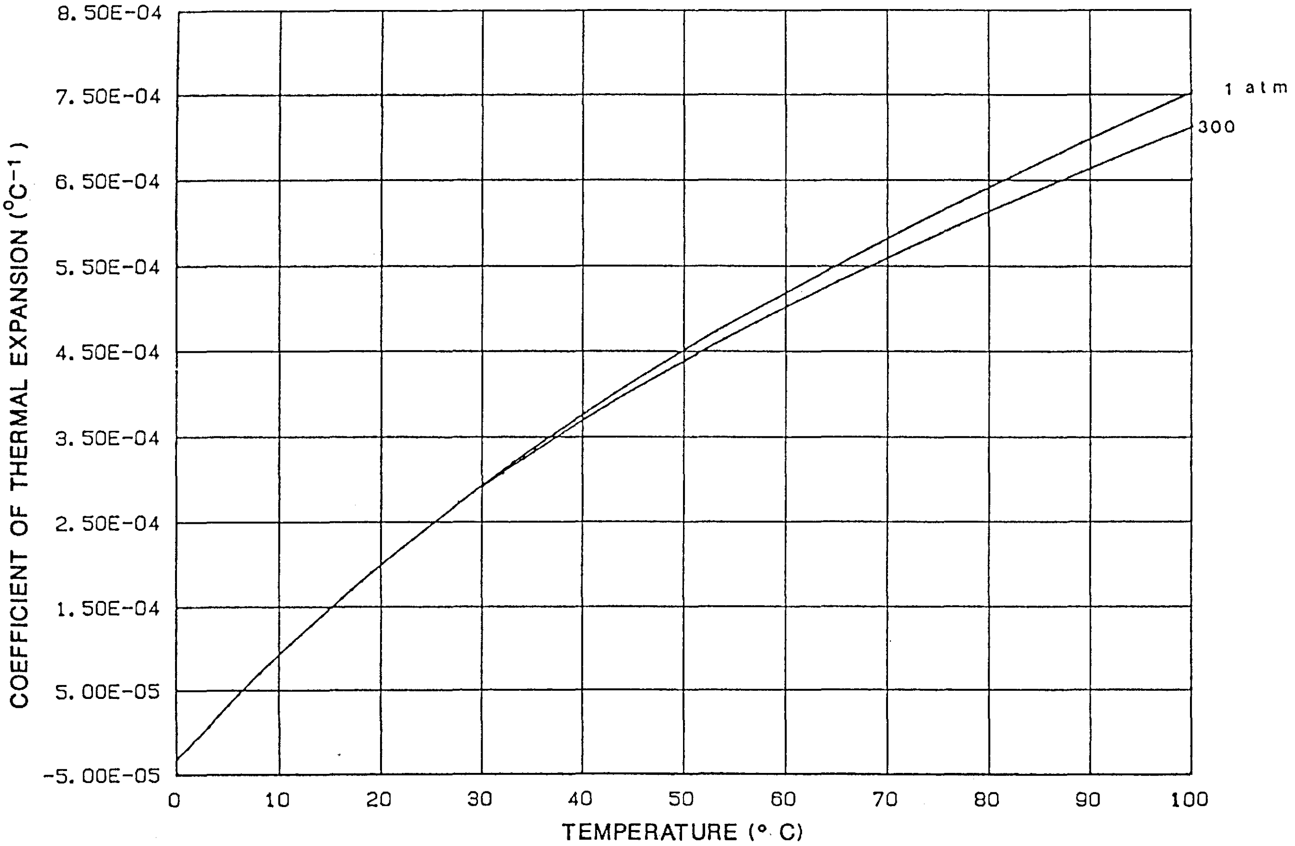


Figure 4.4: Fluid Coefficient of Thermal Expansion: Varation with Temperature and Pressure

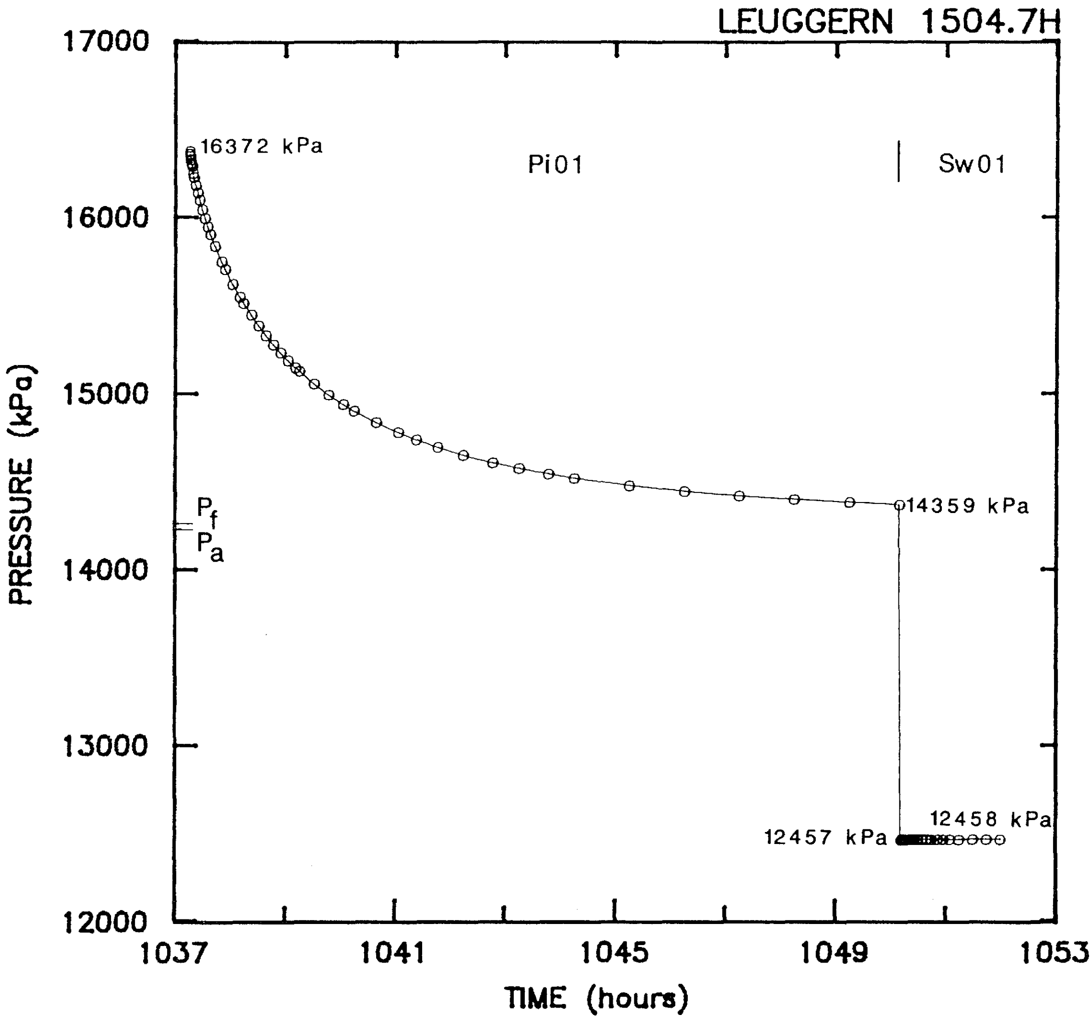


Figure 4.5: Measured Pressure Data for Test Interval 1504.7H, Test Sequence Designations, and Starting and Ending Pressures for Each Sequence

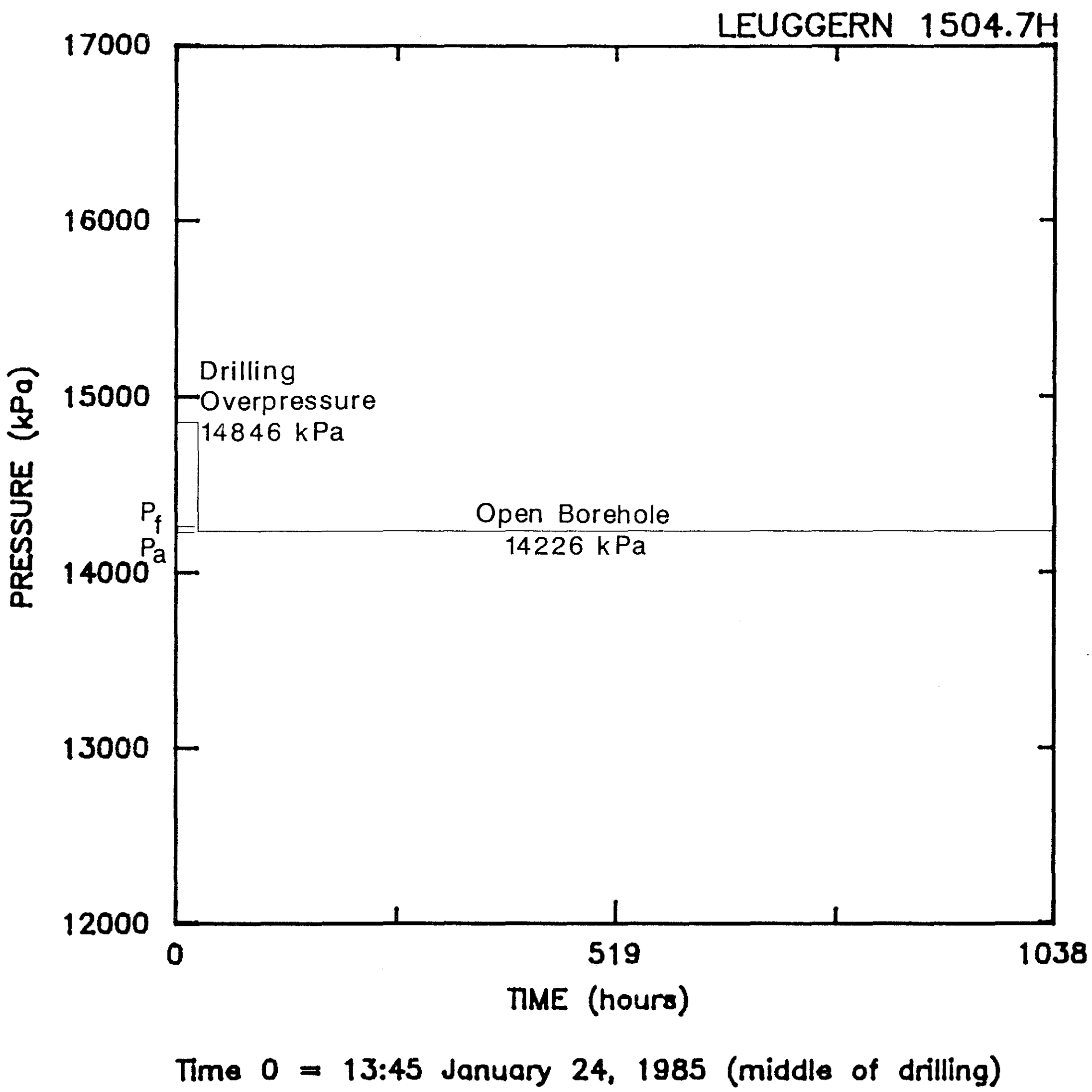


Figure 4.6: Assumed Pressure History on Test Interval 1504.7H From Mid-Point of Drilling

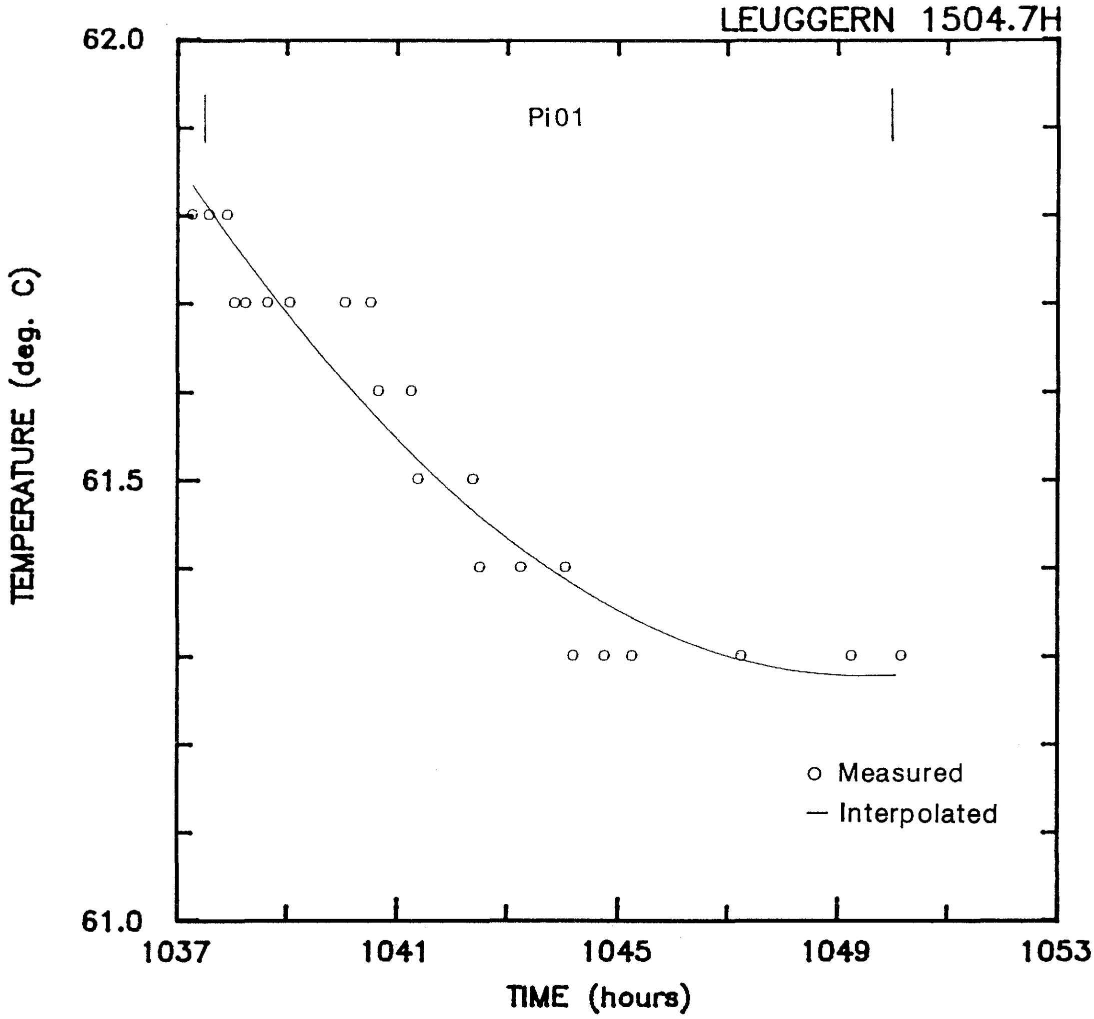


Figure 4.7: Measured and Interpolated Data of the T2 Temperature Transducer for Test 1504.7H

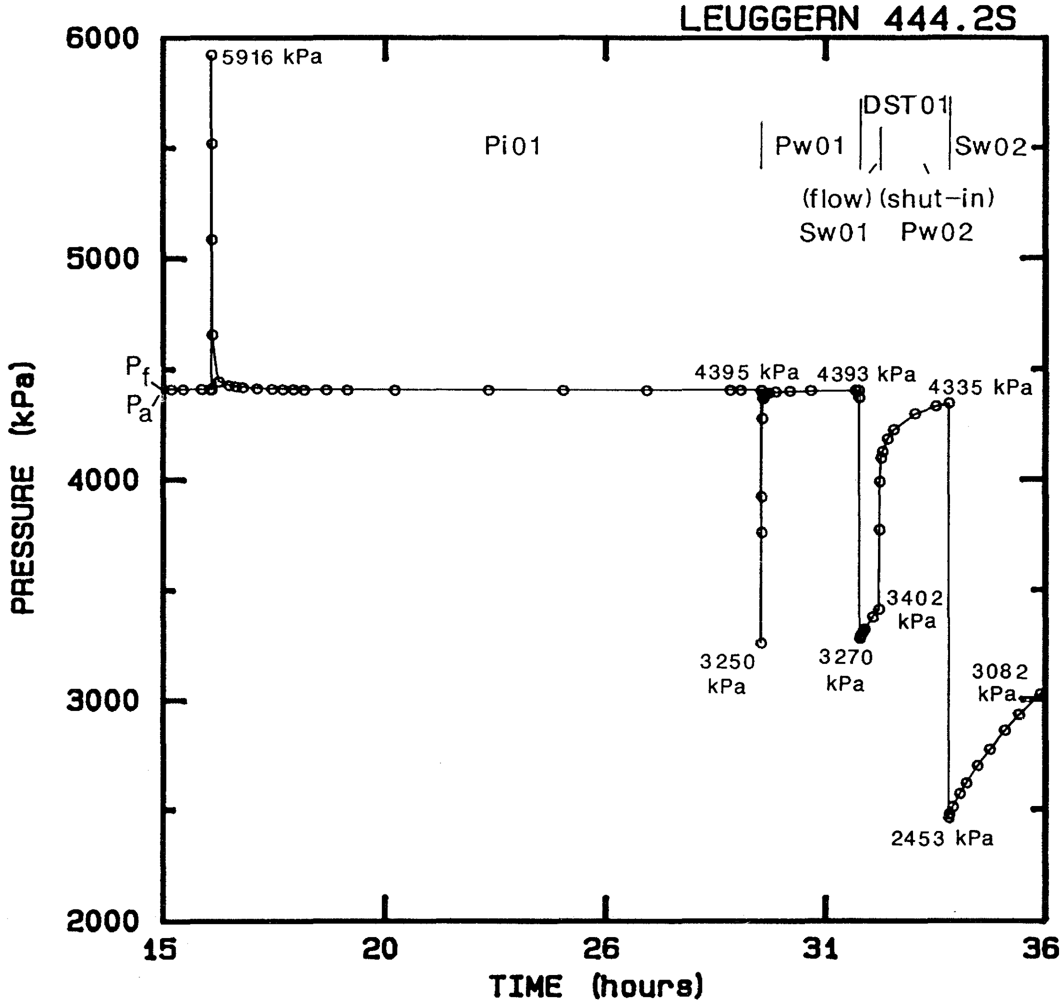


Figure 4.8: Measured Pressure Data for Test Interval 444.2S, Test Sequence Designations, and Starting and Ending Pressures for Each Sequence

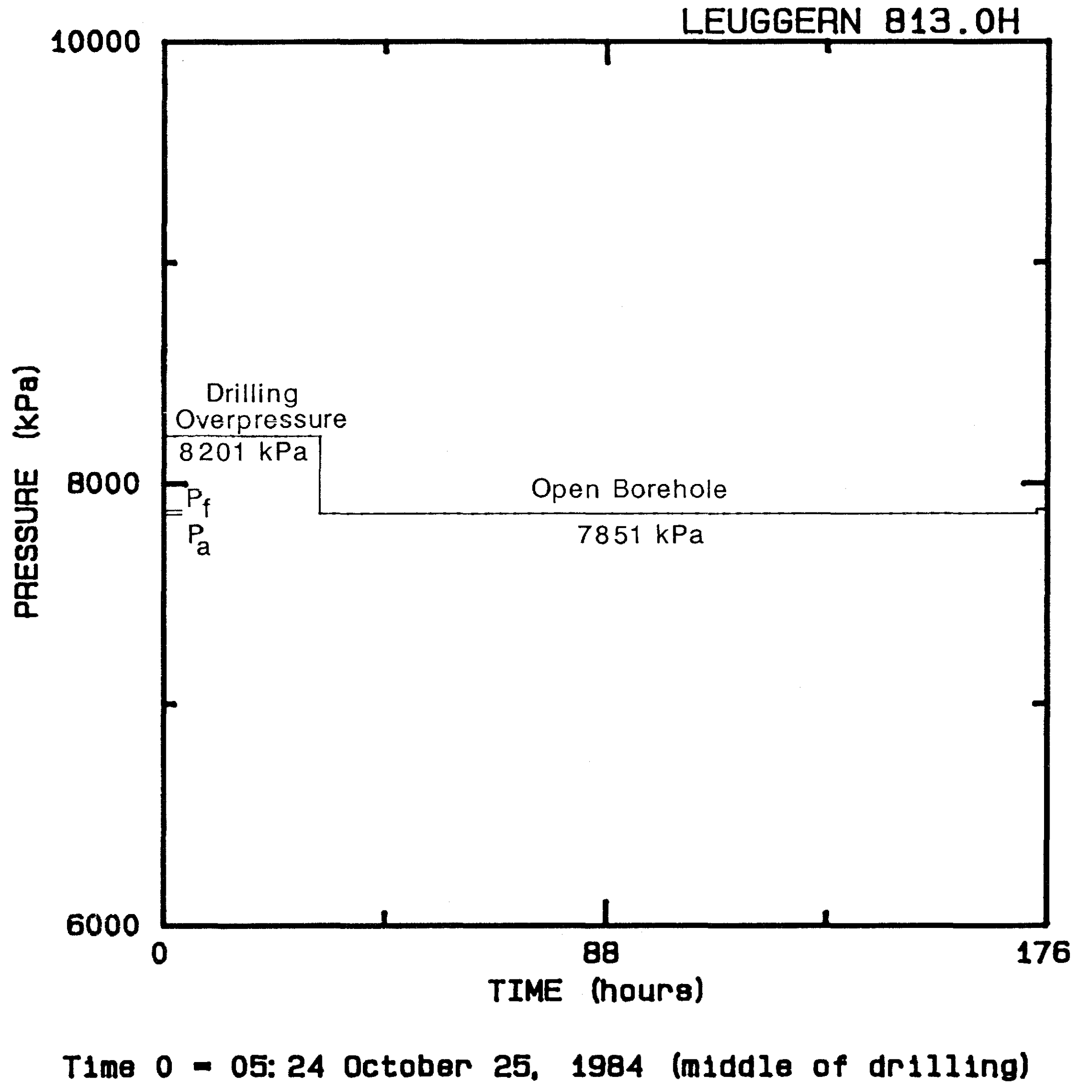


Figure 5.1: Assumed Pressure History on Test Interval 813.0H From Mid-Point of Drilling

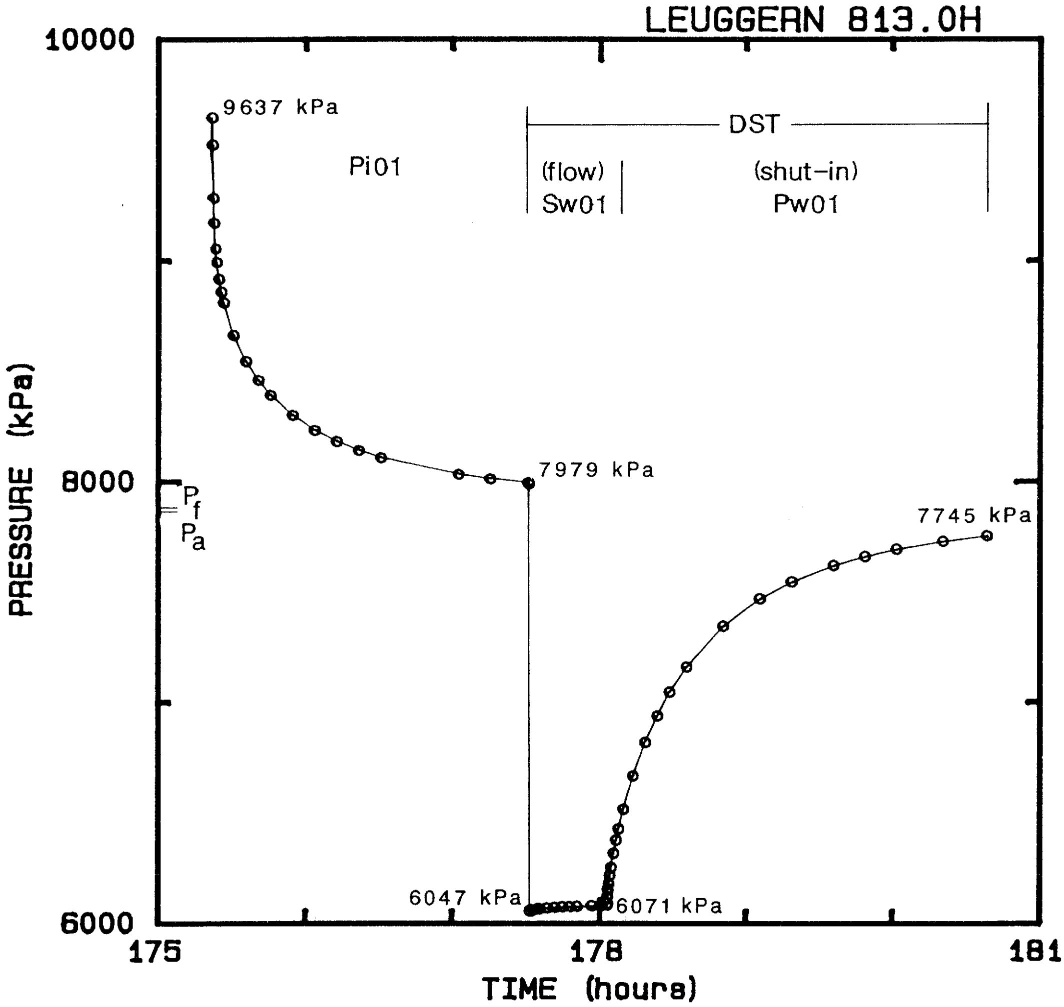


Figure 5.2: Measured Pressure Data for Test Interval 813.0H, Test Sequence Designations, and Starting and Ending Pressures for Each Sequence

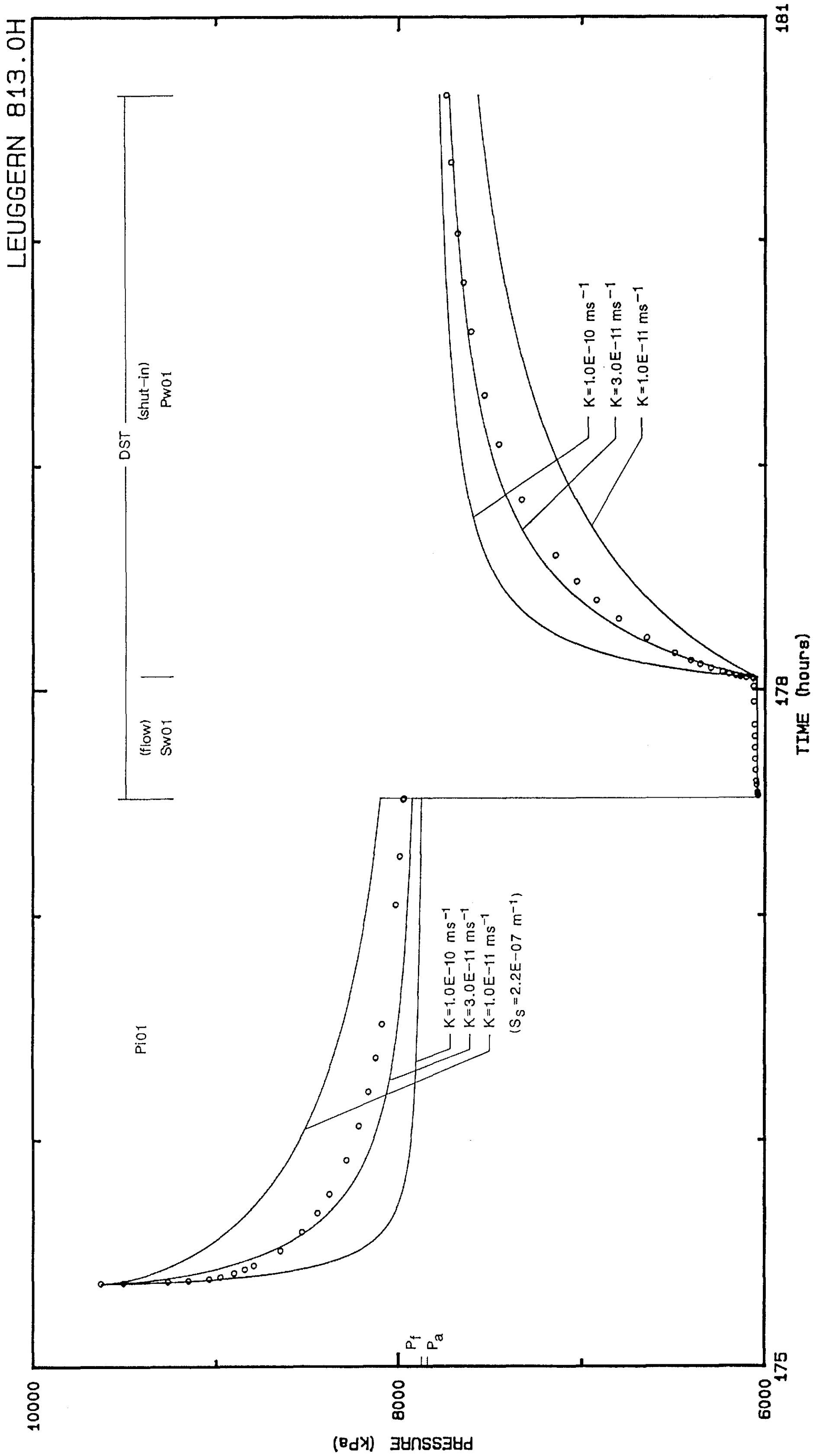


Figure 5.3: Measured (o) and Simulated Pressure Response for the Testing Sequence at 813.0H; Specific Storage of 2.2E-07 m-1

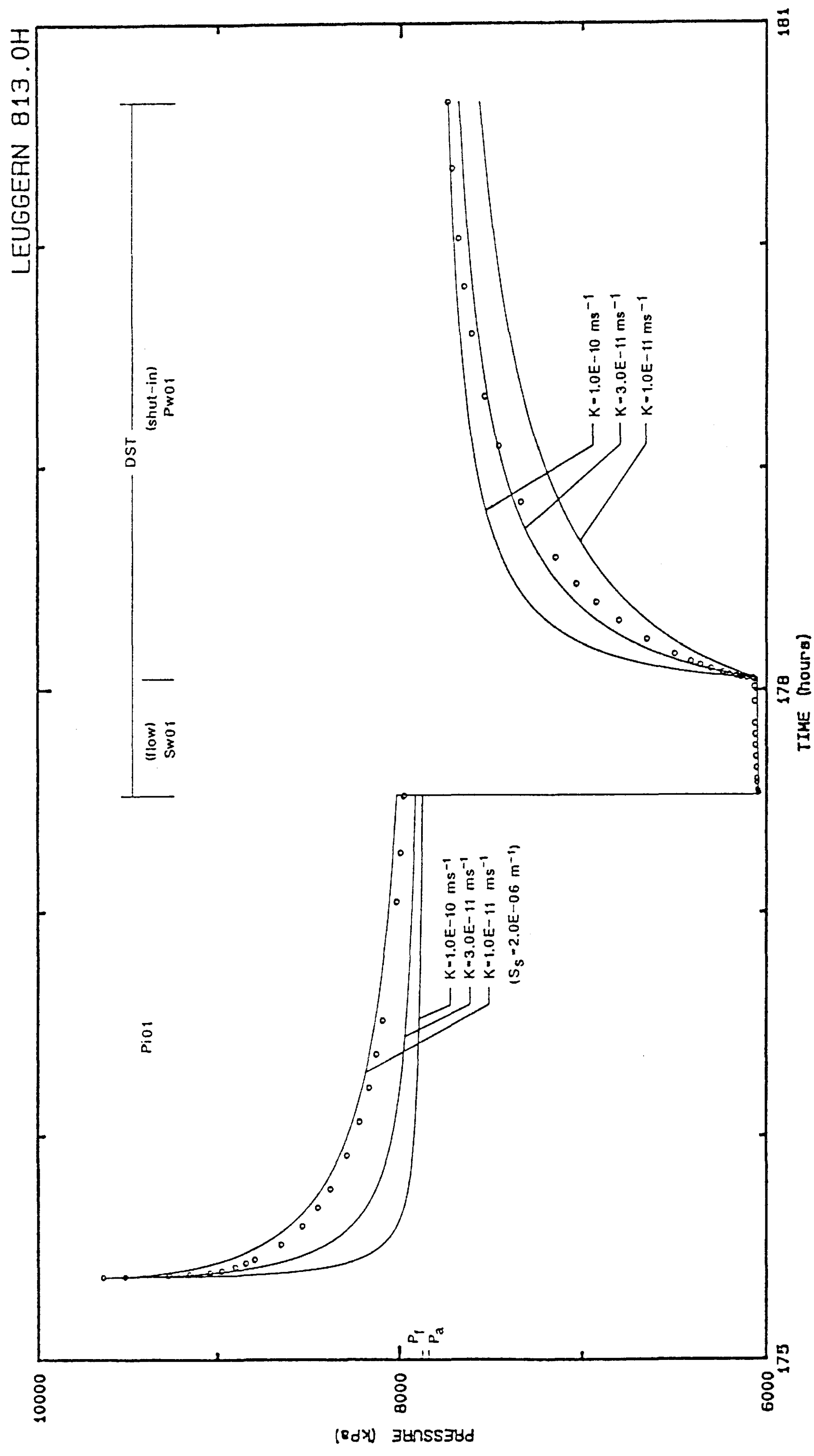


Figure 5.4: Measured (o) and Simulated Pressure Response for the Testing Sequence at 813.0H; Specific Storage of 2.0E-06 m-1

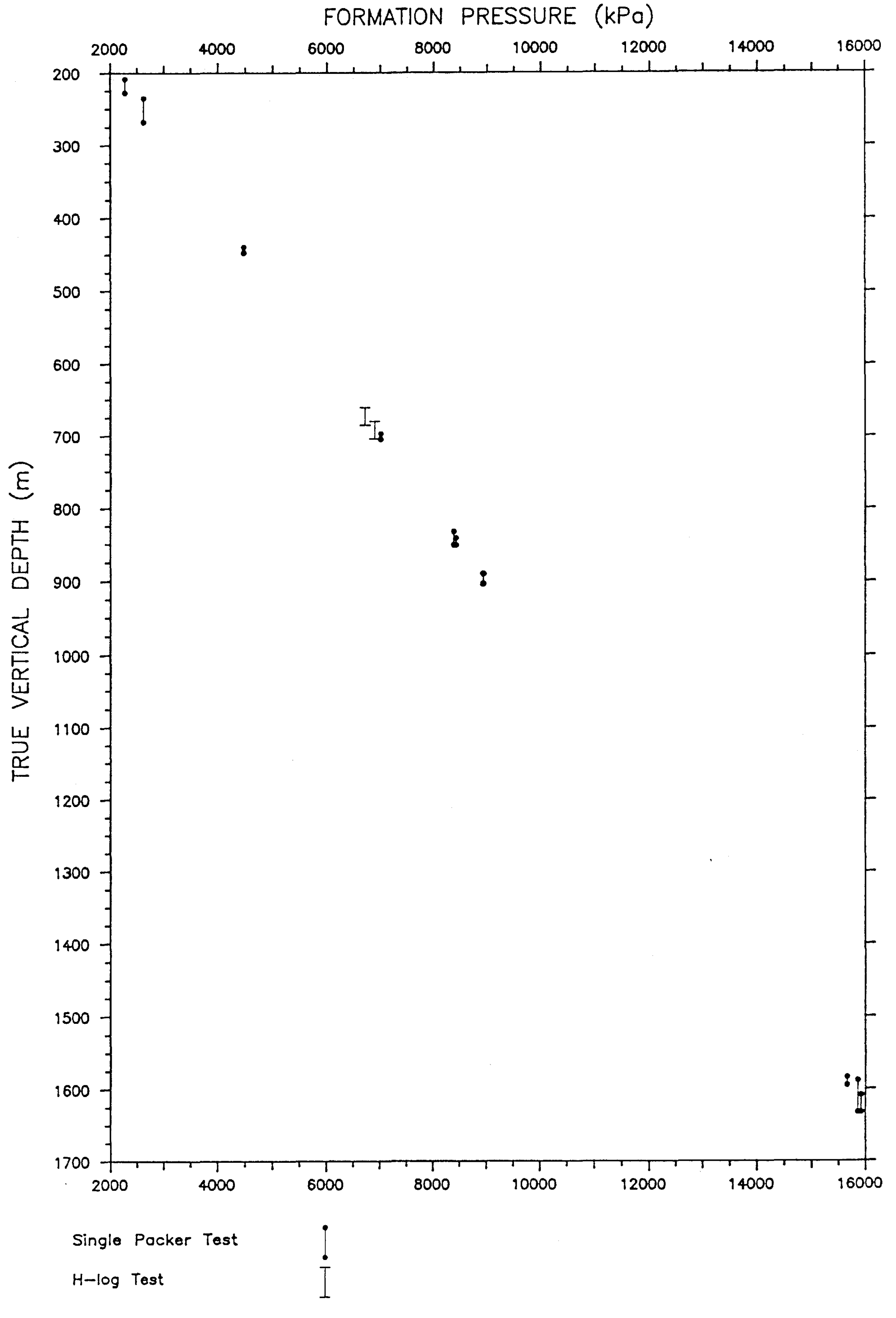


Figure 6.1: Estimated Formation Pressures From Hydraulic Testing at the Leuggern Borehole

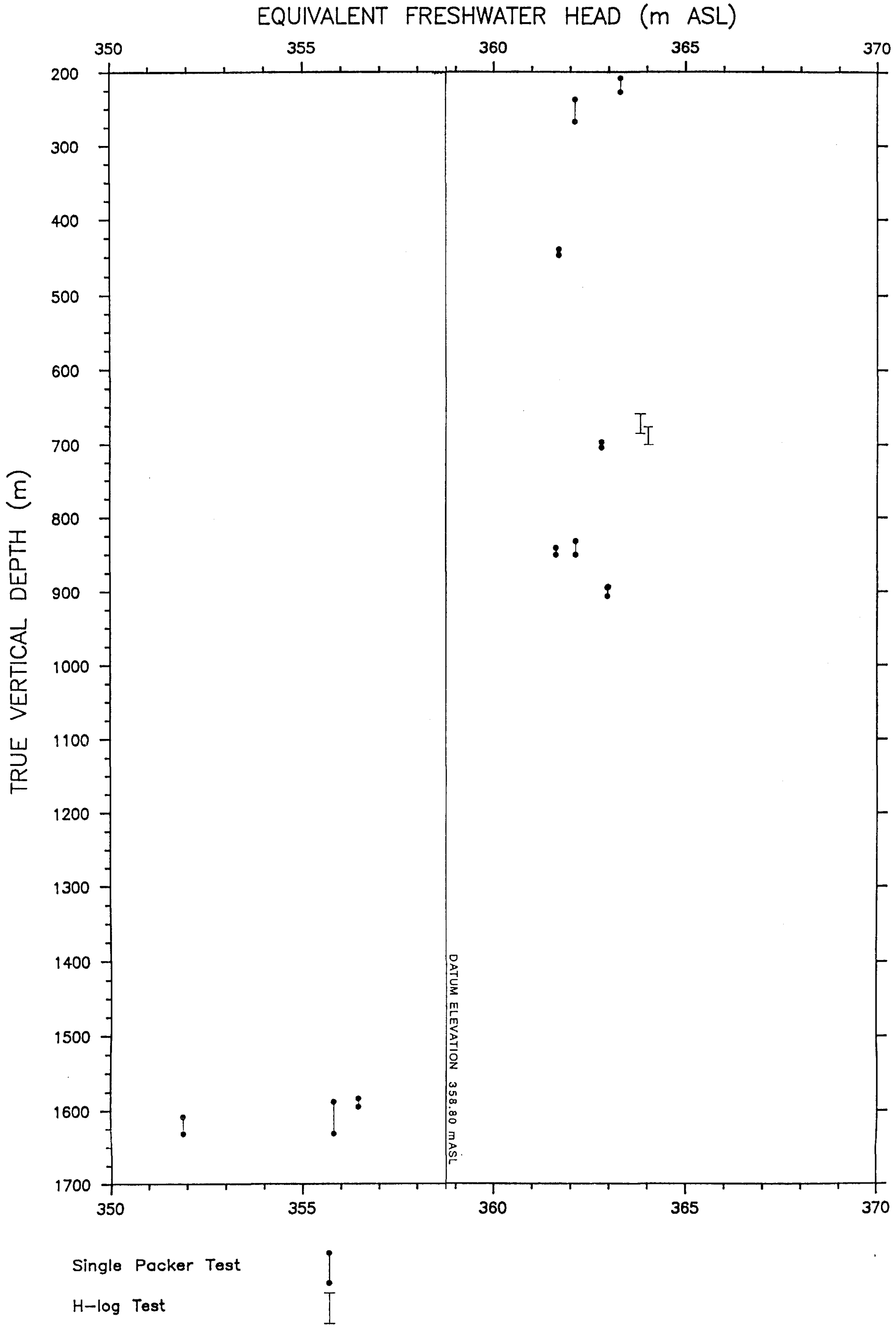


Figure 6.2: Estimated Equivalent Freshwater Heads From Hydraulic Testing at the Leuggern Borehole

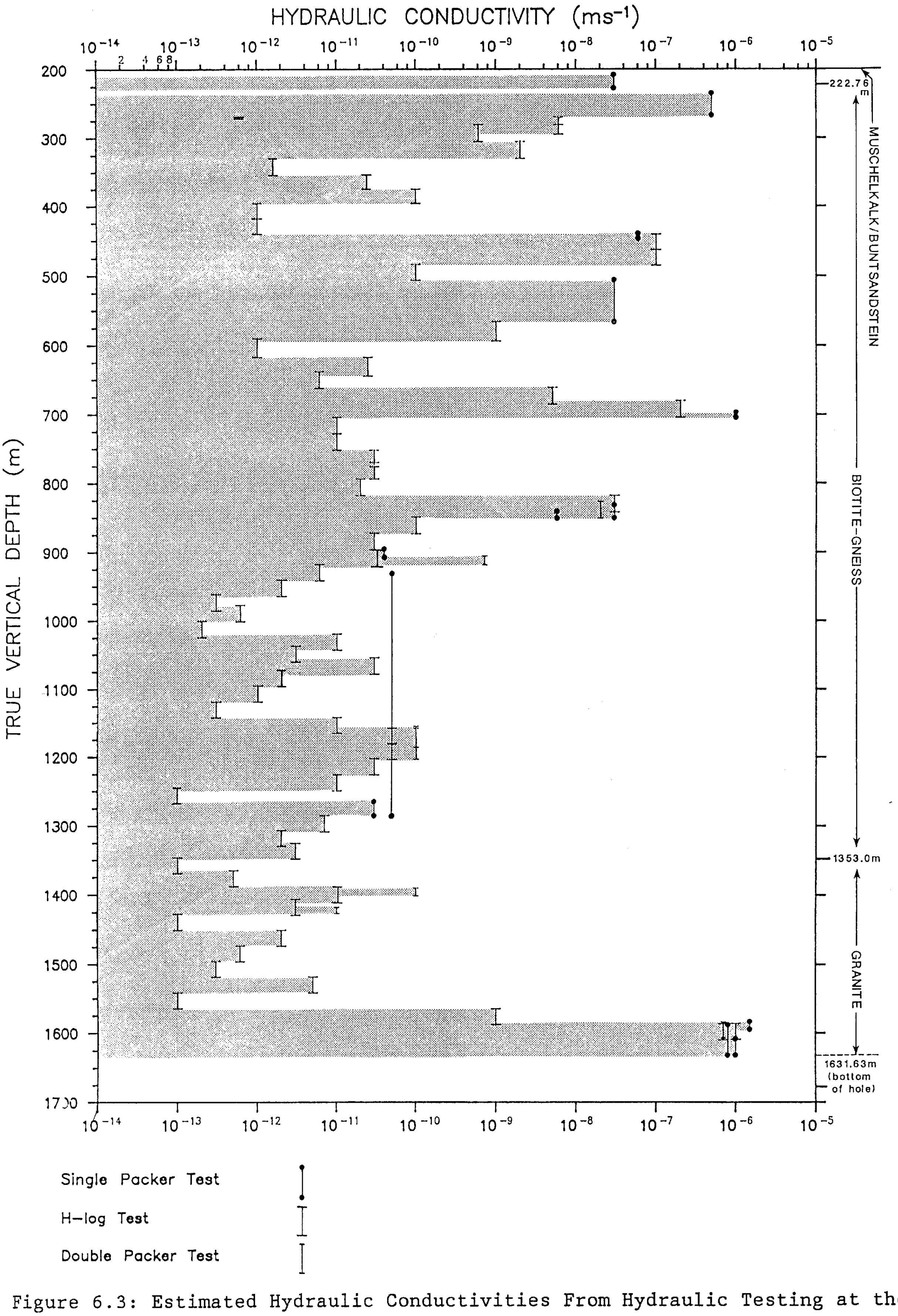


Figure 6.3: Estimated Hydraulic Conductivities From Hydraulic Testing at the Leuggern Borehole

Drilling Overpressure (3 day constant pressure period)	Estimated 99%-Pressure Dissipation Period (days) for a Formation Hydraulic Conductivity of K = 1.0E-07 ms^{-1} (Slug test)	1.0E-12 ms^{-1} (Pulse test)
2000 kPa	13	22
1500 kPa	11	20
1000 kPa	10	19
500 kPa	9	18
200 kPa	9	18

Test Conditions:

Fluid density	999.0 kgm^{-3}
Fluid compressibility	4.37E-10 Pa^{-1}
Medium compressibility	2.0E-11 Pa^{-1}
Effective porosity	0.005
Specific storage	2.2E-7 m^{-1}
Test interval length	22.68 m
Casing (tubing) string diameter	0.101 m
Borehole diameter	0.15 m

Estimated Dissipation Period (in days) at Full Annulus Pressure for Various Amounts of Drilling Overpressure

Table 4.1

Test Type and Designation: **H-log 1504.7H**

Geology of test interval: Granite

Formation: Crystalline

Fractures: Average 10 per meter, with 25% of the fractures open. Mild kakiritization observed in the core.

Borehole fluid: Traced de-ionized water

Drilled borehole diameter in test interval: 140 mm

Average borehole diameter from caliper: 141 mm (26 February, 1985)

Test interval length: 24.97 m

Apparent depth of test interval: 1492.24 m to 1517.21 m

True vertical depth of test interval: 1449.38 m to 1472.41 m

Apparent depth to center of test interval: 1504.72 m

True vertical depth to center of test interval: 1460.88 m

Apparent depth to pressure transducer P2: 1487.16 m

True vertical depth to pressure transducer P2: 1444.69 m

Datum elevation at ground surface: 358.80 m ASL

Barometric pressure: 103.1 kPa

Inside diameter of tubing string: 62.0 mm

Annulus pressure at transducer P3: 14226 kPa

Packer inflation pressure above annulus pressure: 8000 kPa

Drilling period of test interval (estimate):
10:55, 23 January, 1985 to 16:35, 25 January, 1985
Mid-point: 13:45, 24 January, 1985

Testing Period: 18:11, 08 March, 1985 to 09:45, 09 March, 1985

Test designations and start times:

PiO1 19:01:26, 08 March, 1985
SwO1 07:54:40, 09 March, 1985

Time between middle of drilling and start of testing: 43.2 days

Temperature at probe: start of first test: 61.8°C
end of testing: 61.4°C

Physical Description of the Geology and
Testing Conditions at 1504.7H

Table 4.2

Test Type and Designation: **H-log 1504.7H**

Formation		
Compressibility	2.0E-11	Pa^{-1}
Porosity	0.005	
Specific Storage	2.2E-07	m^{-1}
Fluid		
Compressibility (at formation temperature and pressure)	4.32E-10	Pa^{-1}
Density (at formation temperature and pressure)	989	kgm^{-3}
Thermal Expansion Coefficient	5.2E-04	$°C^{-1}$
Test Interval		
Length	24.97	m
Diameter (caliper)	0.141	m
Annulus Pressure	14226	kPa
Formation Pressure (calibrated)	not applicable	
Formation Pressure (assumed)	14260	kPa
Conditions of Analysis		
Borehole Pre-Test Pressure History		yes
Thermal Effects		yes

Parameters Used for Simulation of the Test Interval Pressure Response at 1504.7H

Table 4.3

Test Type and Designation: **H-log 813.0H**

Geology of test interval: Biotite-gneiss

Formation: Crystalline

Fractures: Average 12 per meter, with 75 percent of these being open. No kakiritization evident in core.

Borehole fluid: Traced de-ionized water

Drilled borehole diameter in test interval: 140 mm

Average borehole diameter from caliper: 155 mm (28 October, 1984)

Test interval length: 24.97 m

Apparent depth of test interval: 800.56 m to 825.53 m

True vertical depth of test interval: 793.41 m to 817.73 m

Apparent depth to center of test interval: 813.04 m

True vertical depth to center of test interval: 805.57 m

Apparent depth to pressure transducer P2: 795.48 m

True vertical depth to pressure transducer P2: 788.43 m

Datum elevation at ground surface: 358.80 m ASL

Barometric pressure: 102.7 kPa

Inside diameter of tubing string: 62.0 mm

Annulus pressure at transducer P3: 7851 kPa

Packer inflation pressure above annulus pressure: 8990 kPa

Drilling period of test interval (estimate):
22:17, 23 October, 1984 to 12:30, 26 October, 1984
Mid-point: 05:24, 25 October, 1984

Testing Period: 11:29, 01 November, 1984 to 18:03, 01 November, 1984

Test designations and start times:

PiO1 12:46:17, 01 November, 1984
SwO1 14:55:36, 01 November, 1984
PwO1 15:27:25, 01 November, 1984

Time between middle of drilling and start of testing: 7.3 days

Temperature at probe: start of first test: 38.0°C
end of testing: 37.9°C

Physical Description of the Geology and Testing Conditions at 813.0H

Table 5.1

Test Type and Designation: **H-log 813.0H**

Formation		
Compressibility	2.0E-10	Pa^{-1}
Porosity	0.005	
Specific Storage	2.0E-06	m^{-1}
Fluid		
Compressibility (at formation temperature and pressure)	4.32E-10	Pa^{-1}
Density (at formation temperature and pressure)	996	kgm^{-3}
Thermal Expansion Coefficient	not applicable	
Test Interval		
Length	24.97	m
Diameter (caliper)	0.155	m
Annulus Pressure	7851	kPa
Formation Pressure (calibrated)	not applicable	
Formation Pressure (assumed)	7870	kPa
Conditions of Analysis		
Borehole Pre-Test Pressure History	yes	
Thermal Effects	no	

Parameters Used for Simulation of the Test
Interval Pressure Response at 813.0H

Table 5.2

TEST DESIGNATION	TRUE INTERVAL CENTER DEPTH (m)	FORMATION PRESSURE AT CENTER OF INTERVAL (kPa)	EQUIVALENT FRESHWATER HEAD (m ASL)	ESTIMATED HYDRAULIC CONDUCTIVITY (ms^{-1})	LENGTH OF BOREHOLE HISTORY PERIOD (Days)
217.9S	217.86	2282	363.3	3.0E-08	0.7
251.3S	252.68	2611	362.1	5.0E-07	2.1
444.2S	443.42	4482	362.0	6.0E-08	0.7
676.8H	672.51	6746	363.8	5.0E-09	19.8
696.2H	691.45	6933	363.9	2.0E-07	18.3
705.7S	700.76	7014	362.8	1.0E-06	0.7
850.0SI	841.51	8388	362.1	3.0E-08	1.2
850.0SII	841.51	8388	362.1	3.0E-08	2.1
854.7S	846.11	8428	361.6	6.0E-09	2.0
912.5S	902.10	8983	363.0	4.0E-11	1.5
1643.4S	1589.23	15663	356.5	1.5E-06	1.2
1665.5S	1609.86	15859	355.8	≥8.0E-07	70.0
1676.4S	1619.98	15918	351.9	1.0E-06	11.9

SUMMARY OF FORMATION PRESSURES AND EQUIVALENT FRESHWATER HEADS DETERMINED FROM HYDRAULIC TESTING IN THE LEUGGERN BOREHOLE

Table 6.1

TEST DESIGNATION	TRUE INTERVAL TOP DEPTH (m)	TRUE INTERVAL BOTTOM DEPTH (m)	APPARENT INTERVAL TOP DEPTH (m)	APPARENT INTERVAL BOTTOM DEPTH (m)	INTERVAL LENGTH (m)	ESTIMATED HYDRAULIC CONDUCTIVITY (m/s)	ESTIMATED SPECIFIC STORAGE (1/m)	TEMPERATURE AT END OF TESTING (deg. C)	THERMAL EFFECTS INCLUDED in GTFM
217.9S	208.22	227.50	208.22	227.50	19.28	3.0E-08	2.2E-07	22.1	no
251.3S	237.92	267.44	237.92	267.45	29.53	5.0E-07	2.2E-07	19.4	no
267.8H	267.30	268.34	267.30	268.34	1.04	6.0E-13	2.2E-07	19.8	no
273.8H	267.30	280.31	267.30	280.32	13.02	≤6.0E-09	2.2E-07	20.2	no
281.7H	269.30	294.07	269.30	294.12	24.82	6.0E-09	2.2E-07	20.4	no
292.5H	280.07	304.89	280.08	304.90	24.82	6.0E-10	2.2E-07	20.6	no
317.1H	304.60	329.35	304.65	329.47	24.82	2.0E-09	2.2E-07	21.2	no
341.6H	329.11	353.86	329.22	354.04	24.82	1.5E-12	2.2E-07	21.7	no
364.0H	352.94	374.53	353.12	374.79	21.67	3.0E-11	2.2E-07	21.5	no
385.4H	374.27	395.81	374.53	396.20	21.67	≤1.0E-10 (1)	4.1E-08	21.9	no
407.3H	395.55	418.07	395.94	418.62	22.68	1.0E-12	2.2E-07	23.3	no

(1) wellbore damage; formation may be of lower permeability.

Table 6.2: Summary of Hydraulic Conductivities, Specific Storage, and Temperatures Determined from Hydraulic Testing in the Leuggern Borehole

TEST DESIGNATION	TRUE INTERVAL TOP DEPTH (m)	TRUE INTERVAL BOTTOM DEPTH (m)	APPARENT INTERVAL TOP DEPTH (m)	APPARENT INTERVAL BOTTOM DEPTH (m)	INTERVAL LENGTH (m)	ESTIMATED HYDRAULIC CONDUCTIVITY (m/s)	ESTIMATED SPECIFIC STORAGE (1/m)	TEMPERATURE AT END OF TESTING (deg. C)	THERMAL EFFECTS INCLUDED in GTFM
429.7H	417.82	440.30	418.37	441.05	22.68	1.0E-12	2.2E-07	24.0	no
444.2S	439.61	447.24	440.35	448.05	7.70	6.0E-08	2.2E-07	24.3	no
452.1H	440.05	462.46	440.80	463.48	22.68	1.0E-07	2.3E-08	25.0	no
474.6H	462.23	484.59	463.24	485.92	22.68	1.0E-07	2.2E-07	25.3	no
496.0H	483.36	505.69	484.67	507.35	22.68	1.0E-10	2.2E-07	26.0	no
538.0S	505.69	566.12	507.35	568.60	61.25	3.0E-08	2.2E-07	26.9	no
581.9H	565.38	593.00	567.85	595.87	28.02	1.0E-09	2.2E-07	30.8	no
606.2H	589.40	616.99	592.22	620.24	28.02	1.0E-12	3.0E-07	31.6	no
634.0H	616.75	644.26	619.98	648.00	28.02	2.5E-11	2.2E-07	32.7	no
653.7H	637.54	662.04	641.18	666.15	24.97	6.0E-12	2.2E-07	33.1	yes
676.8H	660.28	684.72	664.35	689.32	24.97	5.0E-09	2.2E-07	34.3	no
696.2H	679.23	703.65	683.71	708.68	24.97	2.0E-07	2.2E-07	34.9	no
705.7S	697.12	704.41	702.00	709.45	7.45	1.0E-06	2.0E-06	33.6	no

Table 6.2: Summary of Hydraulic Conductivities, Specific Storage, and (cont'd) Temperatures Determined from Hydraulic Testing in the Leuggern Borehole

TEST DESIGNATION	TRUE INTERVAL TOP DEPTH (m)	TRUE INTERVAL BOTTOM DEPTH (m)	APPARENT INTERVAL TOP DEPTH (m)	APPARENT INTERVAL BOTTOM DEPTH (m)	INTERVAL LENGTH (m)	ESTIMATED HYDRAULIC CONDUCTIVITY (m/s)	ESTIMATED SPECIFIC STORAGE (1/m)	TEMPERATURE AT END OF TESTING (deg. C)	THERMAL EFFECTS INCLUDED in GTFM
721.0H	703.50	727.92	708.53	733.50	24.97	1.0E-11	2.0E-06	35.3	no
745.2H	727.13	751.54	732.69	757.66	24.97	1.0E-11	1.0E-06	36.0	no
769.9H	751.29	775.66	757.41	782.38	24.97	3.0E-11	2.0E-06	36.6	no
788.3H	769.30	793.66	775.85	800.82	24.97	3.0E-11	2.0E-05	37.2	no
813.0H	793.41	817.73	800.56	825.53	24.97	2.0E-11	1.0E-06	37.9	no
837.8H	817.48	841.77	825.28	850.25	24.97	≤3.0E-08	2.2E-07	38.9	no
847.0D	826.47	850.75	834.53	859.50	24.97	2.0E-08	2.2E-07	41.3	no
850.0SI	832.28	850.71	840.50	859.45	18.95	3.0E-08	2.2E-07	37.8	no
850.0SII	832.28	850.71	840.50	859.45	18.95	3.0E-08	2.2E-07	37.8	no
854.7S	841.53	850.71	850.00	859.45	9.45	6.0E-09	2.2E-07	38.2	no
869.8H	848.67	872.89	857.35	882.32	24.97	1.0E-10	2.2E-07	40.0	no
893.9H	871.97	896.15	881.38	906.35	24.97	3.0E-11	2.2E-07	40.9	no
912.5S	895.66	908.53	905.85	919.15	13.30	4.0E-11	2.2E-07	41.3	no

Table 6.2: Summary of Hydraulic Conductivities, Specific Storage, and (cont'd) Temperatures Determined from Hydraulic Testing in the Leuggern Borehole

TEST DESIGNATION	TRUE INTERVAL TOP DEPTH (m)	TRUE INTERVAL BOTTOM DEPTH (m)	APPARENT INTERVAL TOP DEPTH (m)	APPARENT INTERVAL BOTTOM DEPTH (m)	INTERVAL LENGTH (m)	ESTIMATED HYDRAULIC CONDUCTIVITY (m/s)	ESTIMATED SPECIFIC STORAGE (1/m)	TEMPERATURE AT END OF TESTING (deg. C)	THERMAL EFFECTS INCLUDED in GTFM
918.4H	895.76	919.92	905.95	930.92	24.97	3.0E-11	2.2E-07	41.7	no
923.0D	905.68	918.78	916.20	929.74	13.54	7.0E-11	2.0E-06	42.1	no
940.8H	917.39	941.54	928.30	953.27	24.97	6.0E-12	2.2E-07	42.4	no
964.4H	940.27	964.41	951.95	976.92	24.97	2.0E-12	2.2E-07	43.3	no
986.0H	961.16	985.22	973.55	998.52	24.97	3.0E-13	2.2E-07	44.0	no
1002.2H	976.77	1000.75	989.75	1014.72	24.97	6.0E-13	2.2E-07	44.4	no
1026.6H	1000.15	1024.02	1014.10	1039.07	24.97	2.0E-13	2.2E-07	45.5	no
1046.0H	1018.75	1042.62	1033.55	1058.52	24.97	1.0E-11	2.2E-07	46.1	no
1064.6H	1036.52	1060.42	1052.15	1077.12	24.97	3.0E-12	4.0E-08	46.7	no
1082.9H	1053.99	1077.88	1070.40	1095.37	24.97	3.0E-11	2.2E-07	47.3	no
1102.1H	1072.37	1096.20	1089.60	1114.57	24.97	2.0E-12	4.0E-08	47.9	no
1125.1HI	1094.31	1118.07	1112.59	1137.56	24.97	1.0E-12	2.2E-07	47.5	no

Table 6.2: Summary of Hydraulic Conductivities, Specific Storage, and (cont'd) Temperatures Determined from Hydraulic Testing in the Leuggern Borehole

TEST DESIGNATION	TRUE INTERVAL TOP DEPTH (m)	TRUE INTERVAL BOTTOM DEPTH (m)	APPARENT INTERVAL TOP DEPTH (m)	APPARENT INTERVAL BOTTOM DEPTH (m)	INTERVAL LENGTH (m)	ESTIMATED HYDRAULIC CONDUCTIVITY (m/s)	ESTIMATED SPECIFIC STORAGE (1/m)	TEMPERATURE AT END OF TESTING (deg. C)	THERMAL EFFECTS INCLUDED in GTFM
1125.1HII	1094.31	1118.07	1112.59	1137.56	24.97	1.0E-12	2.2E-07	48.9	no
1128.9S	931.37	1285.51	942.76	1315.05	372.29	5.0E-11	2.2E-07	42.0	no
1149.8HI	1117.84	1141.53	1137.31	1162.28	24.97	--- not analyzed ---		48.6	--
1149.8HII	1117.84	1141.53	1137.31	1162.28	24.97	3.0E-13	2.2E-07	49.5	no
1174.5H	1141.29	1164.95	1162.03	1187.00	24.97	1.0E-11	2.2E-07	49.4	no
1191.6H	1157.52	1181.11	1179.15	1204.12	24.97	5.0E-11	2.2E-07	49.9	no
1192.5D	1154.73	1185.53	1176.21	1208.79	32.58	1.0E-10	2.2E-07	49.7	no
1203.2D	1157.68	1202.84	1179.32	1227.15	47.83	1.0E-10	2.2E-07	51.7	yes
1215.0H	1179.63	1203.19	1202.55	1227.52	24.97	5.0E-11	2.2E-07	50.7	no
1238.6H	1201.88	1225.43	1226.13	1251.10	24.97	3.0E-11	2.2E-07	51.5	no
1263.3H	1225.20	1248.71	1250.85	1275.82	24.97	1.0E-11	4.0E-08	52.3	no
1283.8H	1244.51	1267.97	1271.35	1296.32	24.97	<1.0E-13	2.2E-07	53.3	no
1304.2S	1265.19	1285.51	1293.35	1315.05	21.70	3.0E-11	2.0E-06	53.7	yes

Table 6.2: Summary of Hydraulic Conductivities, Specific Storage, and
(cont'd) Temperatures Determined from Hydraulic Testing in the Leuggern Borehole

TEST DESIGNATION	TRUE INTERVAL TOP DEPTH (m)	TRUE INTERVAL BOTTOM DEPTH (m)	APPARENT INTERVAL TOP DEPTH (m)	APPARENT INTERVAL BOTTOM DEPTH (m)	INTERVAL LENGTH (m)	ESTIMATED HYDRAULIC CONDUCTIVITY (m/s)	ESTIMATED SPECIFIC STORAGE (1/m)	TEMPERATURE AT END OF TESTING (deg. C)	THERMAL EFFECTS INCLUDED in GTFM
1326.5H	1284.55	1307.85	1314.03	1339.00	24.97	7.0E-12	4.0E-08	55.7	yes
1349.2H	1305.69	1328.88	1336.68	1361.65	24.97	2.0E-12	2.2E-07	56.4	yes
1369.3H	1324.43	1347.52	1356.85	1381.82	24.97	3.0E-12	2.2E-07	57.0	yes
1392.1H	1345.52	1368.53	1379.65	1404.62	24.97	1.0E-13	2.2E-07	57.8	yes
1412.5H	1364.31	1387.33	1400.03	1425.00	24.97	5.0E-13	2.2E-07	58.6	no
1433.4D	1389.52	1400.62	1427.38	1439.40	12.02	1.0E-10	2.2E-07	59.7	no
1437.0H	1386.89	1409.95	1424.53	1449.50	24.97	1.0E-11	2.2E-07	59.3	no
1456.8H	1405.18	1428.23	1444.35	1469.32	24.97	3.0E-12	2.2E-07	59.9	yes
1462.0D	1417.01	1425.98	1457.16	1466.89	9.73	1.0E-11 (*)	2.2E-07	60.0	no
1480.0H	1426.56	1449.61	1467.52	1492.49	24.97	1.0E-13	2.2E-07	60.6	no
1504.7H	1449.38	1472.41	1492.24	1517.21	24.97	2.0E-12	2.2E-07	61.4	yes

(*) uncertain formation pressure may add uncertainty to the interpretation.

Table 6.2: (cont'd) Summary of Hydraulic Conductivities, Specific Storage, and Temperatures Determined from Hydraulic Testing in the Leuggern Borehole

TEST DESIGNATION	TRUE INTERVAL TOP DEPTH (m)	TRUE INTERVAL BOTTOM DEPTH (m)	APPARENT INTERVAL TOP DEPTH (m)	APPARENT INTERVAL BOTTOM DEPTH (m)	INTERVAL LENGTH (m)	ESTIMATED HYDRAULIC CONDUCTIVITY (m/s)	ESTIMATED SPECIFIC STORAGE (1/m)	TEMPERATURE AT END OF TESTING (deg. C)	THERMAL EFFECTS INCLUDED in GTFM
1529.4H	1472.18	1495.24	1516.96	1541.93	24.97	6.0E-13	2.2E-07	62.1	yes
1553.8H	1494.70	1517.80	1541.34	1566.31	24.97	3.0E-13	2.0E-06	62.8	yes
1578.6H	1517.66	1540.79	1566.16	1591.13	24.97	5.0E-12	2.2E-07	63.6	no
1603.5HI	1540.65	1563.80	1590.98	1615.95	24.97	- not analyzable -		64.3	--
1603.5HII	1540.65	1563.80	1590.98	1615.95	24.97	1.0E-13	2.2E-07	64.3	yes
1628.3H	1563.71	1586.88	1615.85	1640.82	24.97	1.0E-09	2.2E-07	64.5	no
1643.4S	1583.70	1594.76	1637.40	1649.30	11.90	1.5E-06	2.2E-07	64.8	no
1649.8D	1583.64	1606.85	1637.33	1662.30	24.97	7.0E-07	2.2E-07	65.9	no
1651.5H	1585.16	1608.37	1638.97	1663.94	24.97	1.0E-06	2.2E-07	65.0	no
1652.1H	1585.79	1609.01	1639.65	1664.62	24.97	7.0E-07	2.2E-07	65.0	no
1665.5S	1588.13	1631.63	1642.17	1688.90	46.73	≥8.0E-07	2.2E-07	65.6	no
1676.4S	1608.36	1631.63	1663.93	1688.90	24.97	1.0E-06	2.2E-08	65.8	no

Table 6.2: Summary of Hydraulic Conductivities, Specific Storage, and
(cont'd) Temperatures Determined from Hydraulic Testing in the Leuggern Borehole

APPENDICES

APPENDICES - Preface

In the following appendices, which describe the individual test interpretations for Leuggern borehole, several conventions have been used to present the discussion of testing and the interpreted values of K, P_f, Ss, and Freshwater Head. The recommended hydraulic conductivity and specific storage values for each interval are stated in the text of each test and are summarized in Table 6.2. For some intervals a formation pressure was accurately determined (not assumed) and freshwater head was calculated from this formation pressure. The formation pressure corresponding to a test interval is for the P2 transducer elevation and not the interval center. These formation pressures have been extrapolated to the interval center for the freshwater head calculation. Both the formation pressure and the freshwater head are reported in Table 6.1. The time scale on the figures starts at the middle of the drilling period.

Since this report presents the results of the interpretation of the pressure testing, when a sampling event followed the testing sequence, the sampling event was not discussed. In several instances where swabbing was used to clean the formation between testing events or prior to sampling, the pressure recovery in the test zone may have been simulated to corroborate a prior test interpretation. In these instances, the sampling period would be introduced into the discussion.

Abbreviations

Test Identifiers

Pw01	first pulse withdrawal in a sequence
Pi01	first pulse injection in a sequence
Sw01	first slug withdrawal in a sequence
PSTA	static recovery test where the shut-in valve of the HTT is closed following the compliance period
PSTAT	static recovery test where the shut-in valve of the HTT is closed following the compliance period
DST01	first drill stem test in a sequence
DST01 (flow)	the period of the DST where the shut-in valve of the test tool is open and the pressure recovery in the test interval is monitored
DST01 (shut-in)	the period of the DST where the shut-in valve of the test tool is closed and the pressure recovery in the test interval is monitored
PMP1	first period of drawdown during a pumping test
T1, T2, T3	the temperature sensors found in the sensor carrier which measure the operating temperatures of pressure transducers P1, P2, and P3.
P1, P2, P3	the pressure transducers of the sensor carrier measuring pressures below the test interval (P1), in the test interval (P2), and in the borehole annulus (P3)
s.g.	specific gravity of the fluid

Test 217.9S (208.22 m to 227.50 m)

Four hydraulic tests were completed in the interval from 208.22 to 227.50 m of Leuggern including a pulse injection test, two drill-stem tests in succession, and a pulse withdrawal test. The objectives for testing were to obtain a representative estimate of the static hydraulic head for the interval, to determine the formation yield, and to estimate the hydraulic conductivity and specific storage of the formation.

Drilling of this interval was completed in a period of 12 hours in August, 1984. The simulated pressure history for this test section includes a 1033 kPa overpressure during drilling, a 10 hour period at an annulus pressure of 2133 kPa between drilling and testing, and a short packer compliance period.

The injection test, which began the test sequence, consisted of a pulse of 1112 kPa above annulus pressure. Recovery was monitored over 2 hours to within several kPa of the calibrated formation pressure. The first drill-stem test consisted of a 419 kPa underpressure with a 40 kPa recovery during a flow period of 20 minutes. The interval was then shut-in and pressure recovery monitored to within 6 kPa of formation pressure. The second drill-stem test was initiated by lowering the test interval pressure by 1232 kPa and a recovery of 130 kPa was observed in about 20 minutes during the flow period and after shut-in, the pressure recovery was to near formation pressure. Completing the sequence was a pulse withdrawal test where the interval pressure was lowered by 1650 kPa and recovery was monitored over 30 hours to ensure recovery to formation pressure. By calibrating the simulated recovery curve to the stable measured recovery of this pulse test, the undisturbed formation pressure of the interval was determined to be 2130 kPa. From the calibrated formation pressure, an equivalent freshwater head of 363.3 m ASL was calculated for the center of the test interval.

Simulation of the history-testing sequence was completed using GTFM. Simulations were completed for a range of hydraulic conductivity from 1.0E-08 through 1.0E-07 ms^{-1} at the calibrated formation pressure discussed above. The results are shown in Figure 1. The effect of varying specific storage over a reasonable range for crystalline rock (2.0E-06 to 2.0E-08 m^{-1}) should result in less than half an order of magnitude uncertainty in the final estimate of K for the test zone. From the fit of the drill-stem test flow periods, the most reasonable hydraulic conductivity of the test zone would be 3.0E-08 ms^{-1} at a formation specific storage of 2.2E-07 m^{-1}.

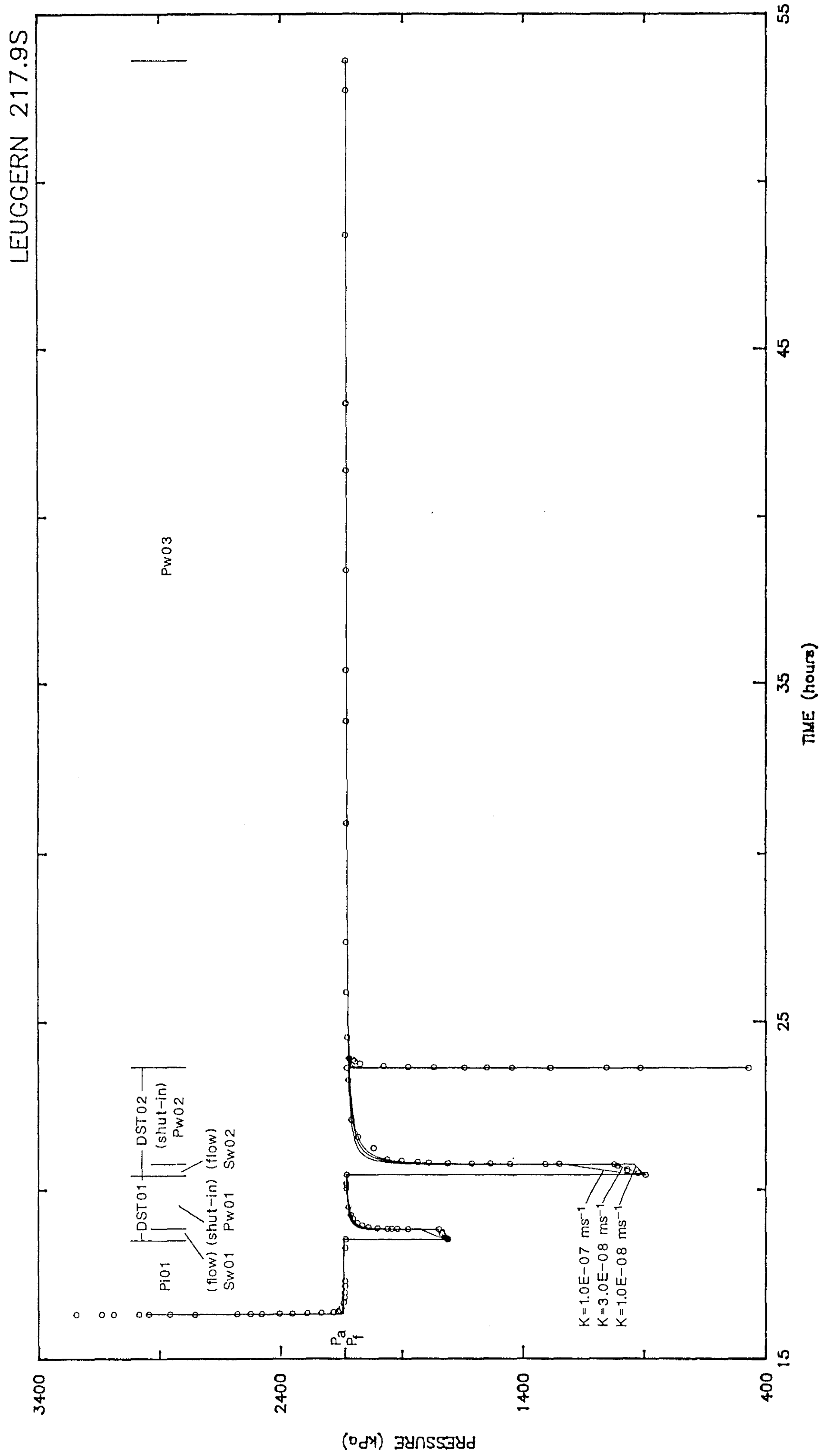


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 251.3S (237.92 m to 267.45 m)

The objectives for testing in this interval were to obtain an estimate of the hydraulic conductivity of the formation and to obtain an estimate of the static formation pressure. Five hydraulic tests were conducted within the zone extending from 237.92 to 267.45 m. According to their order of execution they are, pulse injection, two drill-stem tests, slug withdrawal, and a period of shut-in monitoring of formation pressure or static recovery. During the last test, the interval recovered to a stable pressure which was monitored over about 5 hours. The high hydraulic conductivity of this zone would indicate that this recovery pressure could be an undisturbed formation pressure. Adjusting the input formation pressure while simulating this shut-in recovery test provided an estimated formation pressure of 2425 kPa reported for this interval. This procedure will be referred to as "formation pressure calibration" in subsequent tests. The equivalent freshwater head for the test zone corresponding to the formation pressure at the interval center is 362.1 m ASL.

History effects were included in the test sequence as drilling overpressure of about 600 kPa for 25 hours, a 28 hour open borehole period at annulus pressure and a short period of equipment compliance. Initially, the drilling overpressure was calculated as 50 percent of the average pump pressure for the interval, however, this resulted in a poor fit of simulated to measured pressures for the early tests in the sequence. An adjustment to about 10 percent of pump pressure provided the best fit.

The first test in the sequence, PiO1, was omitted because the test zone was too permeable to allow pulse injection. This test was not included in the borehole history since the short duration of the pressure disturbance would not affect the pressure transient around the borehole. The results of simulating each of the remaining tests are shown in Figure 1 for the range of hydraulic conductivities, 3.0E-06, 1.0E-06, and 3.0E-07 ms^{-1}. A base case specific storage of

2.2E-07 m^{-1} was chosen because of the low uncertainty in the best estimate of K associated with the choice of S_s at the hydraulic conductivity of this zone.

By inspection of the simulation results, the best fit K's for the individual tests are as follows. For the flow period of test DST01 a reasonable estimate of K is about 5.0E-07 ms^{-1}. Test Sw03 is best matched using a K of about 8.0E-07 ms^{-1}. For reporting purposes, a hydraulic conductivity of 5.0E-07 ms^{-1} was assigned to the interval. Although test Sw03 provides better definition of the measured and simulated pressure responses, the positioning of the test later in the sequence results in less certainty in the model results.

Some uncertainty in the best fit K must be reported as the result of very high flow rates through the HTT (42 $Lmin^{-1}$ DST01; 56 $Lmin^{-1}$ DST02) during the flow periods of both drill-stem tests. If these two testing periods are affected by turbulent flow, the pressure losses would result in a K from test interpretation which is less than the formation value.

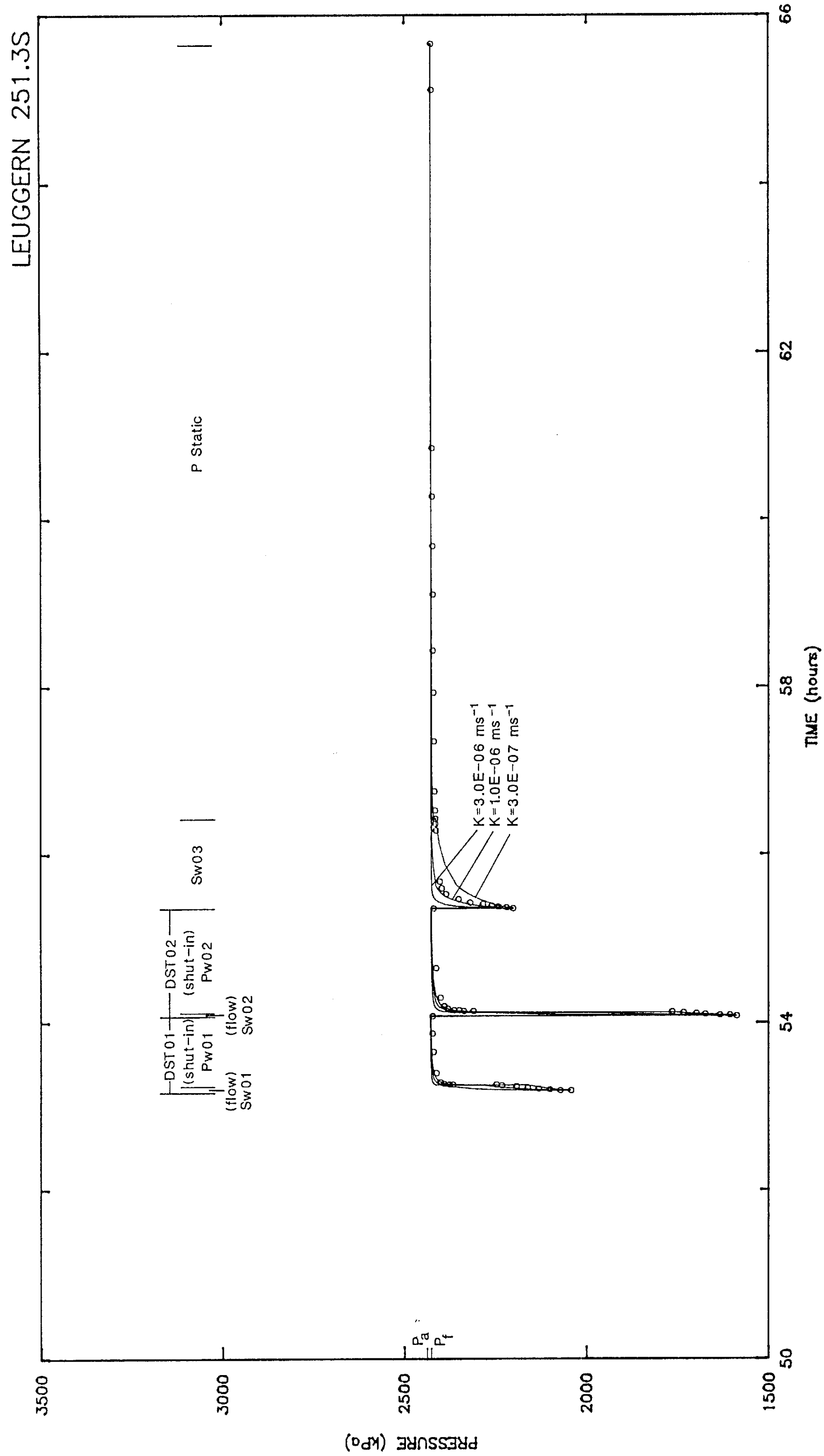


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 267.8H (267.30 m to 268.34 m)

The primary objective of pressure testing of this interval was to check the integrity of the casing shoe seal located at 267.3 m in the borehole. The test section length of exposed borehole was 1.04 m with the upper packer placed in the casing. The top packer of the straddle arrangement was positioned at 243.52 m in the casing, and the bottom packer at 268.34 m within the uncased section of the borehole.

The pretest borehole history included about 350 kPa of drilling overpressure over the two hour drilling period, an open borehole period at annulus pressure of 2468 kPa lasting some 19 days, and a one hour compliance period. Because of the low hydraulic conductivity of the rock (i.e., less than 10 percent recovery in the monitoring period of Pi01 and Pw01), the measured pressure in the interval most likely responds to the borehole history pressure (2468 kPa) rather than the undisturbed formation pressure.

The testing sequence, simulated using GTFM, included tests Pi01, Pw01, and DST01. Testing was completed over 2.5 hours during which, on the average, 10 percent recovery was observed for any of the tests. A base case value was chosen for specific storage. Each of the tests were simulated under isothermal conditions. Although temperature varied by 0.4°C, the variation was observed during two rapid steps during tool movement and therefore thermal effects during individual tests are considered to be negligible.

The simulated pressure response in the test interval for a range of hydraulic conductivity (K = 1.0E-13, 3.0E-13, and 1.0E-12 ms^{-1}) is compared to the measured data in Figure 1. The best-fit hydraulic conductivity is 3.0E-13 ms^{-1} for test Pi01 and 1.0E-12 ms^{-1} for test Pw01. Because of the low hydraulic conductivity of the interval, the pressure recovery in the flow period of the DST was only 1 kPa. Simulation of test Pw02 would require a hydraulic conductivity of at least 3.0E-12 ms^{-1} and perhaps as high as 1.0E-11 ms^{-1}. From tests Pi01 and Pw01, a hydraulic conductivity value representative of the test interval is estimated to be 6.0E-13 ms^{-1}.

Concerning the integrity of the casing shoe seal, no communication between P2 and P3 was observed during testing.

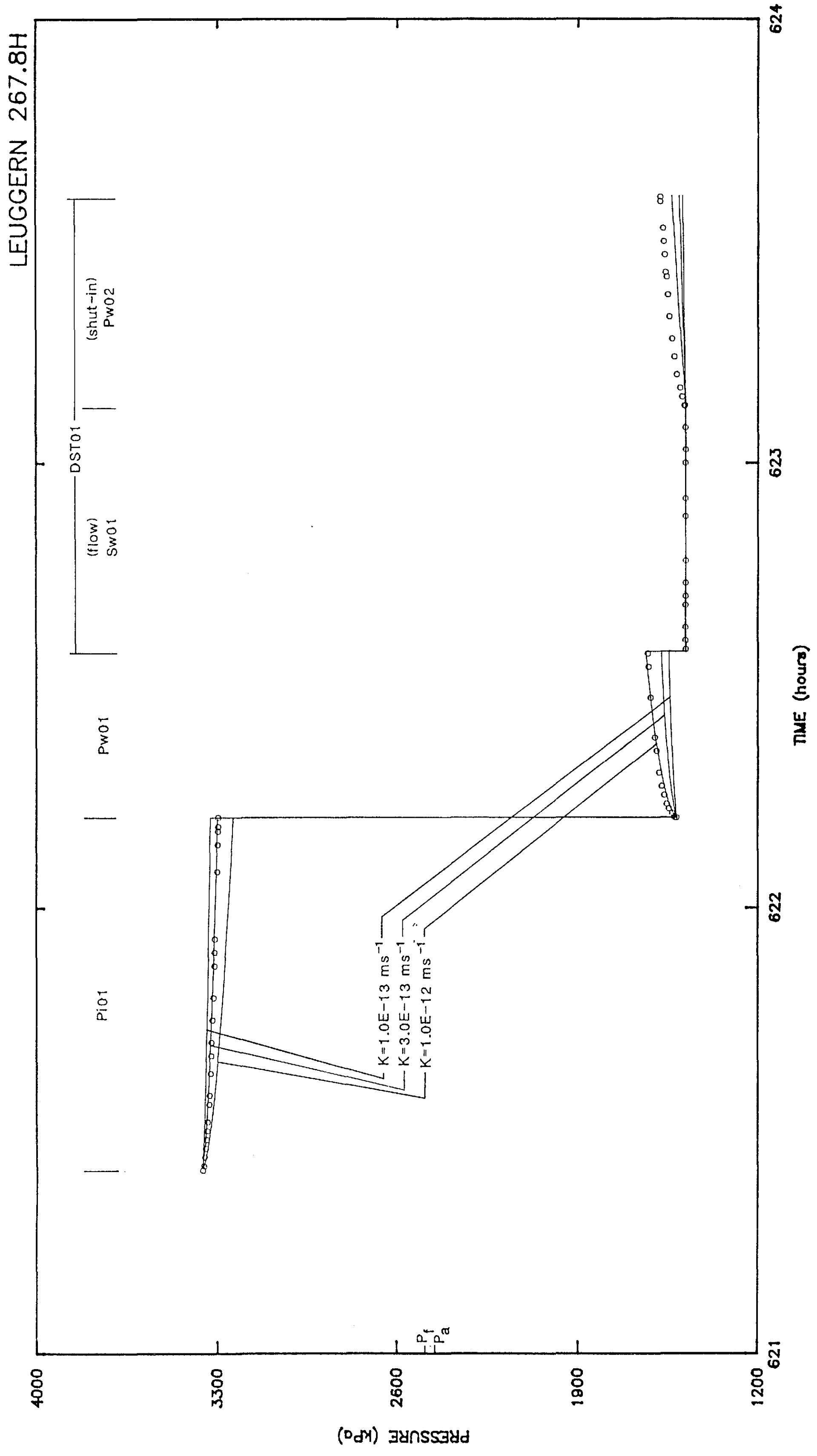


Figure 2: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 273.8H (267.30 m to 280.32 m)

The pressure testing of this interval of the Leuggern borehole between 267.30 and 280.32 m consisted of a pulse injection test (Pi01), a pulse withdrawal test (Pw01), and a drill stem test (DST01). The objective of the testing was to obtain pressure-time data for interpretation of hydraulic conductivity. The testing followed a borehole pressure history period consisting of about 8 days of drilling during which the average applied drilling fluid pump pressure was 700 kPa and an open borehole period at an annulus pressure of 2586 kPa of close to 17 days. The drilling took place as two events, wireline coring down to 267.45 m followed by widening of the borehole from 14 to 21.6 cm (11 to 16 August), then drilling the rest of the test interval (18 to 19 August).

The similarity in formation pressure of 2607 kPa, calculated from the borehole gradient, and the annulus pressure of about 2586 kPa for the interval indicates that the impact of the open borehole period on the ambient pressure in the vicinity of the test interval should be minimal. The influence of history on the simulation of the pressure tests is most likely less than half an order of magnitude uncertainty in the best estimate of hydraulic conductivity for the formation.

The fluid temperature during testing remained constant at 20.2°C. Each of the testing events were included in the simulation using GTFM. All of the pulse tests recovered rapidly to a stable pressure close to annulus pressure. Test Pi01 was monitored for 0.6 hours and test Pw01 for 0.4 hours. The DST flow period showed less than 10 percent recovery of the underpressure slug over 1.2 hours of monitoring. The test data was simulated using a range of hydraulic conductivities from 3.0E-09 to 3.0E-08 ms^{-1}. The results are shown in Figure 1. A best-fit hydraulic conductivity would be approximately 6.0E-09 ms^{-1}.

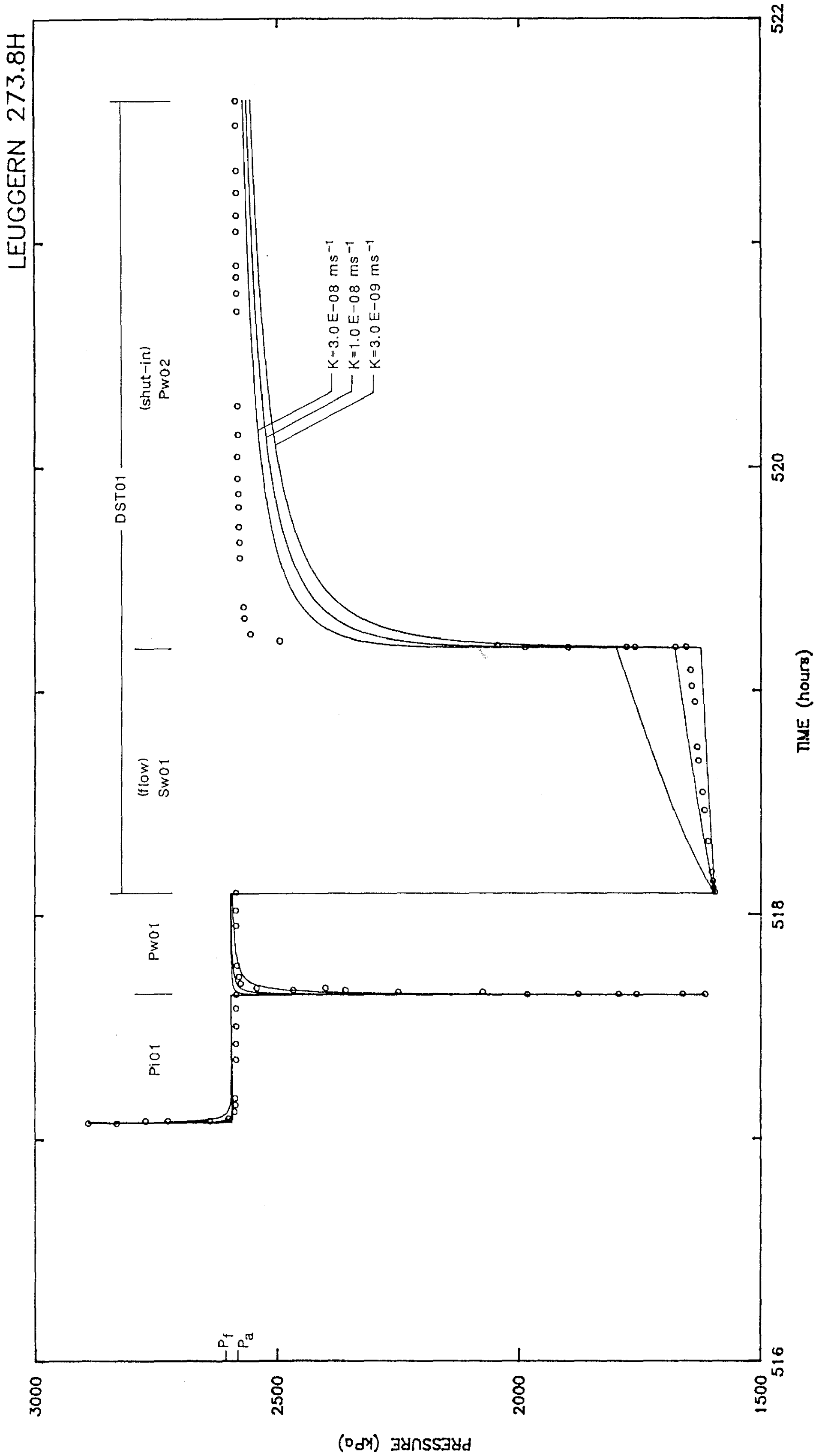


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 281.7H (269.30 m to 294.12 m)

The testing of this section of crystalline rock occurred on 6 September, 1984 and overlapped most of the rock from the H-log test 273.8H (267.30 to 280.32 m) and the upper half of test 292.5H (280.08 to 304.90 m). The same straddle packer configuration was used for each interval.

For simulation purposes the drilling overpressure applied to the interval was about 300 kPa. An annulus pressure of 2724 kPa was applied from the end of drilling to the start of the equipment compliance period. Test 281.7H consisted of a pulse injection, a pulse withdrawal and a drill stem test. Tests Pi01 and Pw01 were monitored for about 0.7 hours, with recovery approaching annulus pressure. During the DST-flow period, recovery of less than 10 percent of the pressure slug was observed in an hour. The DST-shut-in recovery was rapid, with recovery to near annulus pressure in less than 0.5 hours. The objective of the testing of the 281.7H zone was to obtain a hydraulic conductivity of this section of the crystalline rock.

The GTFM simulations which bracket the measured test data are shown in Figure 1 for the full test sequence. GTFM simulations of the tests were made for the range of hydraulic conductivity, 1.0E-09, 3.0E-09, and 1.0E-08 ms^{-1}. The simulated and measured pressure response of test Pi01 appear to be offset from each other in Figure 1 by several minutes. The reason is the change in slope at about 50 percent recovery. Disregarding the offset, the best fit of the measured data is for a K of 1.0E-08 ms^{-1}. Test Pw01 and the flow period of the DST are best simulated using a K of 3.0E-09 ms^{-1}. The shut-in portion of the DST could only be simulated using a K several orders of magnitude higher than 1.0E-08 ms^{-1}. The most reasonable hydraulic conductivity of the interval is therefore about 6.0E-09 ms^{-1}. All tests were simulated under isothermal conditions.

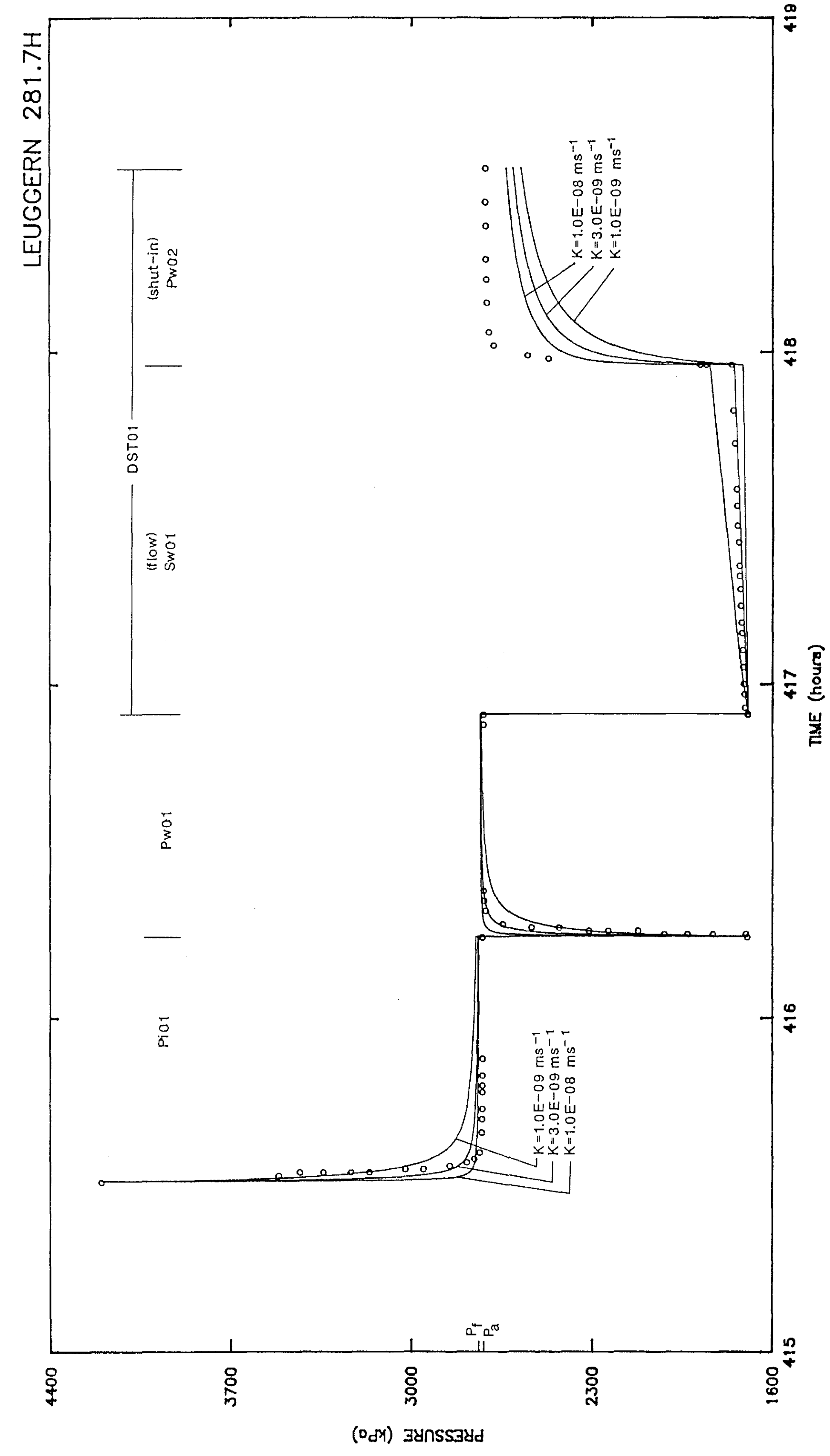


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 292.5H (280.08 m to 304.90 m)

The sequence of hydraulic tests carried out at 280.08 to 304.90 m in the Leuggern borehole consisted of a pulse injection test, two short slug tests, a second pulse injection test, a pulse withdrawal test, and a drill stem test. A formation pressure of 2846 kPa at transducer P2 was calculated from the pressure gradient across the borehole. The simulated pretest borehole pressure history included a drilling overpressure of 265 kPa, an open borehole period at an annulus pressure of 2832 kPa for about 13 days, and a short equipment compliance period.

Simulation of measured pressures for the testing sequence was completed using GTFM. The fluid temperature varied only 0.2°C across the testing period, however, rapid fluctuations in temperature of about 0.1°C are observed shortly after the start of monitoring of each test. These temperature fluctuations could be the result of fluid movement past the sensor carrier during tool movements. Because of the uncertainty in assigning these temperature changes as representative of the entire test interval, the thermal effect was not included in the simulations.

Each of the pulse tests recovered to a stable pressure close to annulus pressure. The significant pressure recovery during the slug injection test (Si01) resulted from keeping the pump pressure on the interval while keeping the shut-in tool open.

The simulated pressure recovery curves are shown with the measured data in Figure 1. Simulations were run for the range of hydraulic conductivity: 1.0E-10, 3.0E-10, and 1.0E-09 ms^{-1}. The best simulation of the measured pressure data for tests Pi01 and Pi02 appears to be using a formation hydraulic conductivity of about 6.0E-10 ms^{-1}. Most of the data is bounded by a range of hydraulic conductivity of 3.0E-10 to 1.0E-09 ms^{-1}. The best fit K for test Pw01 appears to be about 2.0E-10 ms^{-1}. The simulated curves for the flow period of the DST are undistinguishable. The most reasonable fit of the early time data for the DST shut-in period is using a K of about 6.0E-10 ms^{-1}. For reporting purposes, an interval K of 6.0E-10 ms^{-1} was adopted. A base case rock specific storage value was chosen for the calculations as the simulations are relatively insensitive to variation in specific storage at this hydraulic conductivity.

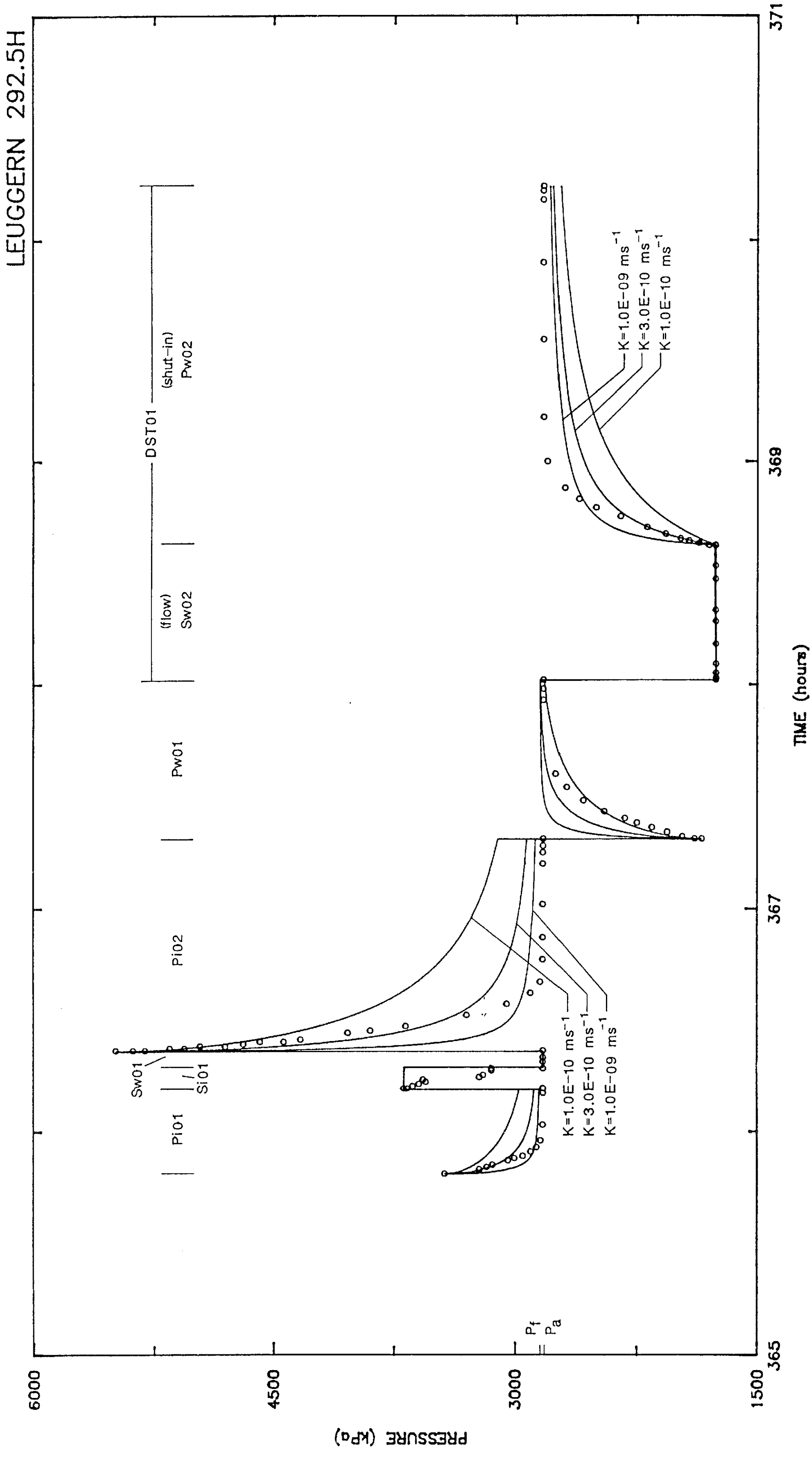


Figure 2: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 317.1H (304.65 m to 329.47 m)

The hydraulic tests completed at the depth interval 304.65 to 329.47 m in the Leuggern borehole included pulse injection and pulse withdrawal, with each of these tests monitored for close to an hour. Recovery of each of these tests was to near the assumed formation pressure of 3086 kPa. Also included was a drill stem test with a 0.5 hour flow period showing 18 kPa recovery and a shut-in period showing rapid recovery to a reference pressure of about 3080 kPa. The objective of the testing was an interpretation of the hydraulic conductivity of the crystalline rock in this interval. The test interval is located within a section of crystalline rock drilled between mid-August and early September, 1984. A formation pressure of 3086 kPa, corresponding to the P2 transducer depth, was calculated from the pressure gradient across the length of the borehole.

The simulated borehole pressure history includes a drilling overpressure of 630 kPa on the interval from the midpoint to the end of drilling, an open borehole period at annulus pressure of 3072 kPa for about 8 days, and a short period of equipment compliance.

Simulation of measured pressures for the testing sequence was completed using GTFM. The fluid temperature in the test interval was relatively stable during pressure recovery and a variation of only 0.1°C was noted during the testing period. A base case specific storage value of 2.2E-07 m^{-1} was chosen for this interval. The hydraulic conductivity of this zone of greater than 1.0E-10 ms^{-1} indicates that the simulated response would be relatively insensitive to variation in specific storage.

The most reasonable fit to tests Pi01, Pw01, Pw02, and the DST flow period was at a formation hydraulic conductivity of about 2.0E-09 ms^{-1} (Figure 1). Generally the measured pressure recovery data falls between the simulated curves for K equal to 1.0E-09 and 3.0E-09 ms^{-1}. Test Pw02 was carried out as part of an aborted DST. Pressure recovery was monitored for three minutes to about 85 percent recovery, then the DST01 sequence was started (Figure 1).

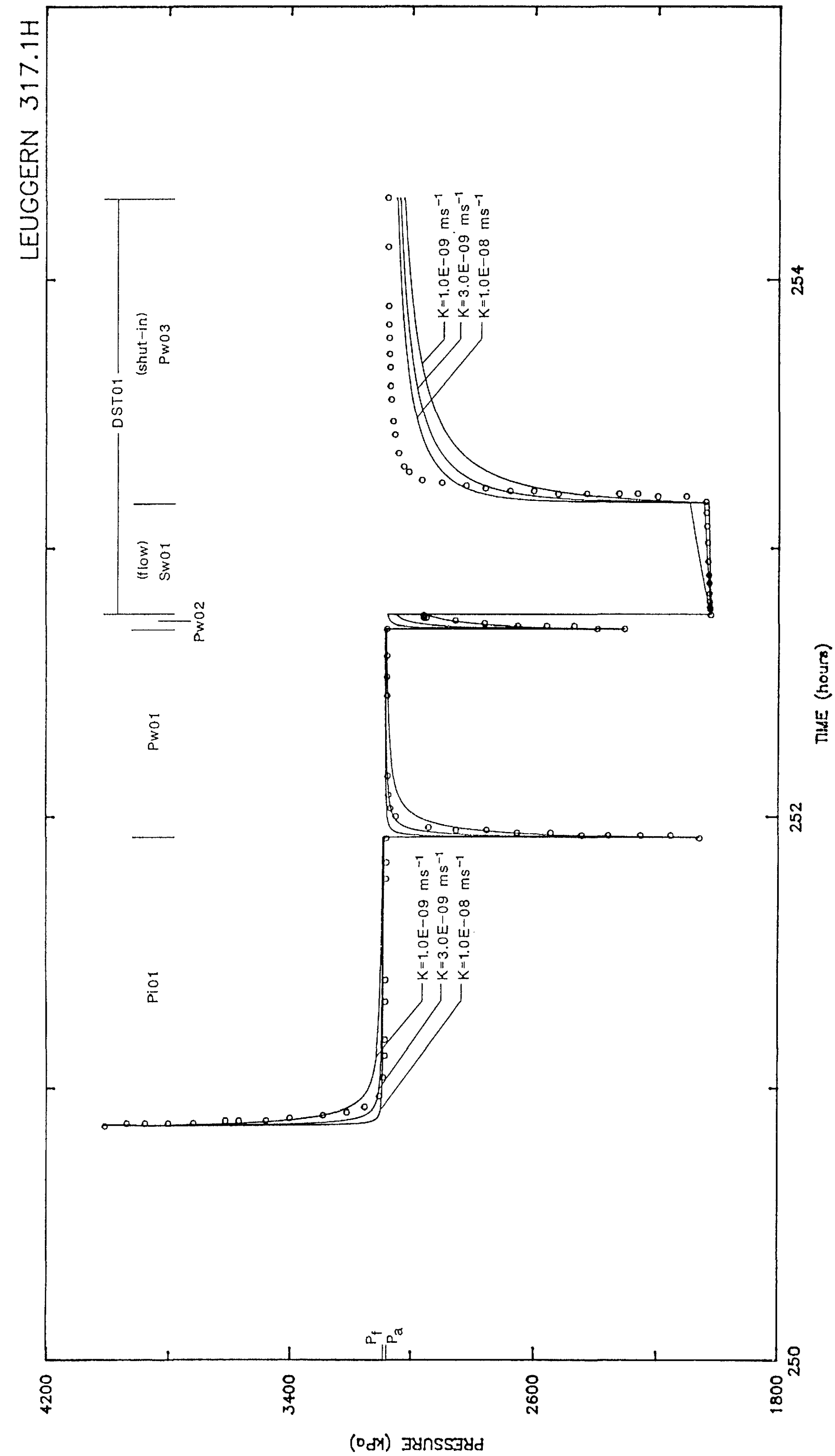


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 341.6H (329.22 m to 354.04 m)

The H-log testing of this interval was completed on 5 September, 1984. The objective of the testing was an interpretation of hydraulic conductivity. The testing sequence consisted of a pulse injection followed by slug withdrawal. Test Pi01 was monitored for about 10 hours to 60 percent recovery. The slug withdrawal test showed only several kPa recovery. The drilling period for this interval was 28 to 30 August, 1984. Between drilling and testing, the interval was exposed to an annulus pressure of 3325 kPa as determined from the field reports. The formation pressure at P2 was calculated from the pressure gradient across the borehole. This assumed pressure was also 3325 kPa.

The simulated borehole pressure history tests includes 50 percent of the overpressure (860 kPa) on the interval during drilling, an open borehole period of 4.2 days at annulus pressure of 3325 kPa, and a short period of equipment compliance.

Simulation of the testing sequence was completed using GTFM. Only the pulse injection test provided sufficient pressure recovery for simulation and therefore is the only test considered in Figure 1. The simulations of pressure recovery for the slug withdrawal test at hydraulic conductivities of 1.0E-12, 2.0E-12 and 3.0E-12 ms^{-1} were indistinguishable. A 0.2°C temperature shift occurred during tool movements at the start of testing and therefore the simulations were run under isothermal conditions. A base case value representing an average rock compressibility and freshwater compressibility at formation temperature and pressure was chosen for the specific storage.

The most reasonable simulation of the measured pressure response for test Pi01 is for a hydraulic conductivity between 1.0E-12 and 2.0E-12 ms^{-1}. For reporting purposes, a value of K equal to 1.5E-12 ms^{-1} was adopted. The sensitivity of the best fit K to a variation of specific storage over a range 2.2E-06 to 2.2E-08 m^{-1} would be between one-half and one order of magnitude. In other words, assuming a best fit K of 1.5E-12 ms^{-1} at a S_s of 2.2E-07 m^{-1}, the range of K corresponding to a reasonable S_s variation from 2.2E-06 to 2.2E-08 m^{-1} would be 5.0E-13 to 3.0E-12 ms^{-1}.

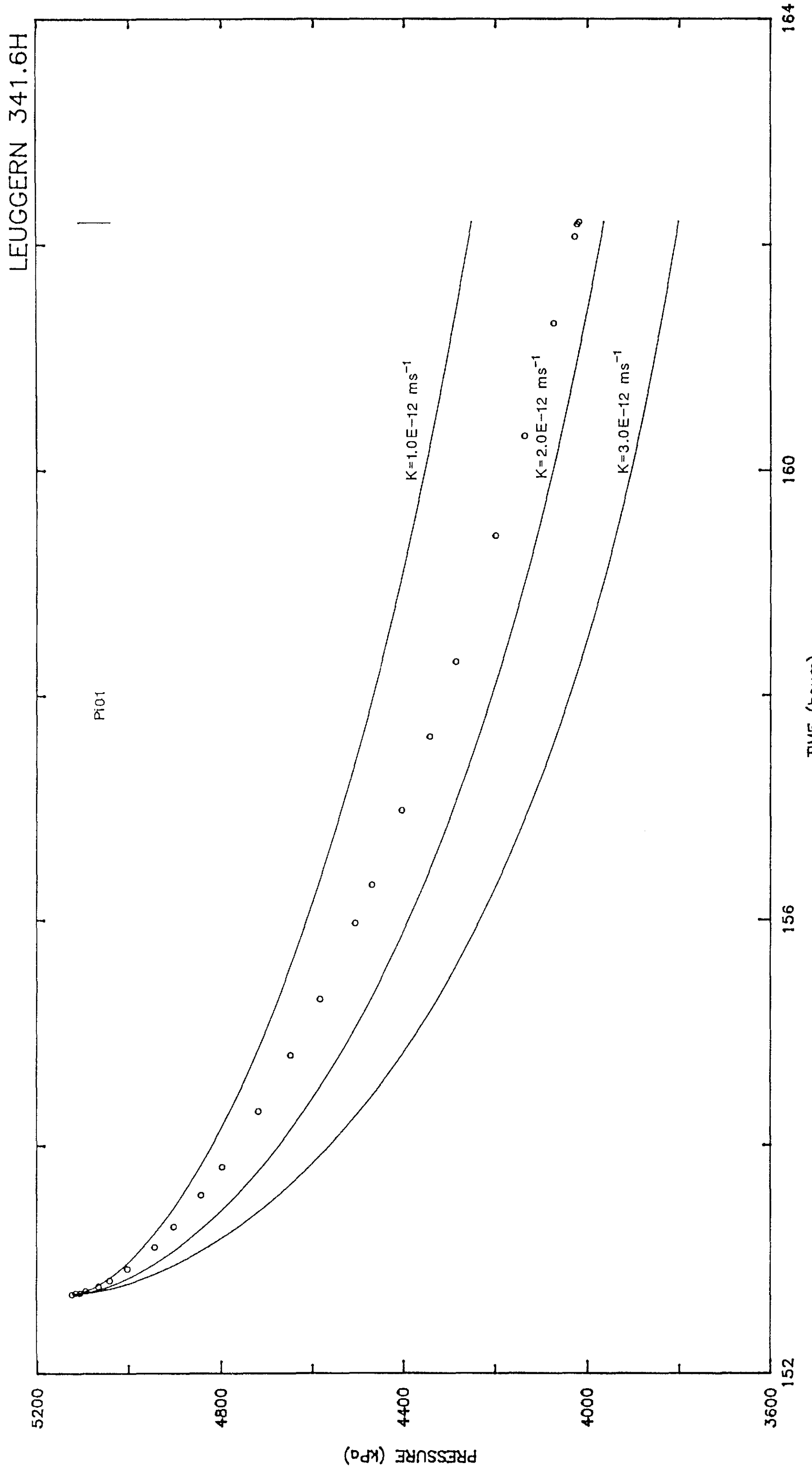


Figure 2: Measured (o) and Simulated Pressure Response for Test Pi01

Test 364.0H (353.12 m to 374.79 m)

Pressure testing of the crystalline rock between 353.12 and 374.79 m in the Leuggern borehole consisted of pulse injection, pulse withdrawal, and slug withdrawal tests with monitoring of pressure recovery. The testing was started at 22:00 hours on 2 October, 1984 and completed at 3:50 hours on 3 October, 1984. The pulse injection test consisted of a pressure pulse of 2368 kPa above annulus pressure with monitoring of the pulse dissipation over 1.5 hours to within 87 percent of recovery. The pulse withdrawal that followed consisted of a lowering of the pressure in the test interval by 1040 kPa below the recovery pressure for the pulse injection test and monitoring recovery over 1.3 hours. The last test in the sequence was a 594 kPa slug withdrawal during which a 2 hour monitoring period of the pressure recovery showed only a 2 kPa pressure change. Tests Pi01 and Pw01 were selected for interpretation of hydraulic conductivity. The formation pressure of 3559 kPa assumed for the interval was taken from the pressure gradient for the borehole.

This section of the borehole was drilled from 22:45 on 31 August, 1984 to 17:18 on 2 September, 1984 and then reamed on 24 September, 1984. The simulated history sequence for the interval includes an 800 kPa drilling overpressure, a 30 day open borehole period at an annulus pressure of 3542 kPa, and a short equipment compliance period.

The temperature of the fluid at the T2 transducer, during pressure recovery, varied less than 0.1°C except during a period of about 30 minutes following tool movement for the pulse injection and pulse withdrawal test. These temperatures are thought to be related to fluid movement in the vicinity of the sensor carrier and so are not included as thermal effects during test simulation. A base case specific storage of 2.2E-07 m^{-1} was used for the simulation of the pressure response.

The best fit hydraulic conductivity for the pulse injection test appears to be 3.0E-11 ms^{-1} as shown in Figure 1. A range of K of 3.0E-11 to 3.0E-12 ms^{-1} brackets the measured response of the pulse withdrawal test. Since the recovery of the slug test was negligible, its' simulation is not included in the results.

The uncertainty in the estimate of hydraulic conductivity based on the choice of specific storage for the rock was determined by varying S_s over two orders of magnitude (2.2E-06 to 2.2E-08 m^{-1}) corresponding to a reasonable range of crystalline rock compressibility. At a S_s of 2.2E-06 m^{-1}, the best fit K is approximately 2.0E-11 ms^{-1} and at a S_s of 2.2E-08 m^{-1}, the best fit K is close to 6.0E-11 ms^{-1}.

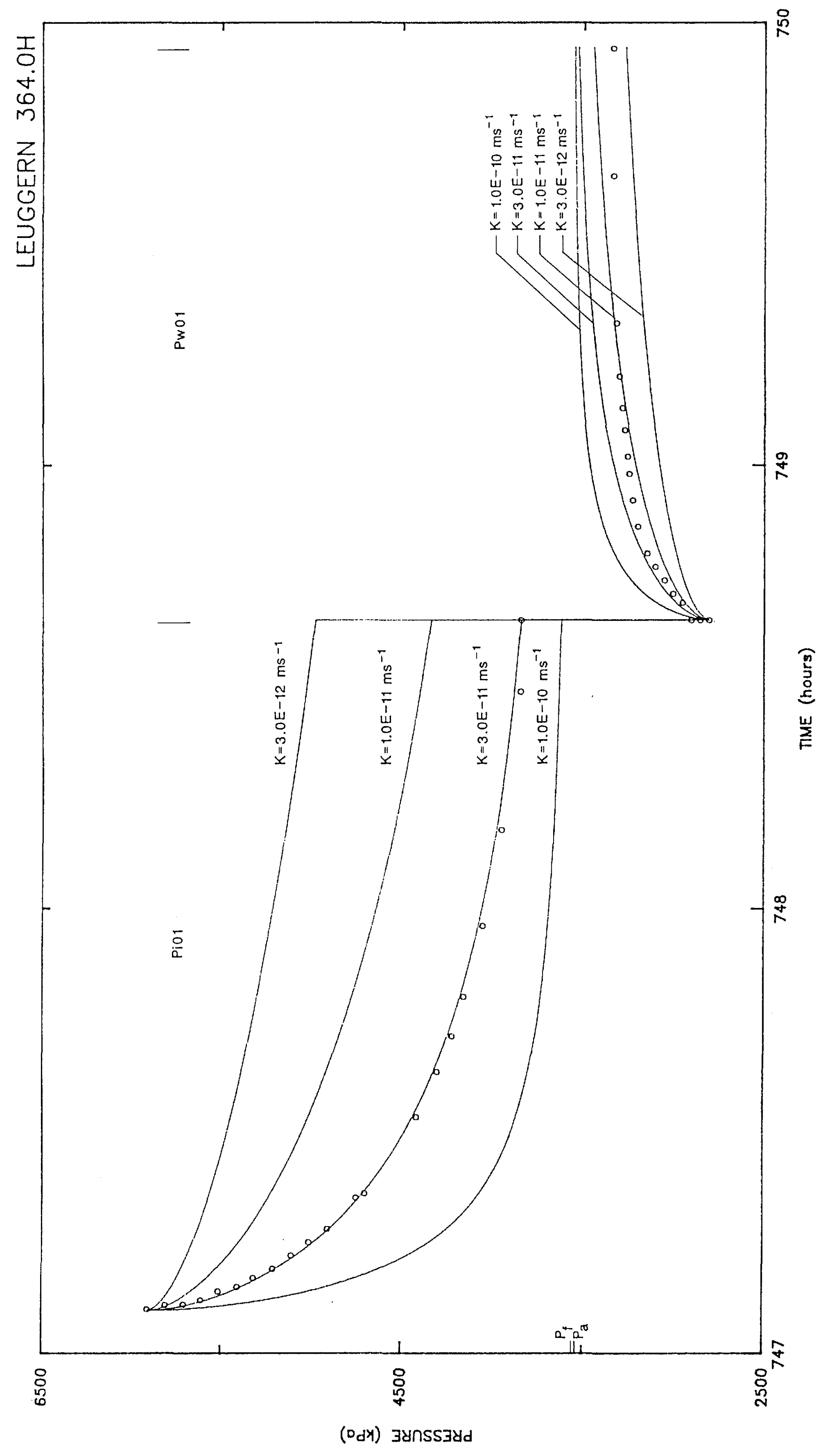


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 385.4H (374.53 m to 396.20 m)

The testing period for the 385.4H zone started on 2 October, 1984. The sequence of tests at this depth consisted of pulse injection, pulse withdrawal, and slug withdrawal with the complete sequence of testing completed in 3.5 hours. The pulse injection test consisted of a rapid pressure increase of 2397 kPa above annulus pressure followed by monitoring of the pressure dissipation over 80 minutes to 75 percent recovery. The pulse withdrawal which followed lowered the pressure in the interval by 1507 kPa. The pressure recovery was monitored for an hour. Normal recovery at early time (less than 10 minutes) was observed but then the pressure curve leveled off and started to invert. A recovery of 34 percent of the initial underpressure was observed in 10 minutes followed by a gradual pressure decrease to the end of the monitoring period. The slug withdrawal test consisted of lowering the interval pressure by 350 kPa and monitoring the interval pressure for about an hour. No pressure recovery was observed during this period and therefore the slug withdrawal test was not simulated. The formation pressure of 3765 kPa reported at this depth in the borehole was assumed from the pressure gradient calculated from single packer testing results.

The history period used in the GTFM simulations consists of 340 kPa of overpressure during drilling, an open borehole period at an annulus pressure of about 3763 kPa for close to 29 days and a short equipment compliance period.

The temperature of the interval fluid at T2 varied by 0.5°C during the initial 30 minutes of pressure response for test Pi01. After the fluctuation, the temperature varied by less than 0.1°C for the remainder of the testing sequence. However, it is uncertain whether these temperature oscillations reflect the overall temperature within the test zone. The simulations were therefore run under isothermal conditions. A specific storage of 4.1E-08 m^{-1} was used for the simulation of the pressure response shown in Figure 1. GTFM simulations were run for the hydraulic conductivities, 1.0E-11, 3.0E-11, and 1.0E-10 ms^{-1}. The most reasonable fit of the early time pressure data is for a K of 1.0E-10 ms^{-1} at the above S_s. The uncertainty in the best fit K resulting from the choice of specific storage was estimated by varying S_s over two orders of magnitude (2.0E-06 to 4.1E-08 m^{-1}). At a S_s of 2.0E-06 m^{-1}, the best fit K is approximately 2.0E-11 ms^{-1} for the early time data and at a S_s of 2.2E-07 m^{-1}, the best fit K is close to 6.0E-11 ms^{-1}. The non-ideal shape of the measured pressure recovery curves adds a high degree of uncertainty to the estimate of hydraulic conductivity derived by simulation of the measured data. For this reason, only a <u>maximum</u> hydraulic conductivity can be reported for this interval as 1.0E-10 ms^{-1}.

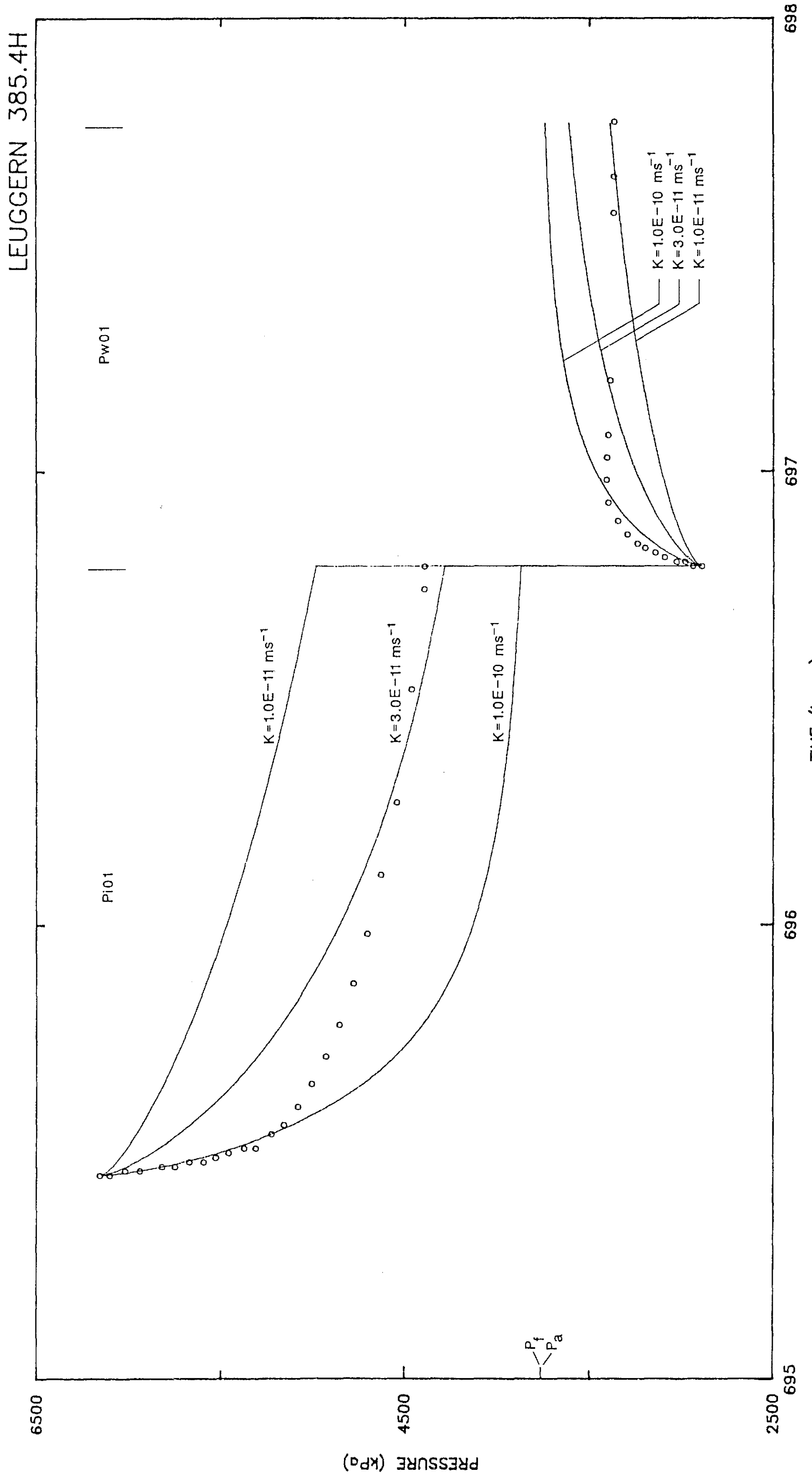


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 407.3H (395.94 m to 418.62 m)

A test sequence of pulse injection followed by slug withdrawal was conducted within the interval 395.94 to 418.62 m. The pulse injection test consisted of a pressure pulse of 2364 kPa above annulus pressure with monitoring of the pulse dissipation over 5.0 hours. About 60 percent of the pressure pulse was dissipated during this time period. The pressure in the test interval was lowered by 1757 kPa during the slug withdrawal event. Monitoring of the interval was continued for 60 minutes with no change in pressure. The pressure recovery data for the pulse injection test was interpreted successfully for an estimate of hydraulic conductivity of the interval. The formation pressure of 3964 kPa reported at this depth in the borehole was assumed from the pressure gradient calculated from single packer testing results.

The drilling of the test interval occurred between 18:47 on 4 September, 1984 and 15:14 on 9 September, 1984. About 200 kPa of overpressure corresponding to the drilling period was applied to the interval during the simulated history. The simulated pre-test pressure history also included an open borehole at an annulus pressure of about 3955 kPa for about 24 days, and a compliance period.

Simulation of the pressure recovery data from the pulse injection test was completed using GTFM. Although the temperature of the test interval indicated an apparent cooling of 0.3°C during the testing sequence, most of the temperature change was found in the early part of the test following tool movement and not during the period of formation testing. The simulations were therefore run under isothermal conditions. A base case specific storage of 2.2E-07 m^{-1} was used for the simulation of the pressure response.

GTFM simulations were run for the hydraulic conductivities, 3.0E-13, 1.0E-12, and 3.0E-12 ms^{-1} as shown in Figure 1. The most reasonable fit of the measured pressure data is for a K of 1.0E-12 ms^{-1} at a base case S_s. The uncertainty in the best fit K resulting from the choice of specific storage was estimated by varying S_s over two orders of magnitude (2.2E-06 to 2.2E-08 m^{-1}). At a S_s of 2.2E-06 m^{-1}, the best fit K is approximately 3.0E-13 ms^{-1} and at a S_s of 2.2E-08 m^{-1}, the best fit K is close to 2.0E-12 ms^{-1}.

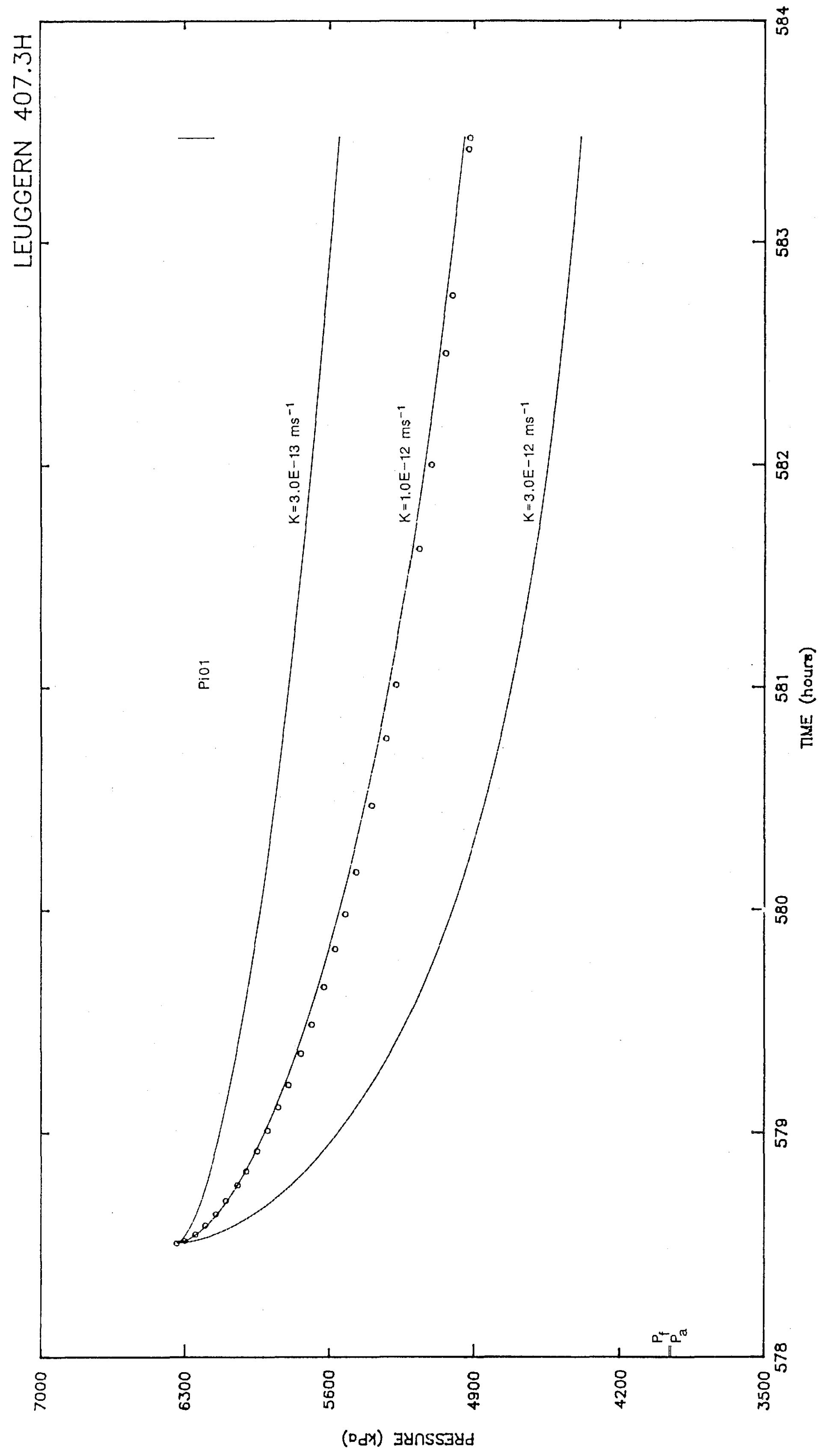


Figure 1: Measured (o) and Simulated Pressure Response for Test Pi01

Test 429.7H (418.37 m to 441.05 m)

During the H-log testing phase of the Leuggern borehole, the interval between 418.37 and 441.05 m was tested for hydraulic conductivity using pressure pulse injection and slug withdrawal. The pulse injection test consisted of a pressure pulse of 2548 kPa above annulus pressure with monitoring of the pulse dissipation over 3.5 hours. About 65 percent of the pulse was dissipated during this time period. The slug withdrawal that followed consisted of a 1900 kPa underpressure event and monitoring over 55 minutes. No pressure recovery was observed. The objective of the testing was met by interpretation of the pressure recovery following pulse injection. A formation pressure of 4182 kPa at the P2 transducer depth in the borehole was assumed from the pressure gradient calculated from single packer testing results.

The drilling period of the test interval was between 15:00 hours on 9 September, 1984 and 19:30 on 10 September, 1984. About 200 kPa of overpressure was attributed to drilling during the simulated history. The simulated pressure history also included an open borehole at an annulus pressure of about 4165 kPa for close to 20 days, and a short equipment compliance period.

During the pulse injection test only a 0.1°C change in temperature was observed. The simulation of test Pi01 was therefore run under isothermal conditions. A base case specific storage of 2.2E-07 m^{-1} was used for the simulation of the pressure response. Figure 1 shows a good fit to the test Pi01 for the GTFM simulation using a K of 1.0E-12 ms^{-1} and a base case specific storage. Since the recovery of the slug test was negligible, its simulation is not included in the results and not shown in Figure 1.

The choice of best fit K for the interval is strongly dependent on the magnitude of specific storage for the rock. For this set of testing results, the S_s was varied over two orders of magnitude (2.2E-06 to 2.2E-08 m^{-1}) to test the uncertainty in the best fit hydraulic conductivity value. At a S_s of 2.2E-06 m^{-1}, the best fit K is approximately 3.0E-13 ms^{-1} and at a S_s of 2.2E-08 m^{-1}, the best fit K is close to 3.0E-12 ms^{-1}.

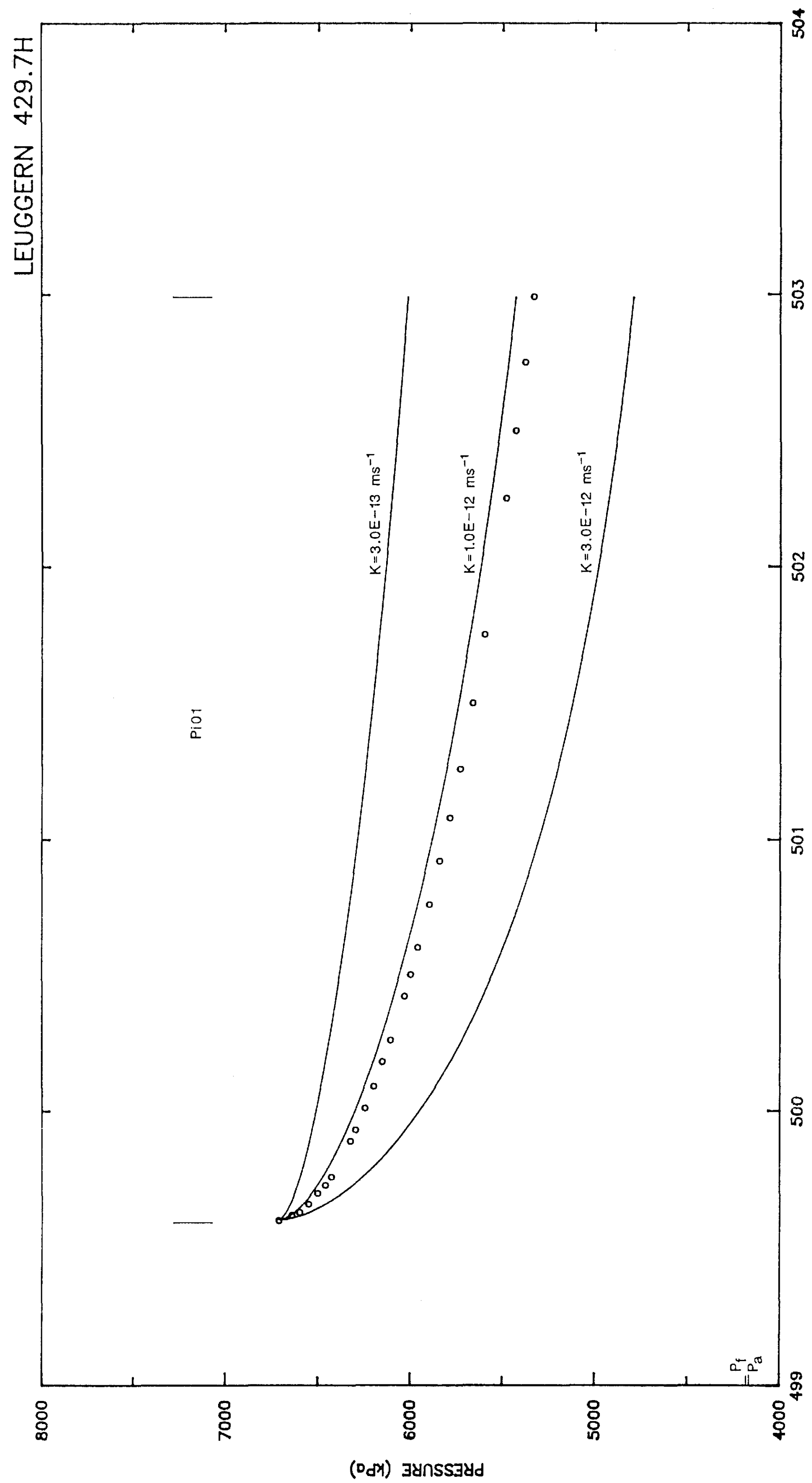


Figure 1: Measured (o) and Simulated Pressure Response for Test Pi01

Test 444.2S (440.35 m to 448.05 m)

Testing of this zone commenced on 11 September, 1984 following 12 hours of drilling and 4 hours of open borehole at an annulus pressure of 4380 kPa. A fluid overpressure at the test zone applied during drilling was estimated to be about 150 kPa. This was included in the history of the testing for the GTFM simulations, from the midpoint to the end of drilling. The simulated history sequence also included a short compliance period.

Pulse injection and pulse withdrawal tests were conducted with fairly long recovery periods of 12 hours and 2 hours, respectively, to demonstrate a stable recovery pressure for this interval. Because of the high permeability and relatively undisturbed history of this interval, formation pressure was taken near this recovery pressure, at 4394 kPa. The pressure stabilized to 4395 kPa for the last 11 hours of test Pi01 and returned to 4393 kPa within 0.7 hours of recovery during test Pw01. Following the pulse withdrawal test and recovery to a stable pressure, a drill stem test was conducted. The shut-in recovery period was followed with a slug withdrawal test. Thermal effects on test interval pressure were not included because of the high hydraulic conductivity of the test zone.

Four consecutive hydraulic tests were included in the GTFM simulations. The drill stem test was simulated as a slug withdrawal followed by a pulse withdrawal with shut-in at the pressure obtained at the end of the flow period. A formation pressure at the center of the test interval was calculated to be 4482 kPa using the true vertical distance between the P2 transducer and the center of the interval, the calibrated formation pressure for the P2 transducer depth and an in-situ fluid density of 999.5 kgm^{-3}. This corresponds to an equivalent freshwater head at the center of the interval of about 362.0 m ASL.

The fit of the simulations to the measured pressures in the test interval are shown in Figure 1. The hydraulic conductivity corresponding to the most reasonable simulation of the measured pressures appears to be 6.0E-08 ms^{-1}. A sensitivity study of specific storage indicated that an increase in this parameter by a factor of 100 would decrease the interpreted K by less than a factor of 2.

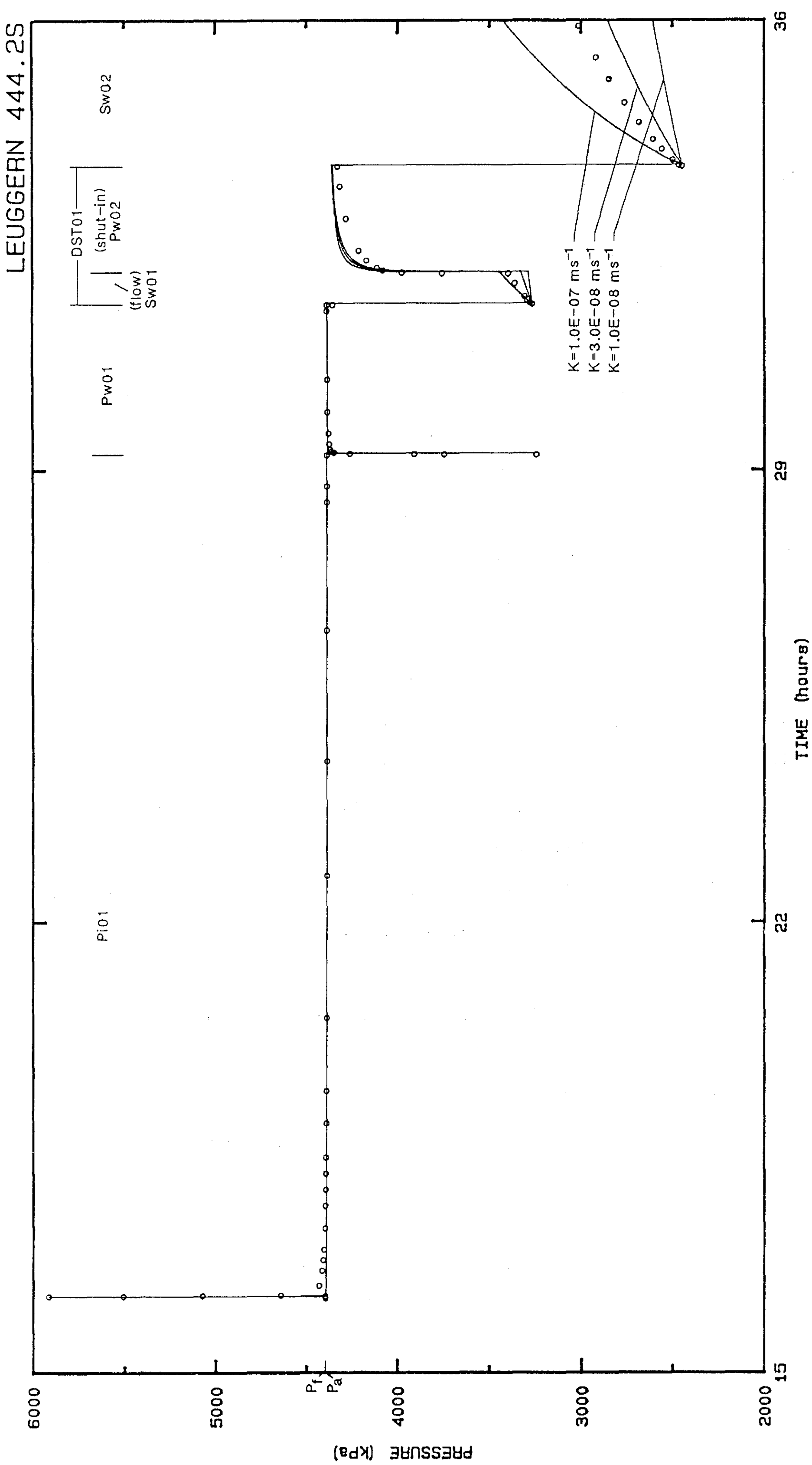


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 452.1H (440.80 m to 463.48 m)

This test period in the Leuggern borehole occurred during the reconnaissance H-logging phase, some 17 days from the midpoint of drilling. Four hydraulic tests, pulse injection, pulse withdrawal, drill stem test and slug withdrawal, permitted an estimation of formation hydraulic conductivity and specific storage. Formation pressure was estimated from an interpolated gradient between high permeability zones at 444 and 538 m. The pretest borehole history period of the GTFM simulations includes a 250 kPa drilling overpressure over half of the 6 day drilling period. This was followed by the influence of the overlapping 444.2S single packer test (440.35 to 448.05 m), simulated as a two day, 1000 kPa underpressure in the borehole. The remainder of the history period consisted of about 12 days of open borehole at an annulus pressure of 4378 kPa.

Despite the inclusion of underpressure in the borehole during the simulated history, through test 444.2S interference and the open borehole condition, the simulated pressure responses shown in Figure 1 are approaching a reference pressure above the measured response. This difference in pressure response suggests that the test interval might have been exposed to a pressure less than the assumed annulus pressure during the open borehole periods.

Based on the match of pressures measured during the drill stem test and the early time slug withdrawal data, the most reasonable hydraulic conductivity is 1.0E-07 ms^{-1} at a specific storage of the fractured granite of 2.3E-08 m^{-1}. A sensitivity study for this interval of the effect of varying specific storage over the range 1.0E-06 to 1.0E-08 m^{-1} on simulation of the pressure response demonstrated that only a marginal improvement in fit to the measured pressures could be obtained (i.e., less than a half-log-cycle shift in K). For the purpose of obtaining the best fit simulation, the low-end S_s was chosen.

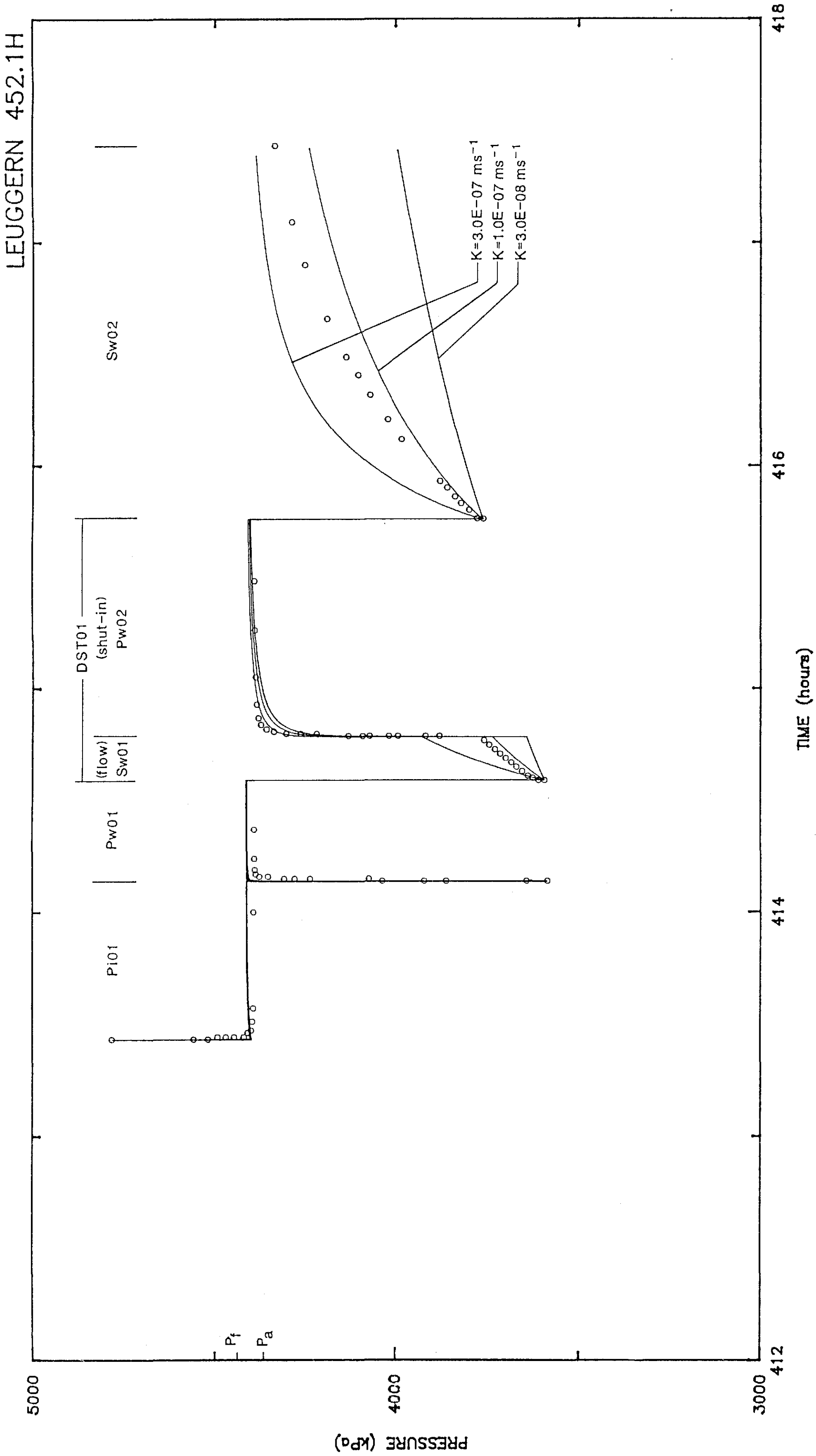


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 474.6H (463.24 m to 485.92 m)

The H-log pressure testing in this interval provided for a quantitative determination of formation hydraulic conductivity. An estimate of formation pressure in the test zone for hydraulic conductivity interpretation purposes is derived from a hydraulic-gradient calculated between the more permeable zones at 444 and 538 m depth.

The pressure history of this interval prior to testing consisted of about 30 hours of drilling and coring with an average overpressure at the bit near 400 kPa. The open borehole period, with the test interval exposed to an annulus pressure of 4549 kPa, lasted 12 days. GTFM simulations included both drilling and open borehole pressures in the pretest pressure history.

The sequence of hydraulic tests in the interval consisted of pulse injection, pulse withdrawal, a drill stem test and a slug withdrawal test. The GLAG field reports indicated difficulties in conducting the pulse injection test. The high permeability of the formation permitted an injected pulse of only about 120 kPa. Pressure recovery following the pulse injection was monitored for about 45 minutes, and was immediately followed by a pulse withdrawal test. The pulse withdrawal was significant (about 1000 kPa) but the recovery period was very short (about 15 minutes). The recovery periods for the remaining tests, DST01 and Sw01, were 70 minutes and 2 hours, respectively, with recovery for the DST approaching a reference pressure (affected by borehole history) between annulus and formation pressures. Test Sw01 was terminated before reaching a steady state pressure. The GTFM simulations for the range of hydraulic conductivity, 3.0E-07, 1.0E-07 and 3.0E-08 ms^{-1}, included each of these tests in sequence. Temperature variation from the start to end of testing was not significant and all simulations were considered isothermal. The formation pressure assumed for this interval was 4590 kPa.

The best simulation of measured pressures is for the flow period of DST01 with a hydraulic conductivity of 1.0E-07 ms^{-1} as shown in Figure 1. The fit of the remaining tests at this hydraulic conductivity is acceptable but can only be considered approximate. A study of the sensitivity of the simulated response to specific storage indicated that variation in S_s over some eight orders of magnitude (1.0E-05 to 1.0E-13 m^{-1}) had as much influence on fit as a half-log-cycle shift in hydraulic conductivity (i.e., 1.0E-07 to 3.0E-07 ms^{-1}) and did not significantly improve the fit between measured and simulated pressure responses. A base case value of S_s (2.2E-07 m^{-1}) was therefore assigned to this interval.

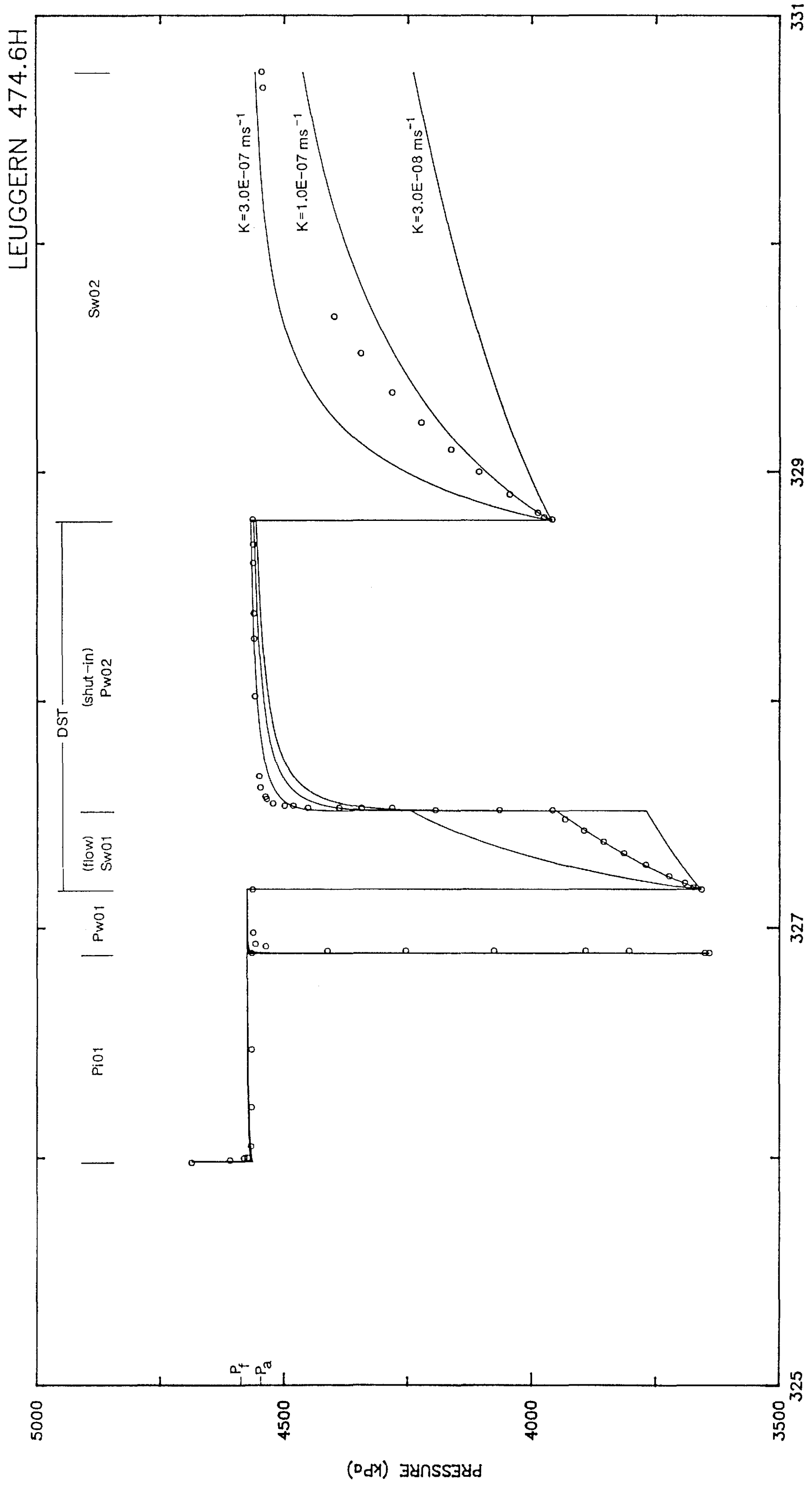


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 496.0H (484.67 m to 507.35 m)

This section of the crystalline was tested on 29 September, 1984, about 12 days after drilling. The testing sequence consisted of pulse injection, 2 pulse withdrawals, and slug withdrawal. All tests were included in deriving the interval hydraulic conductivity. The period of drilling lasted 20 hours during which a 300 kPa drilling overpressure was exerted on the interval. Between drilling and testing, the interval was exposed to an annulus pressure of 4803 kPa. These two periods comprised the pretest borehole pressure history sequence which was incorporated into the GTFM simulations.

A formation pressure of 4850 kPa, at the elevation of P2, was assumed for the test interval calculated from the pressure gradient across the borehole. The magnitude of the pulse for test Pi01 was about 1700 kPa with 90 percent recovery in 1.6 hours. Tests Pw01 and Pw02 both received about 800 kPa pulses, and these tests both showed over 90 percent recovery in an hour. The slug withdrawal test showed only 6 kPa recovery in 1.5 hours of monitoring. All tests were stopped before a static pressure was obtained. Thermal effects on test zone pressure were not considered in the simulations because temperatures at the transducers varied by only ±0.1°C. A representative specific storage of 2.2E-07 m^{-1} was chosen for the crystalline formation, which equates to a rock compressibility of 2.0E-11 Pa^{-1}.

For a range of hydraulic conductivities, 3.0E-11, 1.0E-10 and 3.0E-10 ms^{-1}, the results of the GTFM simulations are shown in Figure 1. The best estimate of hydraulic conductivity for the interval is approximately 1.0E-10 ms^{-1}, at a specific storage for the crystalline rock of 2.2E-07 m^{-1}. An improvement in fit for test Pw01 can be obtained by adjusting S_s to 2.2E-06 m^{-1} from 2.2E-07 m^{-1}.

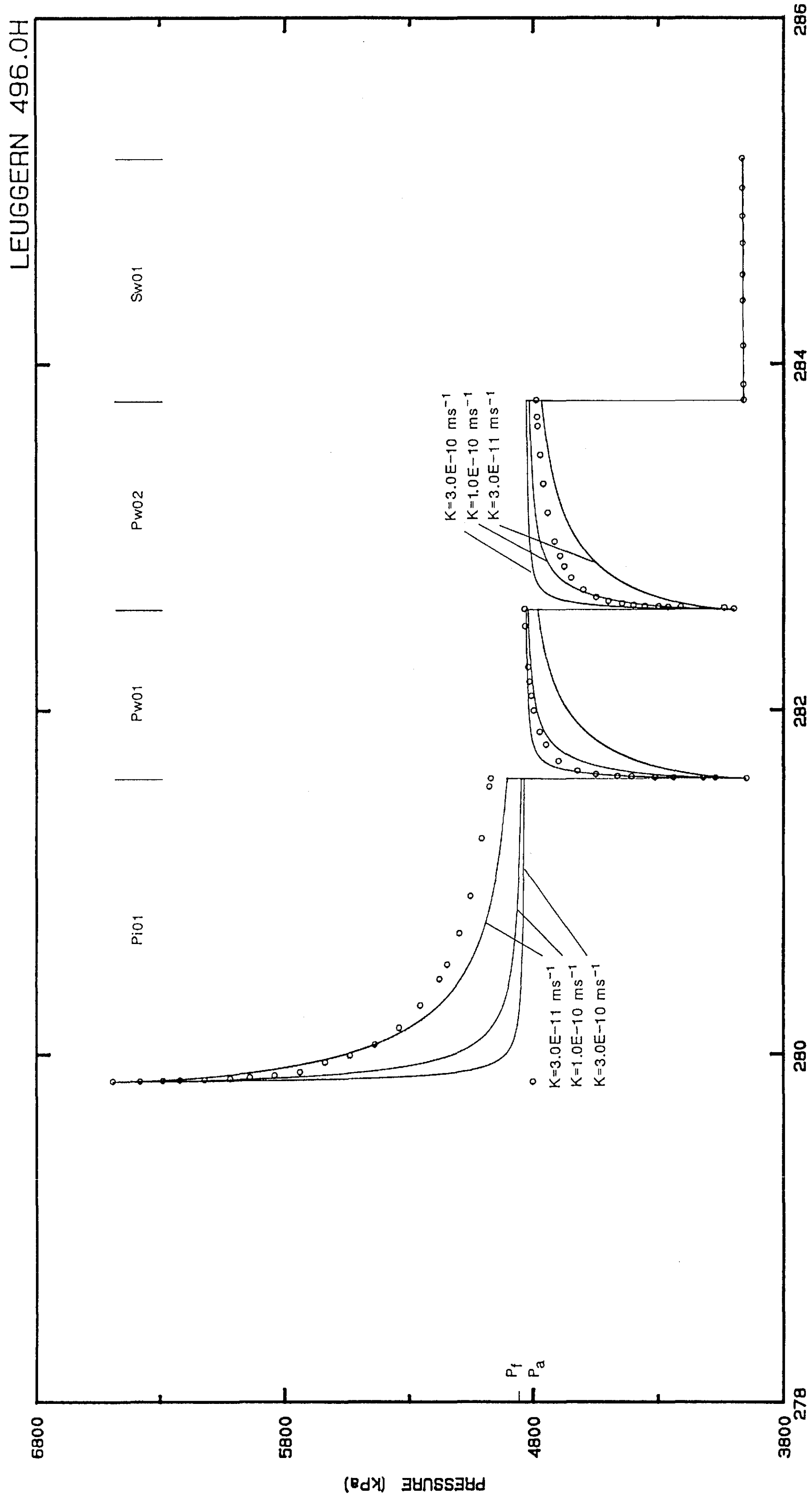


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 538.0S (507.35 m to 568.60 m)

Testing in this interval was completed with the objective of determining a formation pressure and a hydraulic conductivity representative of this section of the crystalline rock. The pressure history of this zone is fairly complex prior to the testing sequence. Initially, drilling difficulties delayed the completion of the interval. The drill period was simulated with a 200 kPa overpressure applied from the midpoint to the completion of drilling. The pressure in the borehole was then lowered below annulus for about 10 hours during a fluid logging exercise. This was simulated by a constant pressure period at 4122 kPa. The borehole was then open to an annulus pressure of 4960 kPa for about 3.5 days. Finally, the borehole fluid was recirculated over a 7-hour period. This recirculation period was not included in history because of its' short duration and the high hydraulic conductivity of the formation.

The sequence of tests from this interval that were simulated using GTFM. The testing sequence consisted of a pulse injection test, a pulse withdrawal test, a DST test and a slug withdrawal test. The pulse injection test conducted initially, although of use in determining a formation pressure, was not included in the simulation as the calculated pressure recovery in the interval was indifferent to the range of hydraulic conductivities anticipated for this zone. In this test interval, formation fluid samples were taken after the period of pressure testing. The sampling event was not included in the pressure simulations. The sequence of four tests which has been used to derive K and S_s in this interval is considered appropriate given the completeness of each of the test responses.

Figure 1 shows the simulated pressure response of tests Pw01, DST and Sw01 for a range of hydraulic conductivity of 1.0E-07, 3.0E-08, and 1.0E-08 ms^{-1}. Each test was simulated under isothermal conditions. Maximum variation in fluid temperature over the test period was ±0.8°C. Thermal effects on test interval pressure were not included because of the high permeability of the test zones. The most reasonable hydraulic conductivity for the formation in this interval is 3.0E-08 ms^{-1} at a specific storage of 2.2E-07 m^{-1}. An improvement in fit to the measured data could be obtained with a increase in K by a factor of 2 or 3. The best estimate of formation pressure, based on recovery to a near stable pressure during test Pi01 after a 40 minute shut-in period and test Sw01 after 70 minutes of recovery, is 5002 kPa.

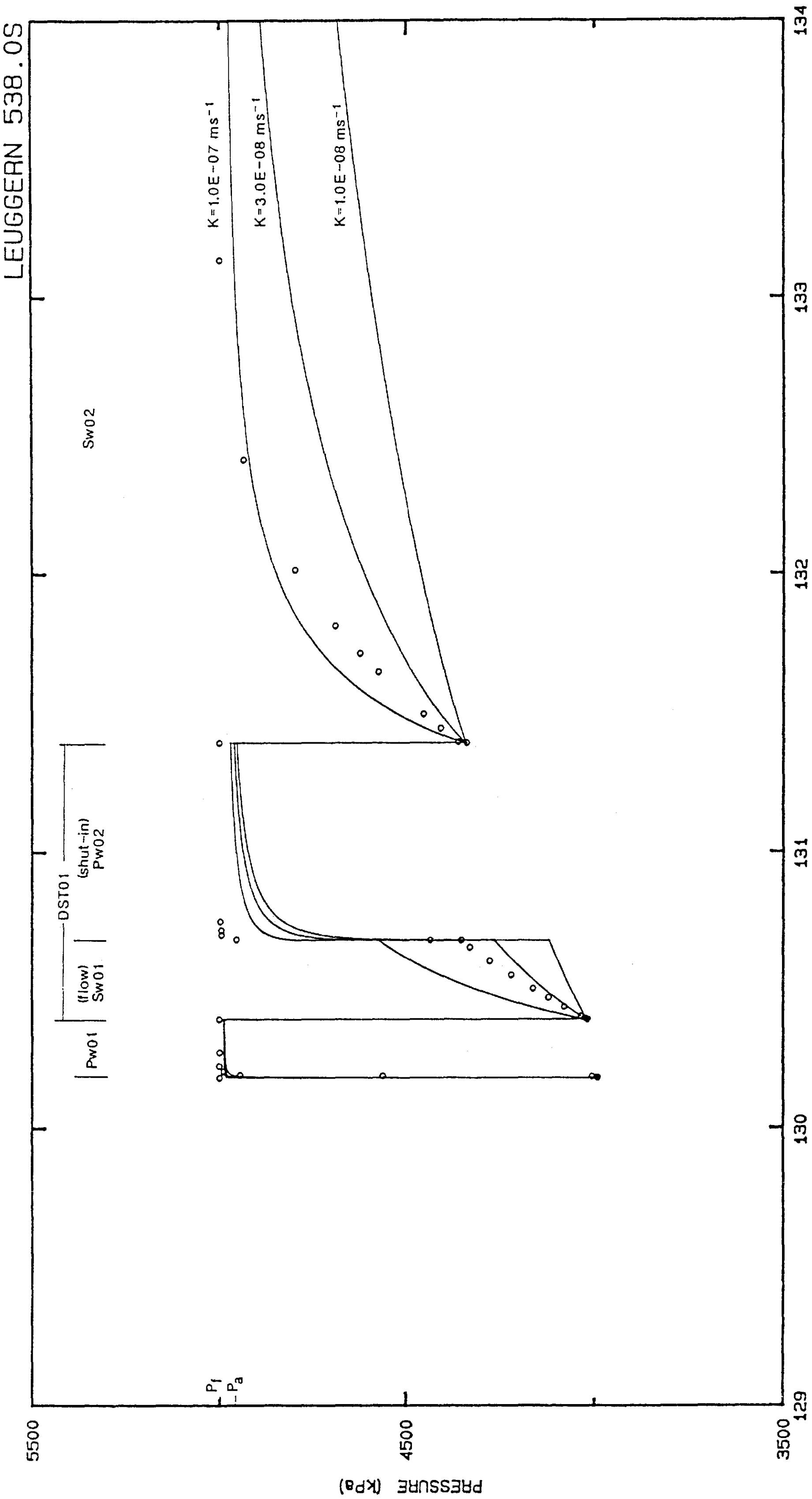


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 581.9H (567.85 m to 595.87 m)

The interpretation of pressure test data from the 582 m depth in the Leuggern borehole provided reasonable estimates of hydraulic conductivity and specific storage of the crystalline rock. Because of the long history period prior to testing, formation pressure for this test interval was calculated from a pressure gradient for the borehole based on the single packer test data.

Borehole pressure history included in the GTFM simulations consisted of a period of 400 kPa drilling overpressure from the mid-point to the end of the drilling period, a 25 day open borehole period at an annulus pressure of 5590 kPa between drilling and the start of testing, and two compliance periods corresponding to separate packer inflation and monitoring events.

Formation pressure assumed for this interval is about 5639 kPa. Base case values of rock compressibility and porosity were chosen as representative of the interval. Fluid compressibility and fluid density are for freshwater at formation temperature and pressure.

The results of the GTFM simulations are shown in Figure 1. The simulations assumed no skin or other boundary conditions close to the borehole. The estimate of the most representative hydraulic conductivity for this zone, based on the simulation of the pulse injection, pulse withdrawal, and early time DST shut-in data, is 1.0E-09 ms^{-1}.

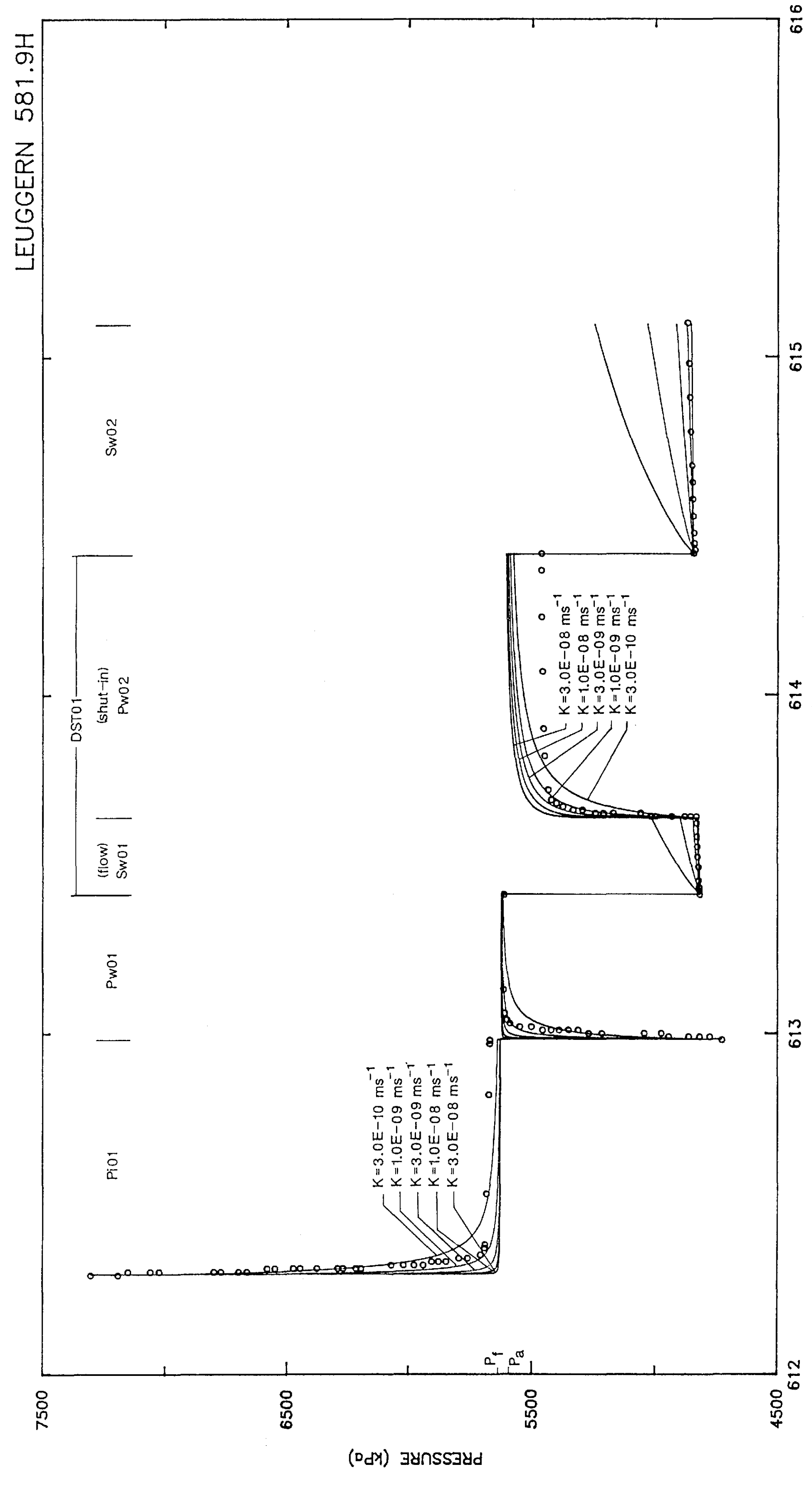


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 606.2H (592.22 m to 620.24 m)

Hydraulic testing of the 592.22 to 620.24 m zone of the crystalline rock was conducted during the H-logging reconnaissance phase, close to 24 days after completion of drilling. Testing by pulse injection and slug withdrawal was completed within 4 hours after packer inflation. The objective of the testing was to provide for an interpretation of hydraulic conductivity. During the pulse injection test, recovery from a pulse of 1818 kPa above annulus pressure was monitored over 3 hours to 42 percent of recovery. The slug withdrawal recovery period was monitored for one hour during which less than one percent change in pressure was observed. An assumed formation pressure of 5858 kPa was estimated for this interval from a pressure gradient based on single packer test pressures for intervals above and below interval 606.2H.

The interval was drilled between 11 and 12 October, 1984. The drilling history was simulated as a 300 kPa total overpressure from the mid-point to the end of drilling. The 24.1 day period between drilling and packer inflation was simulated under open borehole conditions at annulus pressure of 5854 kPa. Prior to pulse injection testing, pressure of about 5878 kPa was applied to the test interval during an hour of packer compliance monitoring.

Only the pulse injection test was chosen as suitable for analysis. Simulation of the slug withdrawal test did not provide any distinction between simulated pressure recovery curves and therefore was not considered further in the analysis. The simulated pressure responses for test Pi01 are shown in Figure 1. The range of hydraulic conductivity, in half-log-cycle increments, was chosen to bound the measured response. GTFM simulations were run under isothermal conditions.

The most reasonable match of the pulse injection data is with a hydraulic conductivity of the test interval at 1.0E-12 ms^{-1}. A sensitivity study of specific storage indicated that an improvement in fit of simulated to measured pressures could be obtained by increasing S_s from the base case value of 2.2E-07 to 3.0E-07 m^{-1}, corresponding to an increase in rock compressibility from 2.0E-11 to 3.0E-11 Pa^{-1}. At the hydraulic conductivity determined for this interval, the simulated pressure response is very sensitive to S_s. For example, the uncertainty in the best estimate of K is close to an order of magnitude for an acceptable range in S_s from 2.0E-06 to 2.0E-08 m^{-1}.

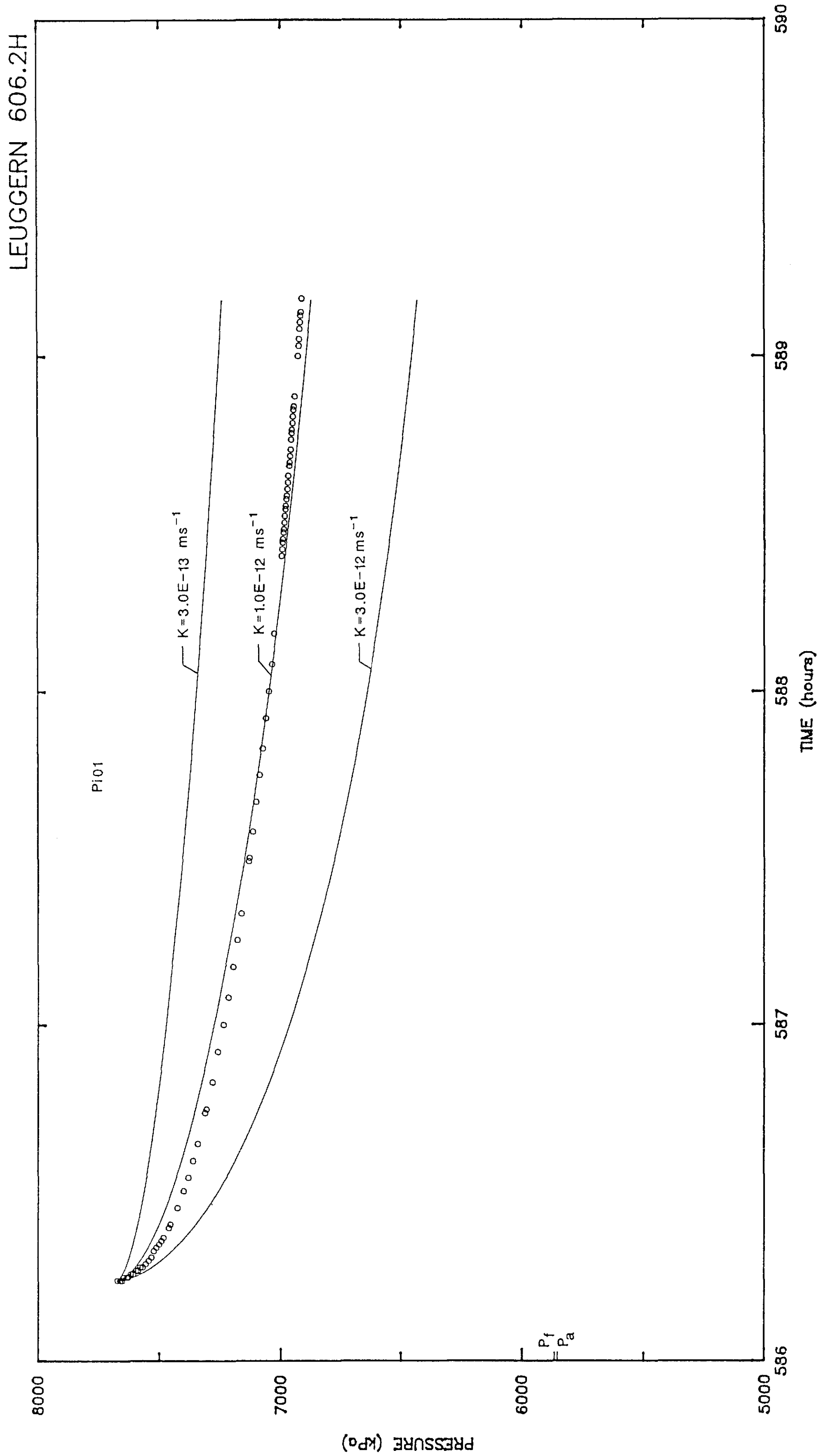


Figure 1: Measured (o) and Simulated Pressure Response for Test Pi01

Test 634.0H (619.98 m to 648.00 m)

This section of the crystalline rock at Leuggern, from a depth in the borehole of 619.98 to 648.00 m, was drilled continuously from 12 to 13 October, 1984. Following the drilling period, the interval remained open for approximately 23 days before H-log testing. The testing period started on 4 November, 1984 with the inflation of the double packer system. The objective of testing this zone is to obtain a representative hydraulic conductivity of the crystalline rock. The sequence of hydraulic tests conducted to fulfill this objective included pulse injection, drill stem and slug withdrawal tests. Only the pulse injection test yielded a response suitable for interpretation. A formation pressure of 6120 kPa was derived from a pressure gradient for the borehole calculated using calibrated formation pressures from single packer tests.

The simulated borehole pressure history includes a 300 kPa overpressure during drilling, an open borehole period at annulus pressure of 6135 kPa for 22 days, and a pressure slightly above annulus during the short compliance period. The pulse injection test consisted of a pressure pulse of about 1650 kPa applied to the interval over several minutes. Close to 95 percent recovery was observed in 1.5 hours. Base case values of porosity and specific storage were chosen at 0.005 and 2.2E-07 m^{-1}, respectively.

The measured and simulated pressures for the pulse injection test, for the range of hydraulic conductivities 1.0E-11, 3.0E-11, and 1.0E-10 ms^{-1}, are shown in Figure 1. The most reasonable simulation of the pulse test appears to be for a hydraulic conductivity of 3.0E-11 ms^{-1}. A slight improvement in fit of the early time data could be obtained by adjusting K lower to about 2.5E-11 ms^{-1}, or by lowering specific storage to an estimated 2.0E-08 m^{-1}.

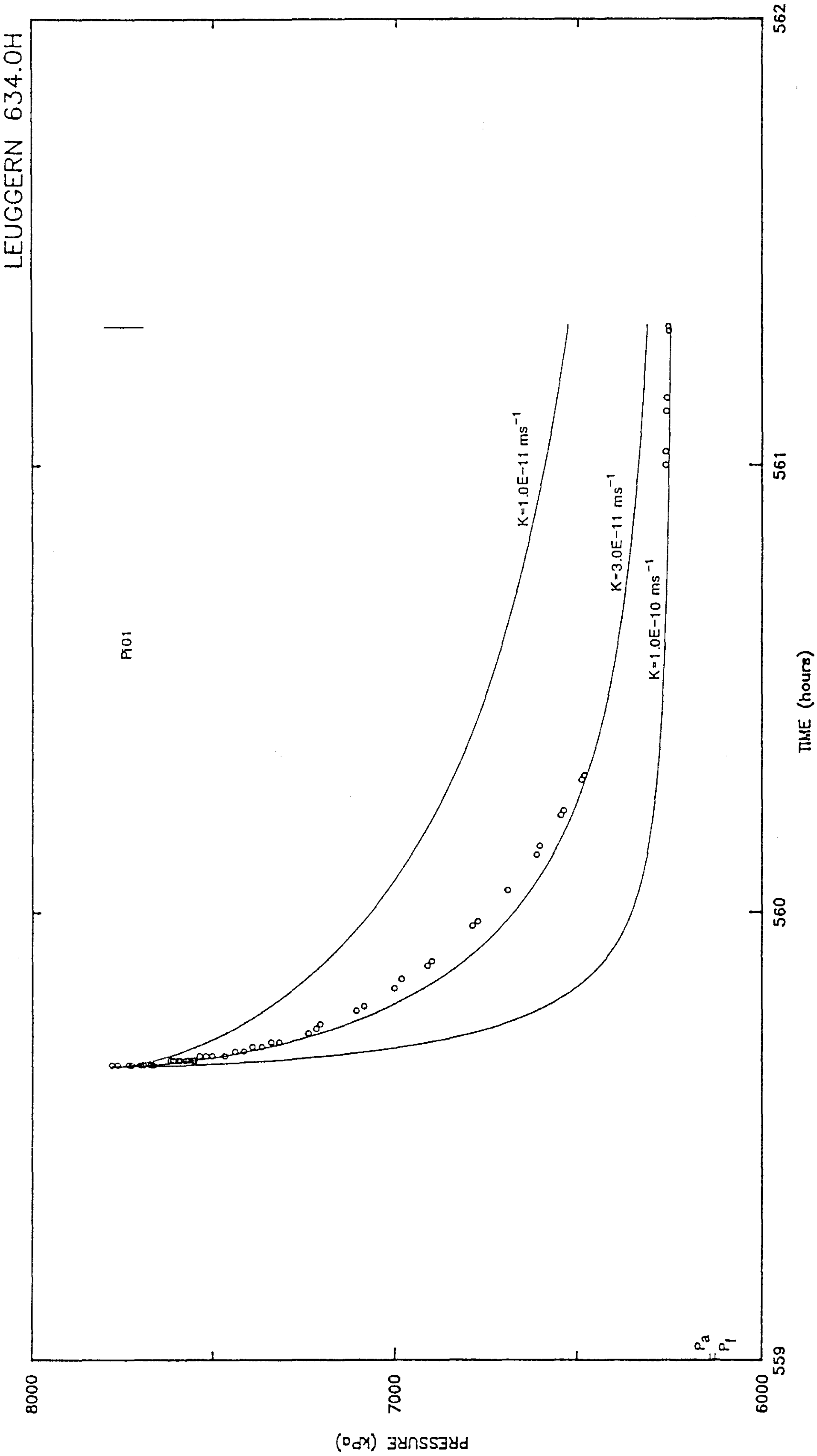


Figure 1: Measured (o) and Simulated Pressure Response for Test Pi01

Test 653.7H (641.18 m to 666.15 m)

This section of the Leuggern borehole was drilled in early October, 1984. The hydraulic tests conducted in the interval from 641.18 to 666.15 m consisted of a pulse injection test and a drill stem test, which yielded results suitable for interpretation of hydraulic conductivity. The assumed formation pressure of 6317 kPa for this interval was calculated from the pressure gradient across the borehole derived using adjacent single packer test results.

The pretest borehole pressure history for the interval consisted of a period of overpressure during drilling of about 300 kPa. This overpressure was applied for half the drilling period or about 18 hours. Between drilling and testing, the interval was exposed to full annulus pressure of 6312 kPa, which is approximately 5 kPa below the assumed formation pressure. The open borehole period lasted about 21 days. An equipment compliance test was conducted for about an hour prior to pulse injection, during which the pressure on the interval was raised 30 kPa above annulus pressure. Each of these history events was included in the GTFM simulations.

Initially, a pressure pulse of about 1900 kPa was applied under shut-in conditions to the test interval and monitored for 3.5 hours. The test interval pressure recovered to within 10 percent of the assumed formation pressure. Fluid temperature in the test interval decreased by about 0.3°C during pressure recovery. Since the effect of cooling during pressure injection would be to over-estimate hydraulic conductivity of the formation, thermal effects were added into the pressure response simulation. During the DST flow period, initiated by underpressuring the interval by about 1467 kPa, pressure recovery was 10 kPa in 60 minutes. The interval pressure recovered to about 30 kPa above the assumed formation pressure in 2 hours during the shut-in period of the DST (Pw01).

Test simulations were conducted for the range of hydraulic conductivity 1.0E-10, 3.0E-11, 1.0E-11, and 3.0E-12 ms^{-1} as shown in Figure 1. A value of specific storage equal to 2.2E-07 m^{-1} was chosen as representative of the test interval. Sensitivity of the best-fit hydraulic conductivity to specific storage was less than half an order of magnitude in K for two orders of magnitude in S_s (1.0E-06 to 1.0E-08 m^{-1}). The most reasonable simulation of the pulse injection data (Pi01) is for a formation K of about 6.0E-12 ms^{-1}. Simulation of the DST shut-in pressure response results in an estimate of K at least one order of magnitude greater than 1.0E-10 ms^{-1}. The hydraulic conductivity chosen for this interval, based on the simulation of test Pi01, is 6.0E-12 ms^{-1}.

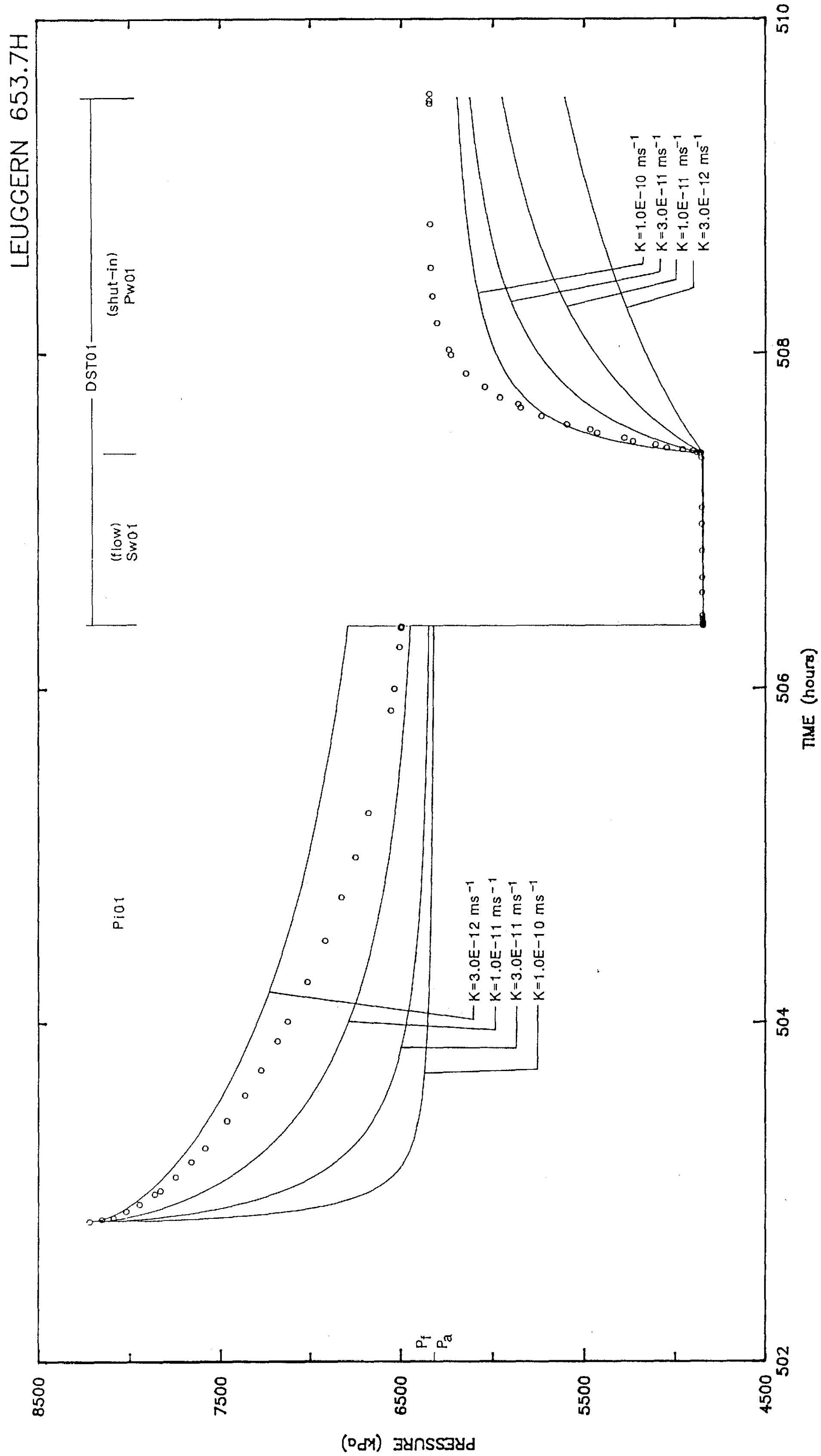


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 676.8H (664.35 m to 689.32 m)

The H-log testing at 664.35 to 689.32 m in the Leuggern borehole consisted of two pulse tests, a drill stem test, and a slug test. All of the tests were conducted over about a five hour period. The drilling phase was completed in October, 1984. Testing started within 20 days of drilling. Simulation of the testing sequence was completed under isothermal conditions. The purpose of the test analyses was to derive a hydraulic conductivity from the measured pressure response data. A formation pressure of 6570 kPa for this interval was derived by calibrating the simulated data to the measured final recovery pressures. This calibrated formation pressure represents an equivalent freshwater head at the center of the interval of 363.8 m ASL.

The simulated pretest borehole pressure history period consisted of an 18.5 hour drilling period with a 300 kPa overpressure, a 19 day open borehole period at annulus pressure of about 6535 kPa, and a one-hour equipment compliance period.

The simulated pressures corresponding to the range of hydraulic conductivities 3.0E-08, 1.0E-08, and 3.0E-09 ms^{-1} are shown in Figure 1. The most reasonable estimate of hydraulic conductivity for the interval is 5.0E-09 ms^{-1}. A base case specific storage value of 2.2E-07 m^{-1} was chosen for the simulations. Because of the relatively high hydraulic conductivity of this zone, the pressure recovery is insensitive to variations in specific storage. For example, a variation in S_s over several orders of magnitude results in a change in best-fit K of less than a half an order of magnitude.

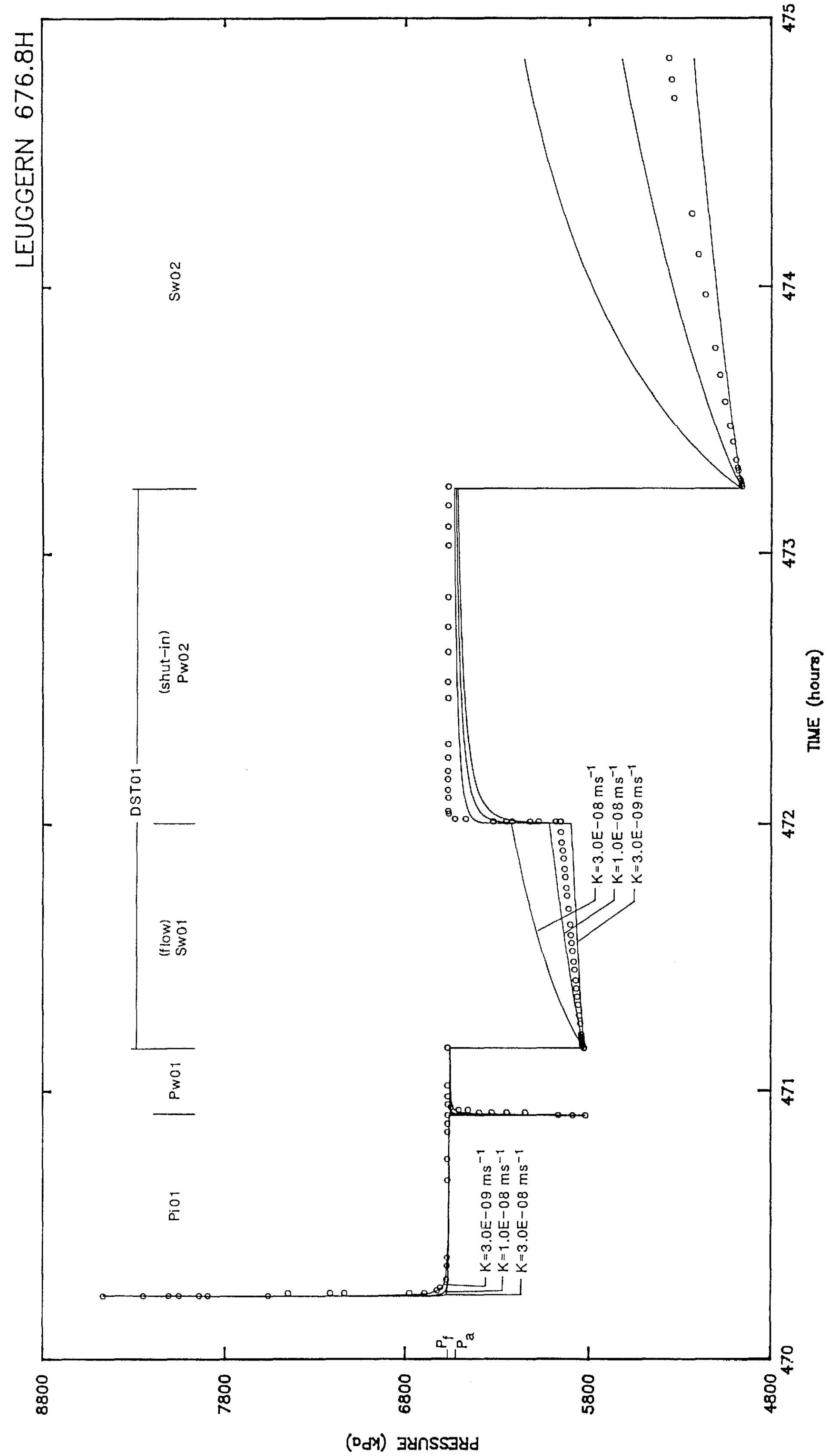


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 696.2H (683.71 m to 708.68 m)

The objective of the H-log testing at 683.71 to 708.68 m depth in the Leuggern borehole was to obtain a representative formation hydraulic conductivity. The testing sequence in the interval consisted of pulse injection and withdrawal, drill stem and slug withdrawal tests. The pulse injection test (Pi01) shows a pressure change of 115 kPa over a monitoring period of 0.5 hours for full recovery. The pulse withdrawal test (Pw01) consisted of a 780 kPa pulse with full recovery within about one minute. The interval was monitored for about 0.25 hours. The DST flow and shut-in sequence was monitored for an hour showing complete recovery from a 776 kPa under pressure. The slug withdrawal test (Sw02) was also monitored for one hour. Complete recovery was obtained after about 30 minutes; monitoring was continued to verify a stable reference pressure.

Prior to testing, this interval was exposed to a drilling overpressure of 350 kPa for about 20 hours, an open borehole period for 17.9 days at annulus pressure of 6734 kPa, and a one hour equipment compliance period. This pretest pressure history was included in the GTFM simulations.

The formation and fluid conditions assumed for analysis include a calibrated formation pressure of 6757 kPa, derived by simulating the stable recovery pressure for each test in the sequence. The calibrated formation pressure was chosen because of the consistent recovery of each test to this pressure. It corresponds to an equivalent freshwater head at the center of the interval of 363.95 m ASL. It seems unlikely that the P_f would be lower than 6757 kPa given the lack of history which could have created a pressure skin above formation pressure around the borehole.

The simulated pressure responses are compared to the measured pressure response in Figure 1. All simulations were completed with a base case specific storage of 2.2E-07 m^{-1}. The simulations show that for a range of hydraulic conductivities (1.0E-06, 3.0E-07, and

1.0E-07 ms^{-1}), a best fit K of about 2.0E-07 ms^{-1} would match the drill stem test flow data and slug withdrawal data (Sw02). The best estimate of hydraulic conductivity is relatively insensitive to variation in specific storage.

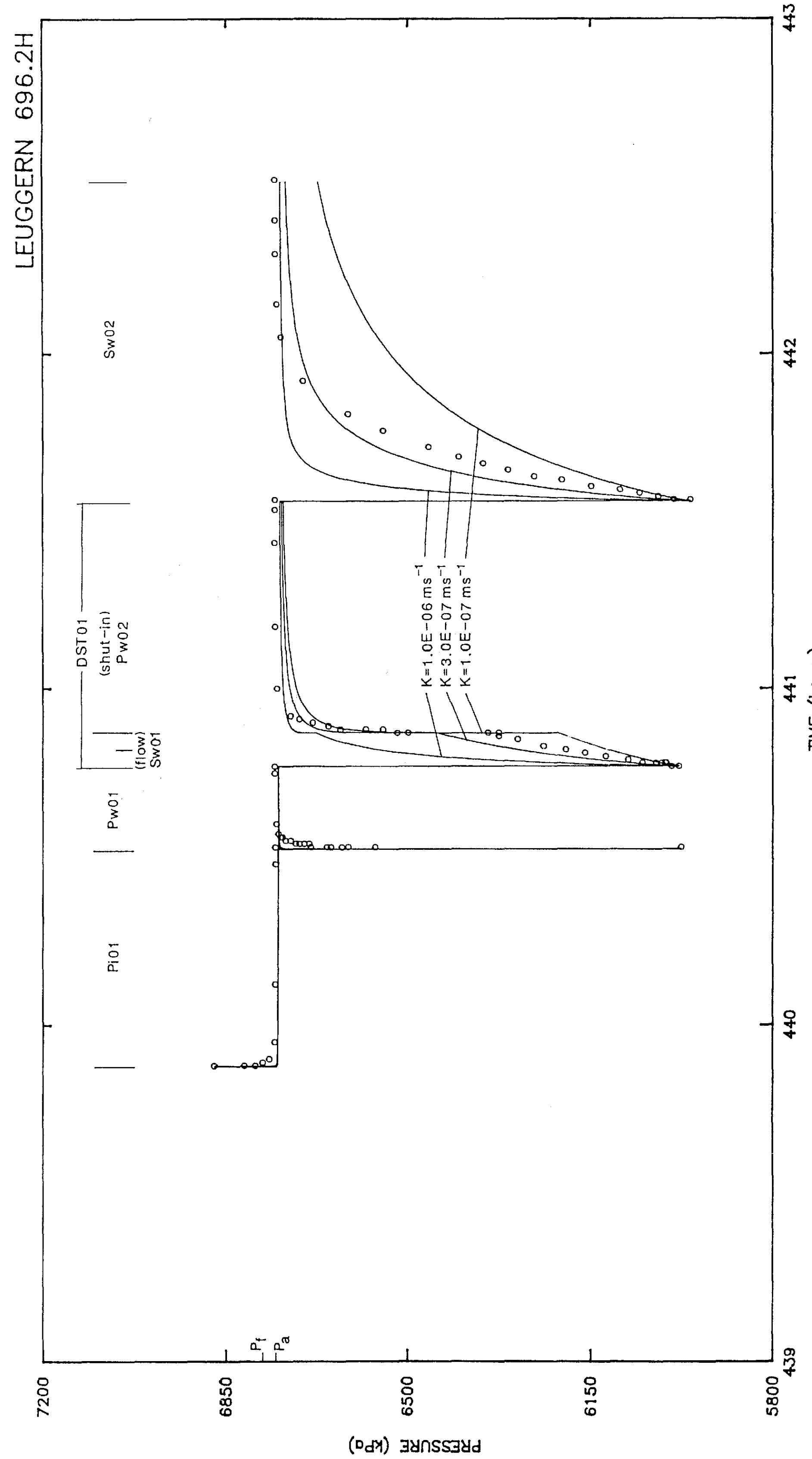


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 705.7S (702.00 m to 709.45 m)

Single packer testing was performed in this interval to obtain a representative formation pressure and formation hydraulic conductivity. Testing commenced approximately 17 hours after the mid-point of the 8 hour drilling period. The pre-test borehole pressure history was simulated with a 350 kPa drilling overpressure for half of the drilling period, followed by a open borehole period at an annulus pressure of 6899 kPa, and a short packer compliance period.

Thermal effects were not included because of the high hydraulic conductivity. The testing sequence for this interval consisted of a pulse injection (Pi01), a pulse withdrawal (Pw01), a drill-stem test (Sw01 and Pw02) and a slug withdrawal (Sw02).

The two initial pulse tests, Pi01 and Pw01, recovered too quickly to be analyzed, qualitatively indicating a zone of high hydraulic conductivity. The drill-stem test consisted of a 5 minute flow period, Sw01, and a 54 minute shut-in period, Pw02. The final slug withdrawal test recovery was monitored for about 2.5 hours. The drill-stem test and the slug withdrawal test, Sw02, are matched very well by a simulated pressure response with a hydraulic conductivity of 1.0E-06 ms^{-1}, a specific storage of 2.0E-06 m^{-1} and a formation pressure at P2 depth of 6930 kPa. Figure 1 shows the simulated best-fit response along with simulated responses for K = 3.0E-06 and 3.0E-07 ms^{-1}.

The simulated pressure response was very sensitive to changes in the simulated formation pressure. A change in the simulated formation pressure produced a change of nearly equal magnitude in the simulated pressure response. Varying the drilling overpressure had a negligible effect on the simulated pressure response, because of the high hydraulic conductivity. Therefore, the formation pressure obtained from this test is considered to be a good estimate of the true formation pressure. A formation pressure representative of the center of the interval was calculated to be 7014 kPa using the true vertical depth between the P2 transducer and the center of the interval, the interpreted formation pressure at P2 depth, and an in-situ fluid density of 998 kgm^{-3}. The equivalent freshwater head at the center of the interval is 362.8 m ASL.

Varying the formation specific storage within one order magnitude of the base case value of 2.2E-07 m^{-1} did not have a significant effect on the simulated response. A value of 2.0E-06 m^{-1} was chosen for this interval based on the large number of fractures and brecciated zones.

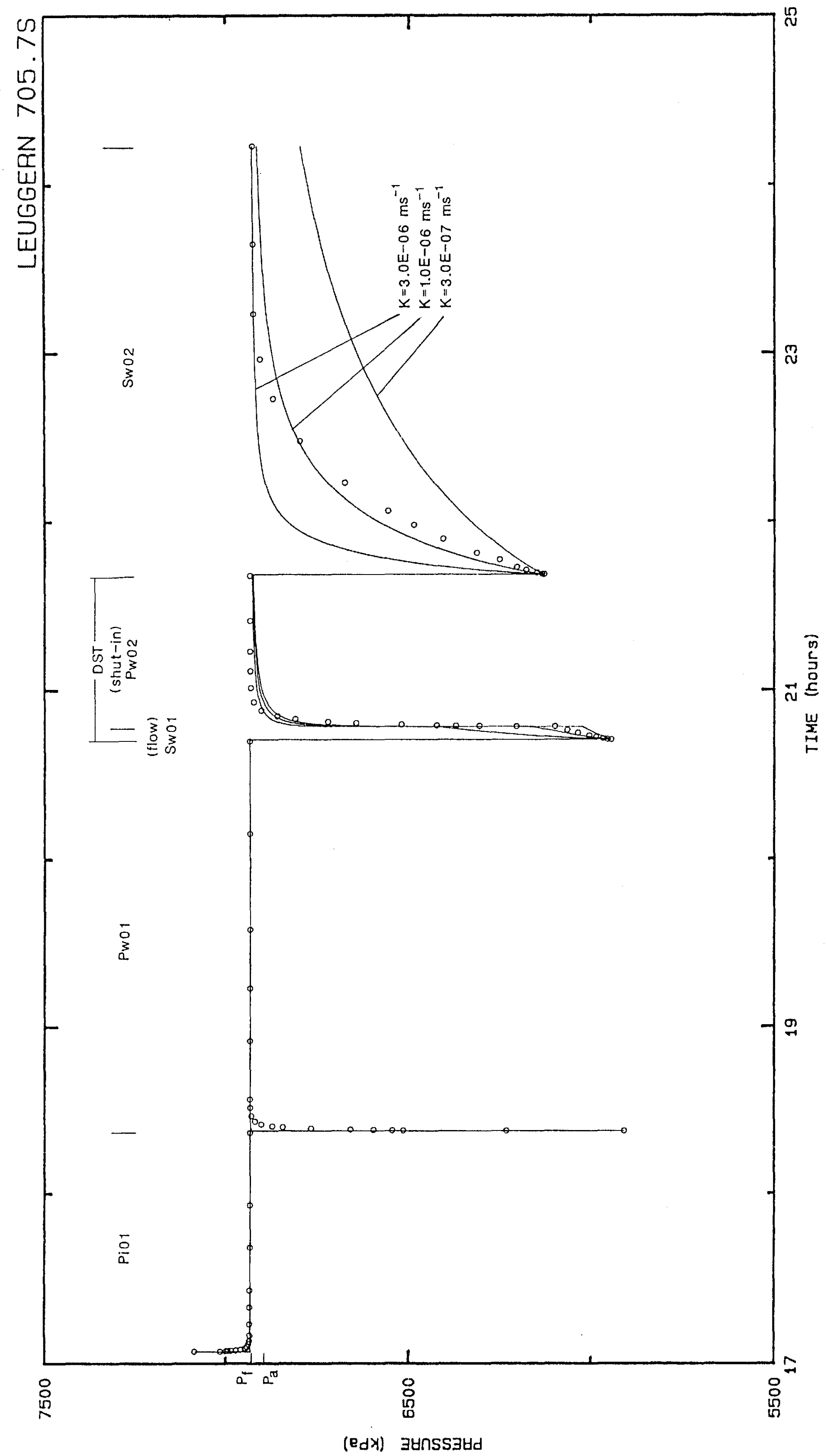


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 721.0H (708.53 m to 733.50 m)

This interval was tested during H-log sequence #3 in order to determine a formation hydraulic conductivity. This test was immediately preceded by the 722.2H H-log test, which covered the interval from 709.68 to 734.65 m apparent depth. Test 722.2H was abandoned 20 minutes after the start of a single pulse injection due to suspected packer leakage. Test 721.0H consisted of a pulse injection (Pi01), a slug withdrawal (Sw01), and a pulse withdrawal (Pw01). A formation pressure of 6990 kPa at P2 depth was estimated from the values determined by single packer tests of surrounding intervals.

For simulation purposes, a 22 hour drilling period (half the drilling period) at 325 kPa (half the drilling overpressure) over annulus pressure was modeled as part of the pre-test history. Test 722.2H was included in the pre-test borehole pressure history for this test as a constant pressure period at 6987 kPa. The pre-test pressure history also includes two open borehole periods at an annulus pressure of 6972 kPa (one for 13.8 days prior to test 722.2H and one for 35 minutes after test 722.2H and prior to 721.0H) and a 1 hour packer compliance period.

The best-fit simulation corresponded to a hydraulic conductivity of 1.0E-11 ms^{-1} and a specific storage of 2.0E-06 m^{-1}. Figure 1 shows the best-fit response and gives an indication of the sensitivity of the response to hydraulic conductivity. A good fit was achieved for both pulse tests but the simulated response for the flow period (Sw01) was slower than the measured response. The hydraulic response at test Sw01 is not considered representative of the hydraulic conductivity of the interval. In this case, the measured pressure response during Sw01 is faster than the simulated response which indicates a hydraulic conductivity greater than 3.0E-11 ms^{-1}. This result is inconsistent with the simulation results for Pi01 and Pw01. The discrepancy could be caused by inflow from the annulus through tubing joints and into the tubing string thereby creating an enhanced pressure recovery.

Varying the specific storage had a significant effect on the response during Pi01 and Pw01 but little effect on the response of Sw01. A one order of magnitude change in specific storage produced a 50 to 100 kPa change in the magnitude of the Pi01 response during the first hour of recovery. The best-fit value of 2.0E-06 m^{-1} was selected because it provided a much better match to the early time (first hour) observed data for the pulse tests than the base case specific storage of 2.2E-07 m^{-1}.

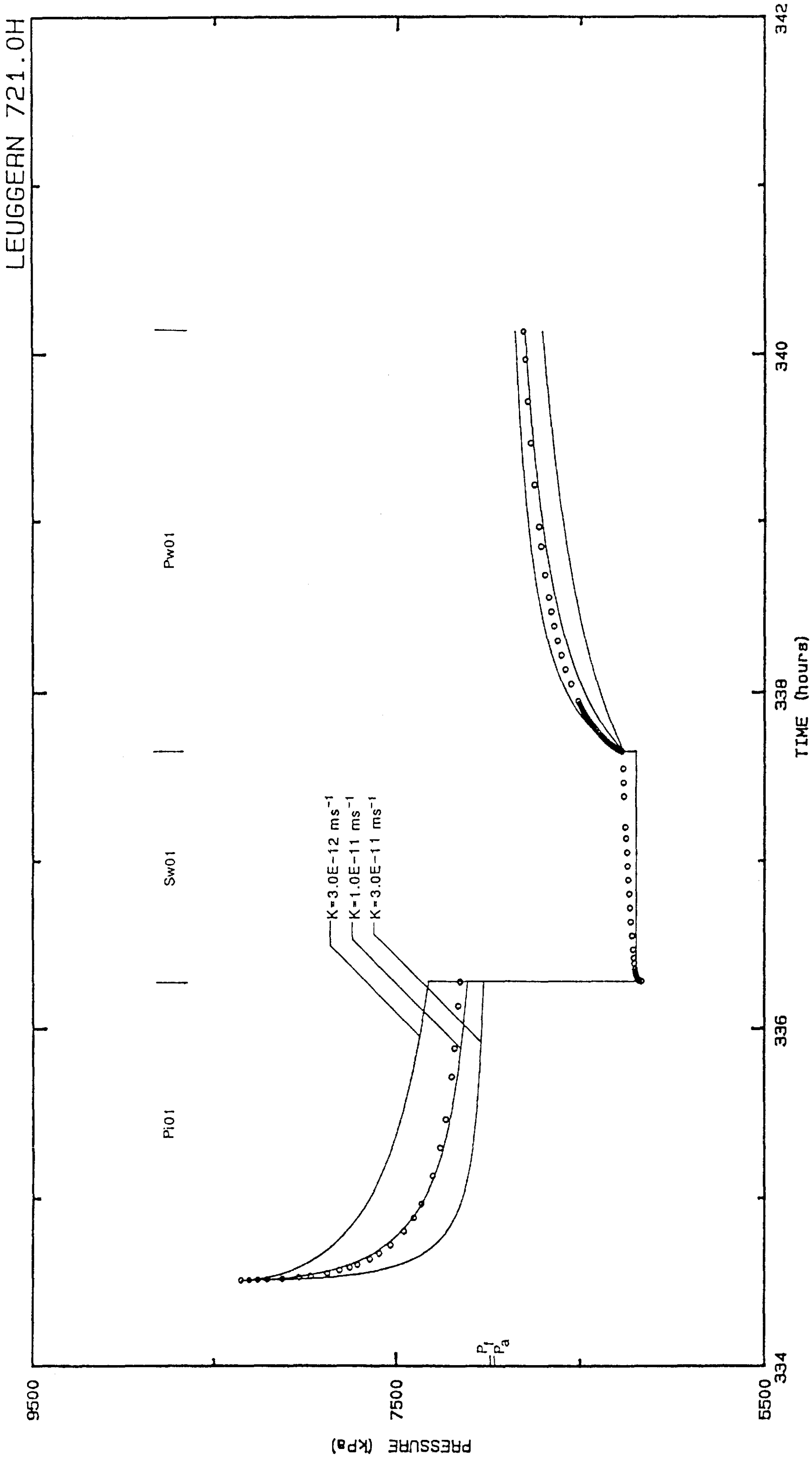


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 745.2H (732.69 m to 757.66 m)

H-log testing was performed in this interval on 2 November, 1984 in order to determine the hydraulic conductivity of the crystalline rock. The interval was drilled in a 23.3 hour period and was open for 12.1 days prior to the start of testing. The pre-test pressure history period was simulated with a drilling period at 300 kPa over annulus pressure, an open borehole period at an annulus pressure of 7203 kPa, and a 1.5 hour packer compliance period. The testing sequence was comprised of the following tests: a pulse injection (Pi01), a pulse withdrawal (Pw01), and a slug withdrawal (Sw01).

Due to the long open borehole period between drilling and testing, a formation pressure could not be determined from testing, as the simulated pressure response was very insensitive to changing formation pressure. Instead, a formation pressure representative of the interval of 7220 kPa at P2 depth was interpolated from the values determined from the surrounding single packer tests.

The best-fit simulated pressure response, based on a match to Pi01, is obtained using a formation pressure of 7220 kPa, a hydraulic conductivity of 1.0E-11 ms^{-1} and a specific storage of 1.0E-06 m^{-1}. Figure 1 shows the simulated response for three different hydraulic conductivities; 1.0E-11, 3.0E-10, and 1.0E-10 ms^{-1}. The rapid recovery of test Pw01 makes it impossible to match using the best-fit K value. A hydraulic conductivity of 3.0E-11 to 1.0E-10 ms^{-1} is required to obtain an adequate fit for Pw01.

The simulated pressure response was sensitive to specific storage, particularly in the first hour of pulse testing. Simulations with a specific storage of 2.2E-07 m^{-1} yielded a response about 50 kPa above the measured Pi01 response in early time while a specific storage of 2.0E-06 m^{-1} resulted in a response about 50 kPa below the measured response. These simulation results seem to indicate a specific storage between 2.0E-06 to 2.2E-07 m^{-1}. Therefore a value of 1.0E-06 m^{-1} was selected for this interval.

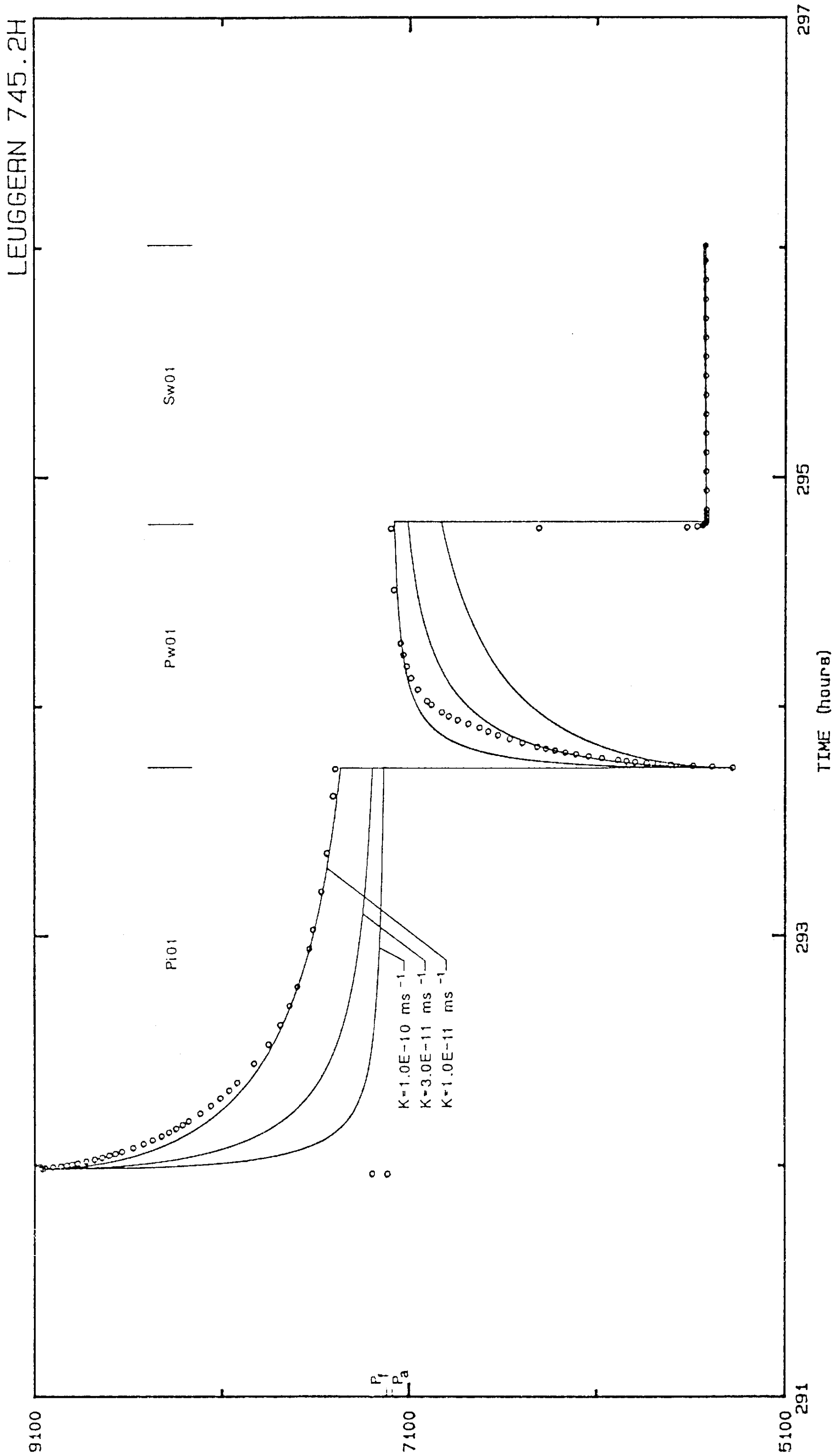


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 769.9H (757.41 m to 782.38 m)

This interval was tested on 2 November, 1984, as part of H-log sequence #3, in order to determine a formation hydraulic conductivity. An earlier test, test 765.0H (752.20 to 777.47 m), performed 2.5 hours before test 769.9H, was aborted during an initial pulse injection test after packer leakage was discovered. Since test 765.0H covered most of the interval tested in 769.9H, it was included in the pressure history for 769.9H. The pre-test pressure history was simulated by an 18 hour drilling period at 325 kPa over annulus pressure, a 9.8 day open borehole period at an annulus pressure of 7439 kPa, pulse injection test 765.0H, a 1 hour open borehole period near annulus pressure, and 1 hour packer compliance period.

The 769.9H testing sequence included a 63 minute pulse injection test (Pi01), a 29 minute pulse withdrawal test (Pw01), and a 82 minute slug withdrawal test (Sw01). A 0.2°C temperature rise was measured during the first 5 minutes of test Pw01, however, the temperature change was only recorded by the T2 transducer and is not considered to be representative of the formation. The formation pressure for this interval (measured at P2 depth) was estimated to be 7460 kPa based on an interpolation between formation pressures calculated for single packer tests 705.7S, 850.5SI, and 850.0SII.

A simulation with a hydraulic conductivity of 3.0E-11 ms^{-1}, a specific storage of 2.0E-06 ms^{-1} and a formation pressure of 7460 kPa produced the best match to the measured data from Pi01. As can be seen in Figure 1, the simulated responses for Pw01 did not recover as quickly as the measured data indicating a higher formation hydraulic conductivity than Pi01. However, given the fact that Pi01 was the first test in the sequence, the hydraulic conductivity determined from the Pi01 fit must be considered the best estimate. The flow period, Sw01, is insensitive to changes in hydraulic conductivity below about 1.0E-10 ms^{-1} and therefore does not provide any additional information on a representative K value.

Variation of the specific storage by one order of magnitude changes the simulated response by about 60 kPa. A value of 2.0E-06 m^{-1} was selected for this interval because it produces the best fit while maintaining an acceptable value for the compressibility of the crystalline rock (2.0E-09 to 2.0E-12 Pa^{-1}).

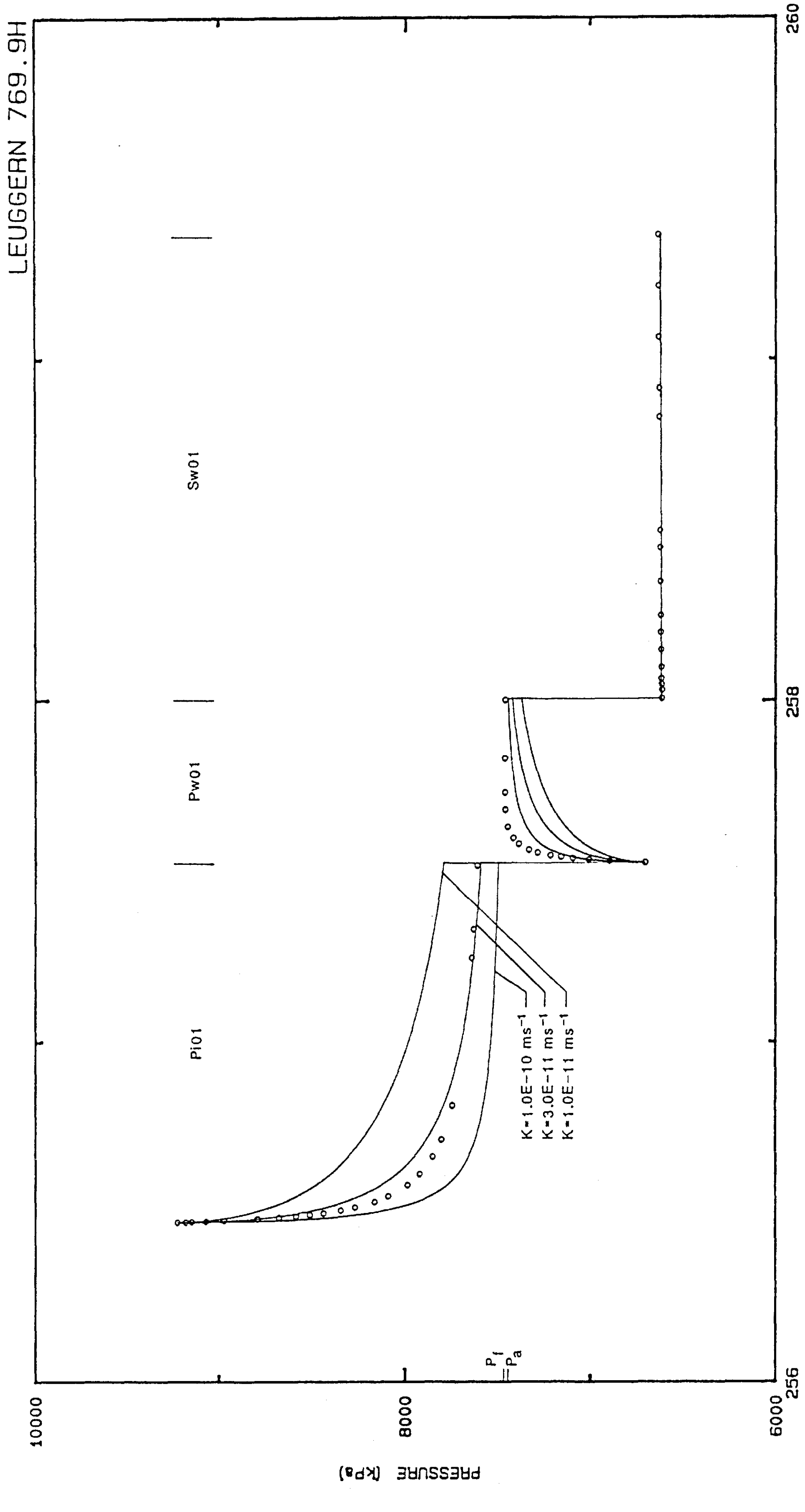


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 788.3H (775.85 m to 800.82 m)

This interval was tested as a part of H-log sequence #3 in order to determine a representative formation hydraulic conductivity. An initial pulse injection test was aborted after 2 minutes due to a problem with the data collection computer and has been included as a part of the pre-test borehole pressure history. The simulated borehole pressure history includes a 17 hour drilling period with a 300 kPa overpressure, open borehole conditions for 8.9 days at an annulus pressure of 7615 kPa, a 90 minute packer compliance period, the aborted pulse injection test, and a 20 minute flow period with the shut-in valve open which followed the aborted pulse test.

The testing sequence consisted of three hydraulic tests: a pulse injection (Pi01), a pulse withdrawal (Pw01), and a slug withdrawal (Sw01). The measured temperature was constant throughout testing so thermal effects were not incorporated into the simulations. A formation pressure (at true P2 depth) of 7635 kPa was estimated by interpolating between values determined in single packer tests 705.7S, 850.0SI, 850.0SII, and 854.7S.

GTFM simulations were conducted for a specific storage of 2.0E-06 m^{-1} and a hydraulic conductivity range from 3.0E-11 to 3.0E-10 ms^{-1}. The hydraulic conductivity that gives an adequate match to both pulse tests is 1.0E-10 ms^{-1} while the best fit hydraulic conductivity considering Pi01 only lies between 3.0E-11 and 1.0E-10 ms^{-1}. In all three of the simulations, Pi01 seems to be recovering to a pressure lower than the measured response. Figure 1 shows an alternative solution which uses a specific storage of 2.0E-05 m^{-1}. The best-fit hydraulic conductivity of 3.0E-11 ms^{-1} gives a good fit for Pi01 and a reasonable fit for Pw01. The value selected for specific storage is 2 orders of magnitude higher than the base case value and must be considered questionable in the absence of information on the crystalline rock properties at Leuggern. Nonetheless, the best-fit parameters for this interval are considered to be a hydraulic conductivity of 3.0E-11 ms^{-1} and a specific storage of 2.0E-05 m^{-1}.

The sensitivity of the pressure response to hydraulic conductivity can be seen in Figure 1. Variation of the specific storage by one log cycle produces a change in the response of similar magnitude to that caused by varying the hydraulic conductivity by one half log cycle. This provides a basis to estimate the uncertainty in the interpreted K value. Since the best-fit specific storage is 2 orders of magnitude higher than the base case value, the hydraulic conductivity may be underestimated by one order of magnitude.

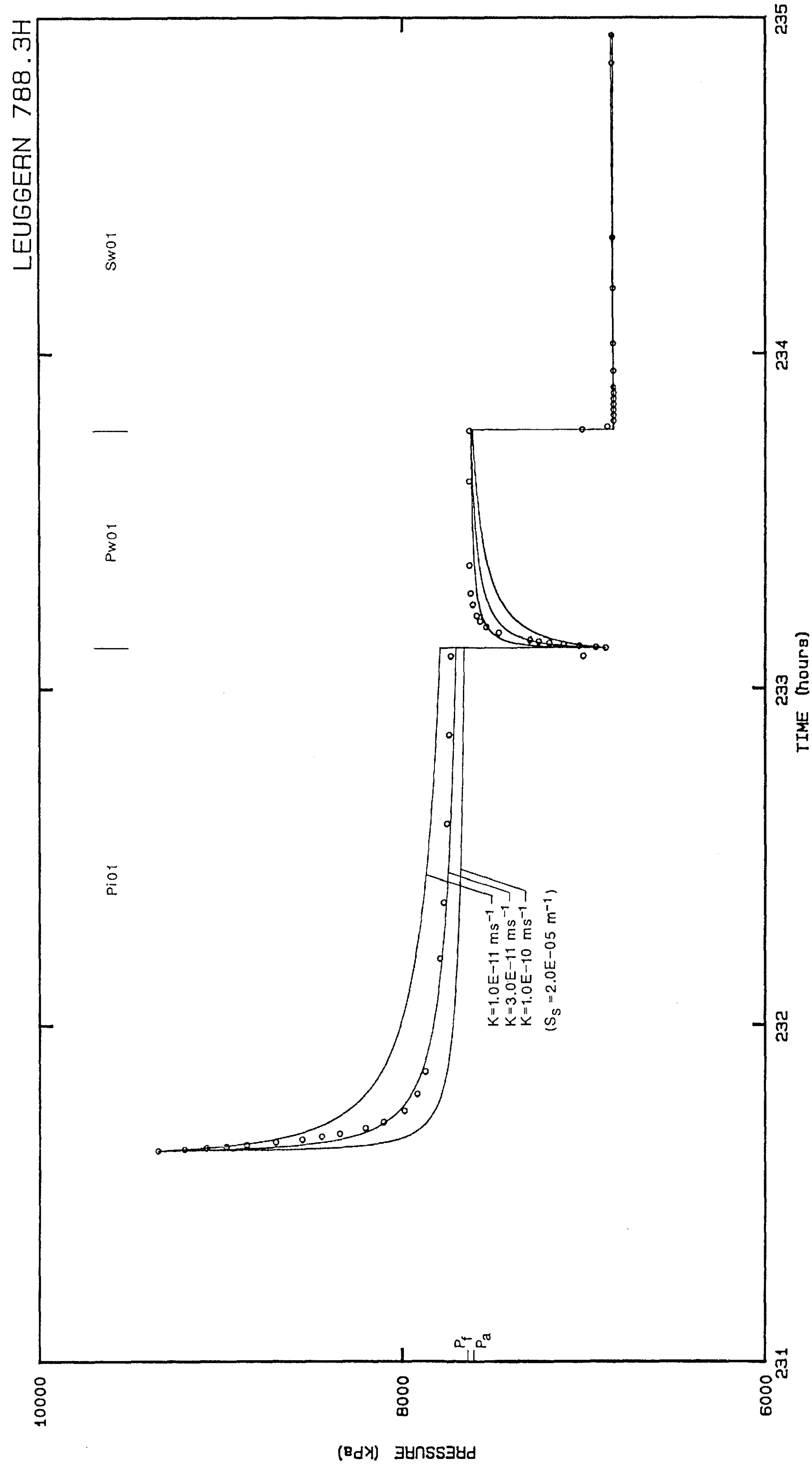


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 813.0H (800.56 m to 825.53 m)

H-log testing was performed in this interval on 1 November 1984, as a part of H-log sequence #3, in order to determine the hydraulic conductivity of the formation. The pre-test pressure history was simulated with a 31 hour drilling period with a 350 kPa drilling overpressure, a 6.0 day open borehole period at an annulus pressure of 7851 kPa, and a 1 hour packer compliance period.

Test 813.0H consisted of a 2.2 hour pulse injection (Pi01) and a 3.1 hour drill-stem test (0.5 hour Sw01 followed by 2.6 hour Pw01). The temperature changed by only 0.1°C during testing so thermal effects were not included in the simulation. A formation pressure at P2 depth, representative of the interval, was estimated by interpolating between the values obtained from surrounding single packer tests.

Simulated pressure responses were generated for three values of hydraulic conductivity ranging from 1.0E-11 to 1.0E-10 ms^{-1} and a specific storage of 2.2E-07 m^{-1}. The best-fit hydraulic conductivity is 3.0E-11 ms^{-1}. To achieve a better fit of the late time response of Pi01 would require an inconsistently high formation pressure or a hydraulic conductivity of perhaps 2.5E-11 ms^{-1}. However, an improved fit of the late time response can only be achieved at the expense of the early-time fit. Figure 1 shows the simulated response for a specific storage of 2.0E-06 m^{-1} and the same range of hydraulic conductivities, 1.0E-11 to 1.0E-10 ms^{-1}. In this case, the best-fit hydraulic conductivity is about 1.0E-11 ms^{-1}, which provides a better fit to the measured Pi01 response, but a worse fit to the Pw01 response. Variation of the the specific storage by one order of magnitude (one log cycle) results in the best-fit hydraulic conductivity changing by approximately one half of a log cycle in magnitude.

The best-fit formation parameters for the interval are considered to be a K of 1.0E-11 ms^{-1} and a specific storage of 2.0E-06 m^{-1}. However, due to the lack of information available to determine a specific storage value it must be concluded that this interval has a hydraulic conductivity between 1.0E-11 and 3.0E-11 ms^{-1} and a specific storage between 2.0E-06 and 2.2E-07 m^{-1}. In the summary tables, a hydraulic conductivity of 2.0E-11 ms^{-1} and a specific storage of 1.0E-06 m^{-1} is chosen for this interval.

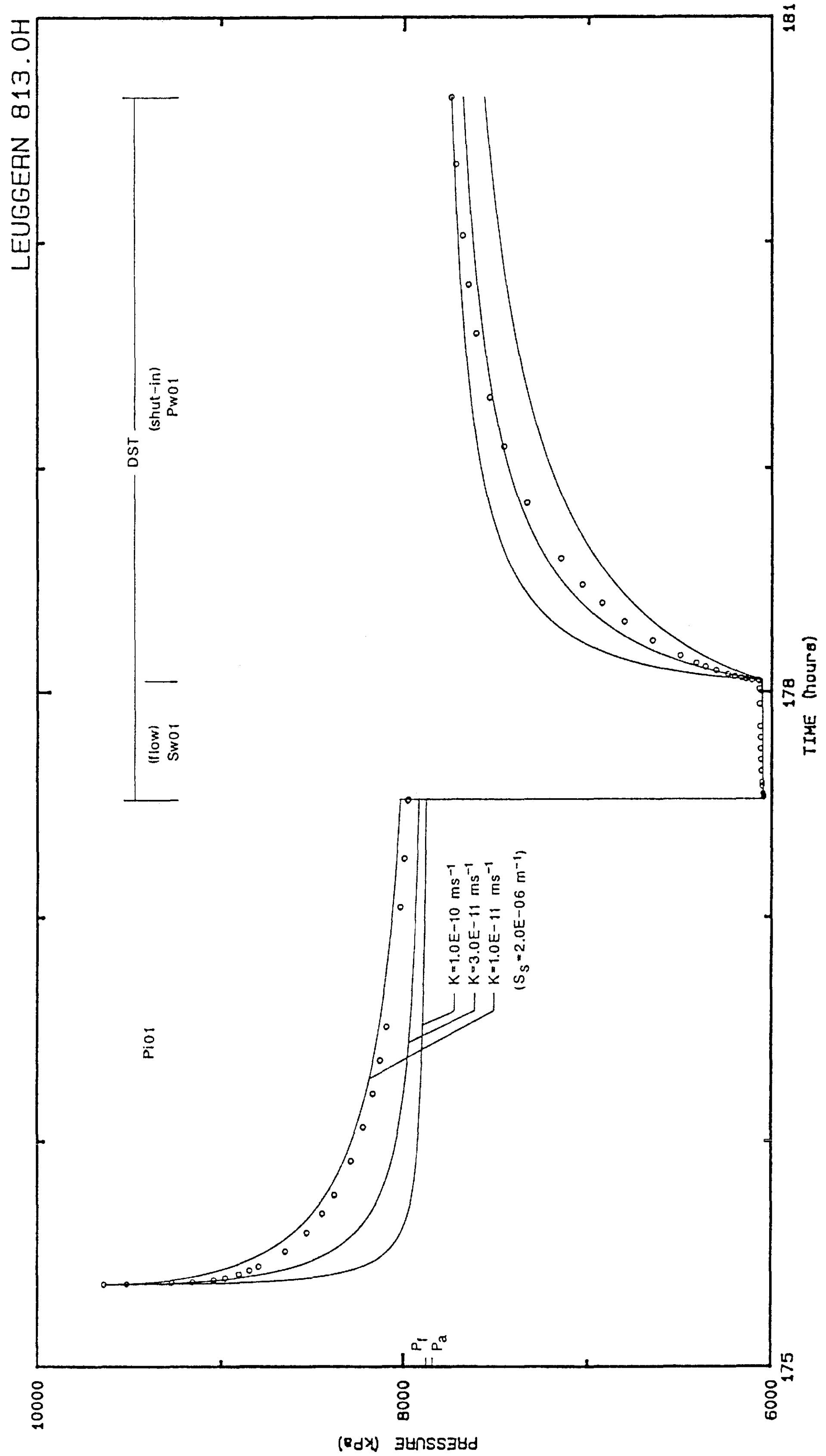


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 837.8H (825.28 m to 850.25 m)

H-log test 837.8H, the first testing sequence in H-log sequence #3, was performed on 1 November, 1984. The purpose of testing was to determine a hydraulic conductivity representative of the crystalline rock in this interval. The simulated pressure history for this interval includes a 325 kPa drilling overpressure for 21.7 hours, an open borehole period at an annulus pressure of 8087 kPa for 3.8 days, and an 80 minute packer compliance period.

The testing sequence included the following tests: a 49 minute pulse injection (Pi01), an 11 minute pulse withdrawal (Pw01), a 1.1 hour drill-stem test comprised of a 12 minute flow period (Sw01) and a 54 minute buildup (Pw02), and a 3.8 hour slug withdrawal (Sw02). During testing, communication between the P1 and P2 transducers was noted indicating a hydraulic connection between the packed off test interval and the zone below the bottom packer. The pressure changes measured below the test interval during testing were 30 to 50 percent of the magnitude of the pressure changes measured in the test interval. The P1-P2 communication will cause the interpreted hydraulic conductivity to be an overestimate because the induced pressure pulses will be effectively dissipated over a longer interval. The length of the zone below the bottom packer is only 9.20 m, therefore, the estimation of an upper bound for the conductivity of this interval is possible.

An assumed formation pressure of 8105 kPa at P2 depth was interpolated from values determined in single packer tests 705.7S, 850.0SI, and 850.0SII. Thermal effects were not included in the simulation because of the high hydraulic conductivity (greater than 1.0E-10 ms^{-1}).

Figure 1 shows the results of GTFM simulations for hydraulic conductivities ranging from 1.0E-08 to 1.0E-07 ms^{-1} and a specific storage of 2.2E-07 m^{-1}. The pulse tests, Pi01, Pw01 and Pw02, all recovered to a static pressure too quickly to allow for a quantitative determination of hydraulic conductivity. At this high conductivity, variations in the simulated specific storage do not have a significant effect on the simulated pressure response. As a result, the base case value on 2.2E-07 m^{-1} was selected for this interval. The simulated curves over the range of hydraulic conductivity bound the measured pressures for Sw02 with a lower conductivity matching the early measured pressures and the higher conductivity simulation matching the measured pressures near the end of the recovery period. The best-fit hydraulic conductivity is considered to be 3.0E-08 ms^{-1}. Given the P1-P2 pressure communication, the value of 3.0E-08 ms^{-1} should be considered as an upper limit for the hydraulic conductivity of this interval.

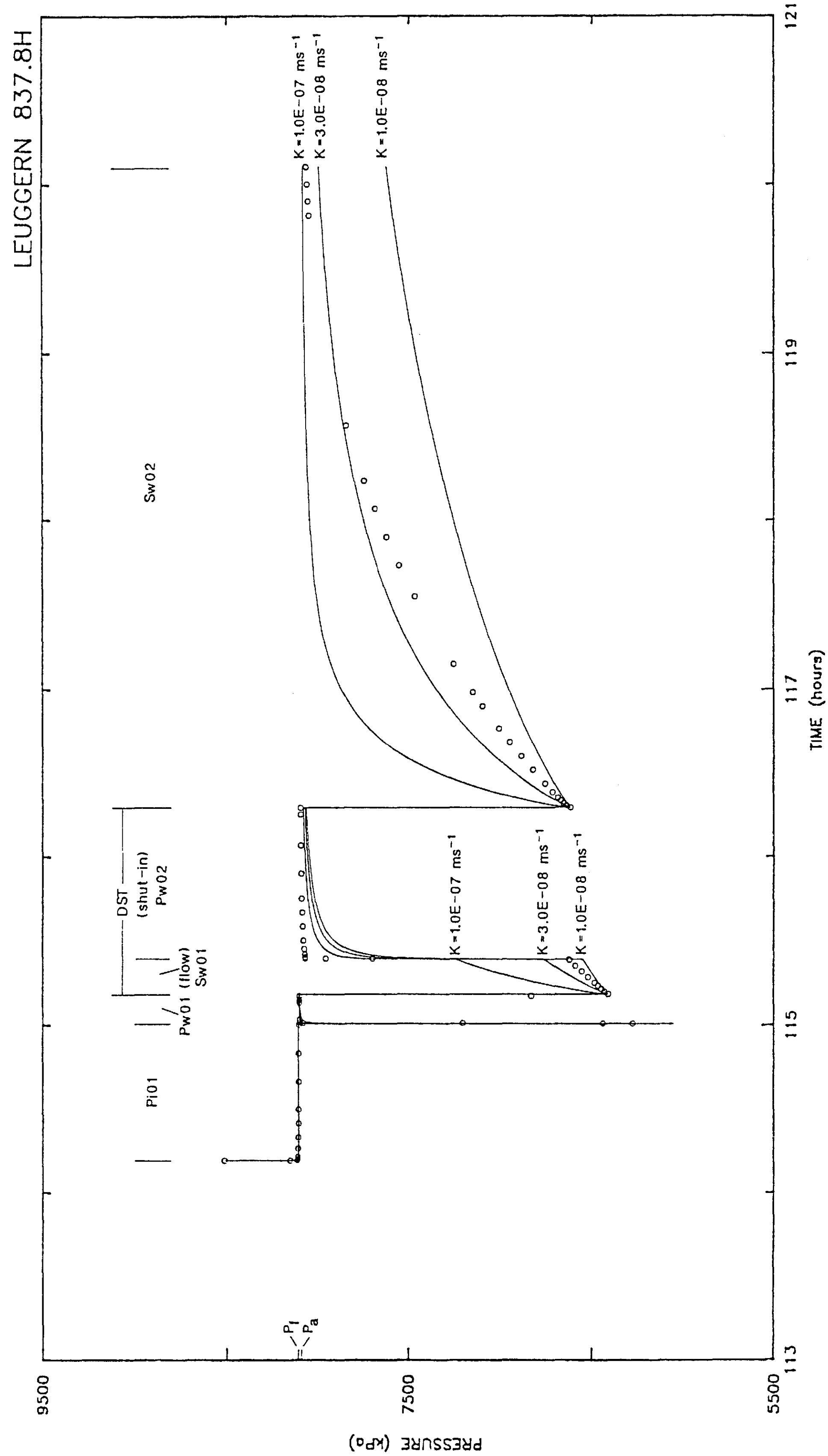


Figure 2: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 847.0D (834.53 m to 859.50 m)

Testing in this interval was performed on 21 and 22 March, 1985 to determine a representative formation hydraulic conductivity. Between 29 October and 1 November, 1984 four tests were performed (850.0SI, 850.0SII, 854.7S, and 837.8H), all of which covered at least a portion of this interval. However, given the nearly 5 month open borehole period between these tests and 847.0D testing, they were not included in the pre-test borehole pressure history. The drilling overpressure was likewise not included. The simulated pre-test pressure history for this interval consists of a 144.8 day open borehole period at an annulus pressure of 8147 kPa, a 61 minute packer compliance period at 8172 kPa, and a 47 minute shut-in period at a constant pressure of 8164 kPa.

Testing in this interval consisted of the following: a 0.2 hour pulse withdrawal test (Pw01), a 12.9 hour drill-stem test (12.0 hour Sw01 and 0.9 hour Pw02), a 1.0 hour drill-stem test (0.3 hour Sw02 and 0.7 hour Pw03), and a 2.4 hour slug withdrawal test (Sw03). All three of the pulse tests, Pw01, Pw02, and Pw03, recovered too quickly for analysis, qualitatively indicating a high hydraulic conductivity. An assumed formation pressure of 8195 kPa (at true P2 depth) was interpolated from values determined in single packer testing of surrounding intervals. The measured temperature decreased by about 1.5°C over the 16.5 hour testing sequence. However, during the three short (less than 1 hour) pulse tests, the measured temperature changes were negligible and thermal effects were not included in the simulations.

Simulations were run using hydraulic conductivities ranging from 3.0E-09 to 3.0E-08 ms^{-1} and a specific storage of 2.2E-07 m^{-1}. The results, shown in Figure 1, indicate an interval hydraulic conductivity of between 1.0E-08 and 3.0E-08 ms^{-1}, based on the best fit of the simulated pressure response to the measured pressure response for Sw01, Sw02, and Sw03. Simulations showed that by varying the specific storage by one order of magnitude, the best-fit hydraulic conductivity changed by a factor of less than 2. Because of this relative insensitivity of K to specific storage in this interval, the base case value of 2.2E-07 m^{-1} was selected.

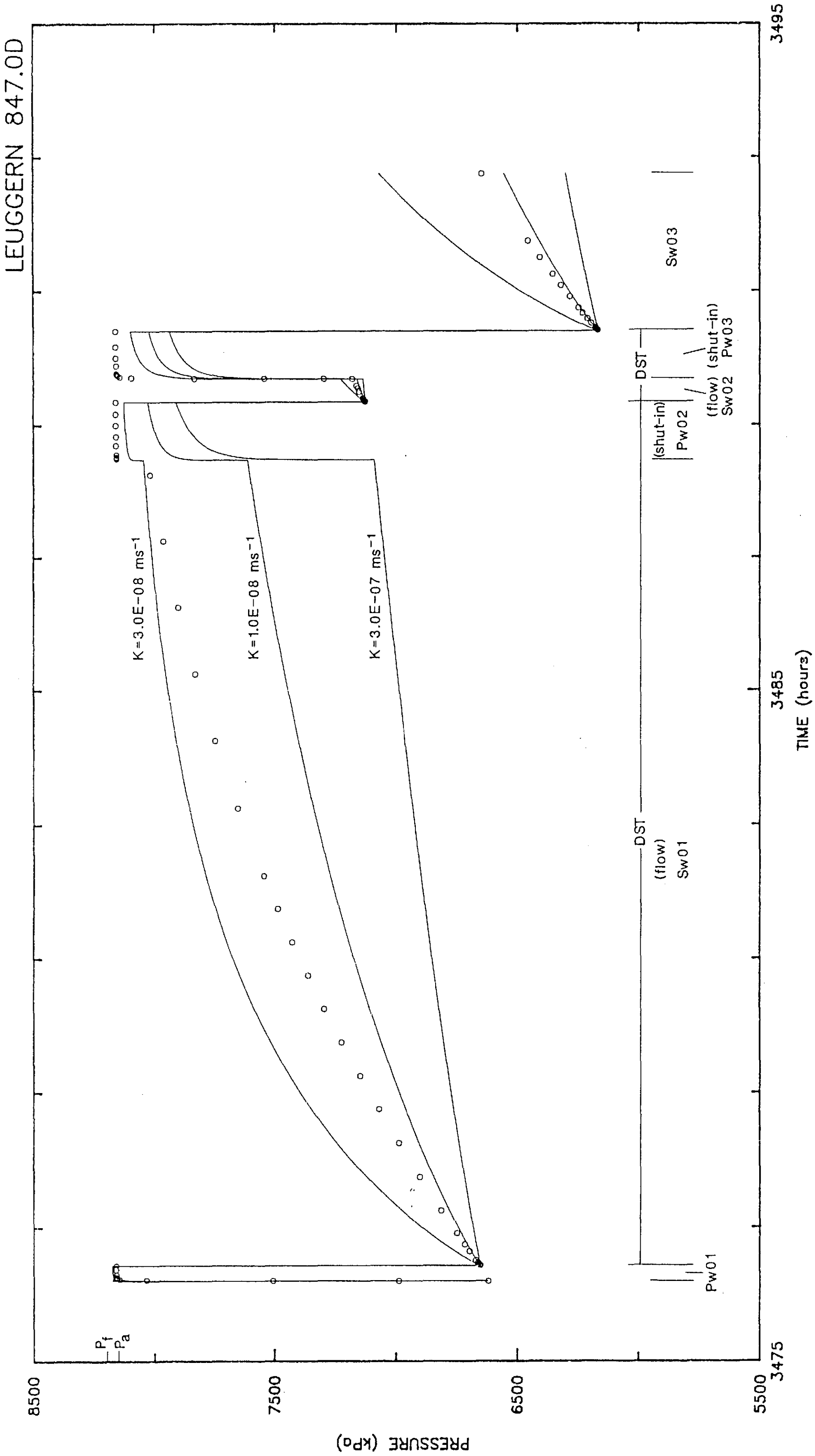


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 850.0SI (840.50 m to 859.45 m)

Two separate single packer tests were conducted in this interval in order to estimate formation pressure and hydraulic conductivity. The first testing period, 850.0SI, was started approximately 30 hours after the mid-point of drilling the interval. The very rapid, squared-off pressure response to shut-in, evident during the first part of the testing sequence, led to suspicion that the tool was malfunctioning or that there was a blockage in the tool. The test tool was removed and replaced and the second test, 850.0SII, was performed. The pre-test borehole pressure history used in the GTFM analysis of 850.0SI includes a 350 kPa overpressure for half of the drilling period, an open borehole period exposing the interval to an annulus pressure of 8245 kPa for 13.5 hours subsequent to drilling, and a 1 hour packer compliance period prior to the 850.0SI test sequence.

Test 850.0SI consisted of three pulse injection tests (Pi01, Pi02, Pi03) and a drill-stem test sequence (Sw01, Pw01). The three pulse injection tests all recovered too quickly for quantitative analysis, qualitatively indicating a high hydraulic conductivity. The drill-stem test consisted of a 10 minute flow period followed by a 17 minute shut-in period, which also recovered too quickly for analysis.

Simulations yielded a formation pressure at P2 depth of 8250 kPa, a hydraulic conductivity of 3.0E-08 ms^{-1}, and a specific storage of 2.2E-07 m^{-1} as shown in Figure 1. The formation parameters were determined based on a match of the simulated Sw01 pressure response to the measured response.

A formation pressure representative of the center of the interval was calculated to be 8388 kPa using the true vertical depth between the P2 transducer and the center of the interval, the interpreted formation pressure at P2 depth, and an in-situ fluid density of 997 kgm^{-3}. This corresponds to an equivalent freshwater head at the center of the interval of 362.1 m ASL.

At the end of testing, the test tool was pulled from the borehole. Surface inspection of the tool gave no evidence of a plug or mechanical problems. Test 850.0SII showed a similar pressure response as observed during this test. Therefore, it is concluded that the pressure response was not affected by equipment problems.

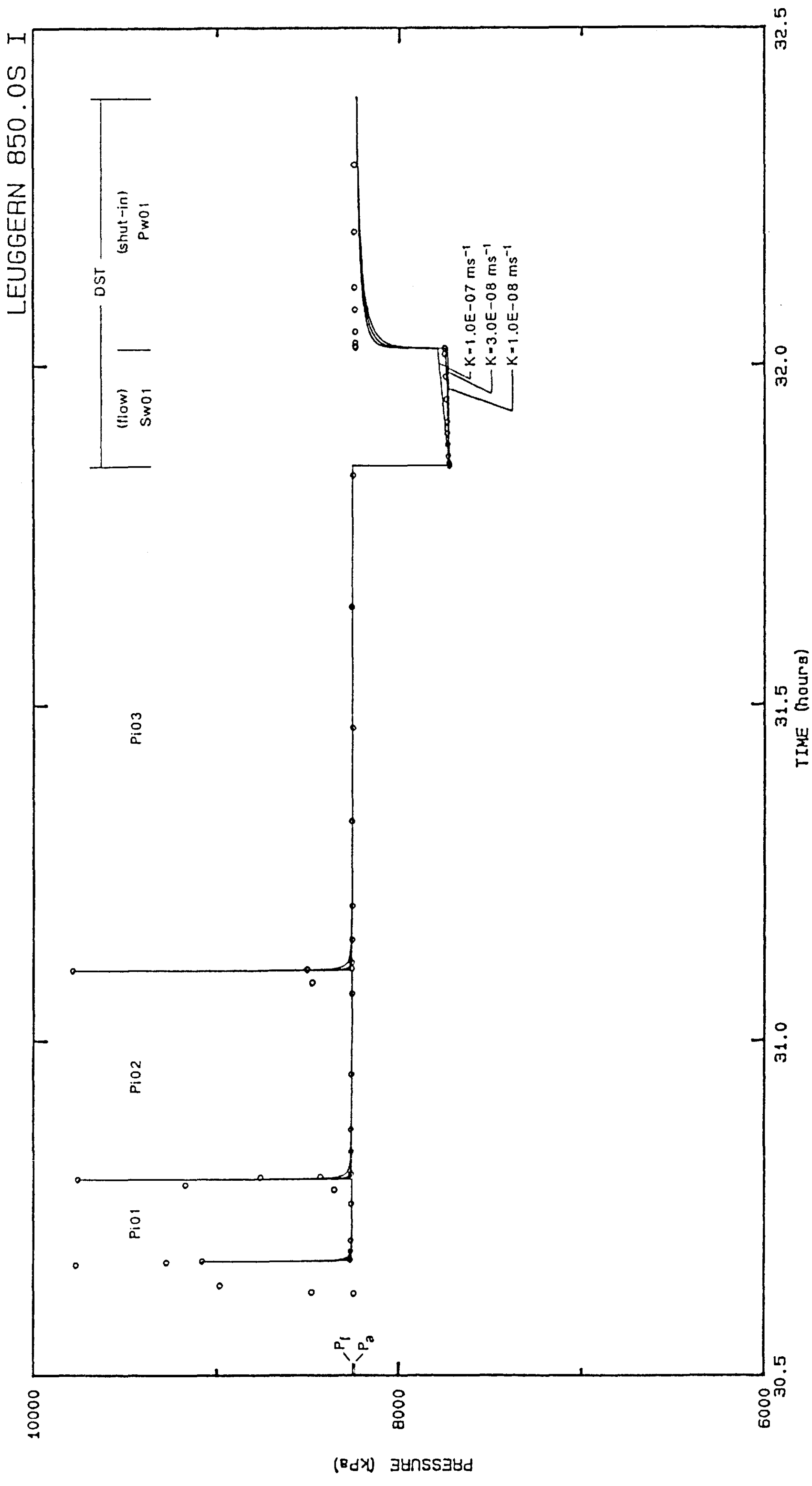


Figure 2: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 850.0SII (840.50 m to 859.45 m)

Test 850.0SII was conducted in the same interval as 850.0SI. Following test 850.0SI, three swabs of between 100 and 200 m were pulled with the shut-in open in an attempt to dislodge a suspected plug in the test tool. To ensure that there were no tool problems, the test tool was pulled from the borehole and a new test tool was set in the same interval in preparation for 850.0SII. The test sequence began 50 hours after the mid-point of drilling and about 17.5 hours after the end of 850.0SI.

In order to simulate test 850.0SII using GTFM, the pre-test pressure history was simplified. It consists of a 16 hour drilling period (8595 kPa), a 13.5 hour open borehole period prior to 850.0SI (8245 kPa), a constant pressure period representative of test 850.0SI (8260 kPa), a slug withdrawal representative of the swabbing period, a 19 hour open borehole period prior to 850.0SII (8235 kPa), and a packer compliance period. This simplification is justified by the high hydraulic conductivity in the interval, the short duration of the tests in 850.0SI, and the long open borehole period between 850.0SI and 850.0SII. A slug withdrawal (with an initial pressure of 6300 kPa and a simulated hydraulic conductivity of 3.0E-08 ms^{-1}) was used to simulate the swabbing period. This is justified by the fact that the simulated slug recovery shows a similar slope to the measured data from the swabbing period.

Test 850.0SII consisted of a pulse injection test (Pi04) followed by a drill-stem test (Sw02, Pw02). The pulse test recovered too fast for analysis. The test interval and equipment configuration are the same as for 850.0SI as are the formation and fluid properties used in the simulations. Simulations produced the same formation parameters as in test 850.0SI: a formation pressure at P2 depth of 8250 kPa, a hydraulic conductivity of 3.0E-08 ms^{-1}, and specific storage of 2.2E-07 m^{-1}. A plot of the simulated pressure response is included in Figure 1.

A formation pressure representative of the center of the interval was calculated to be 8388 kPa using the true vertical depth between the P2 transducer and the center of the interval, the interpreted formation pressure at P2 depth, and an in-situ fluid density of 997 kgm^{-3}.

The agreement between formation parameters found in the two test sequences indicates there probably was not a significant problem with the hydrologic test tool in test 850.0SI. Simulations were run to establish the effect of varying the formation pressure and specific storage. The range of formation pressures giving an adequate fit was 8240 to 8260 kPa with 8250 kPa giving the best fit. Any value outside this range resulted in a greater than 10 kPa error in the fit to the late-time pressures observed during the pulse sequences. The simulated pressure response was relatively insensitive to specific storage so the base case value of 2.2E-07 m^{-1} was used.

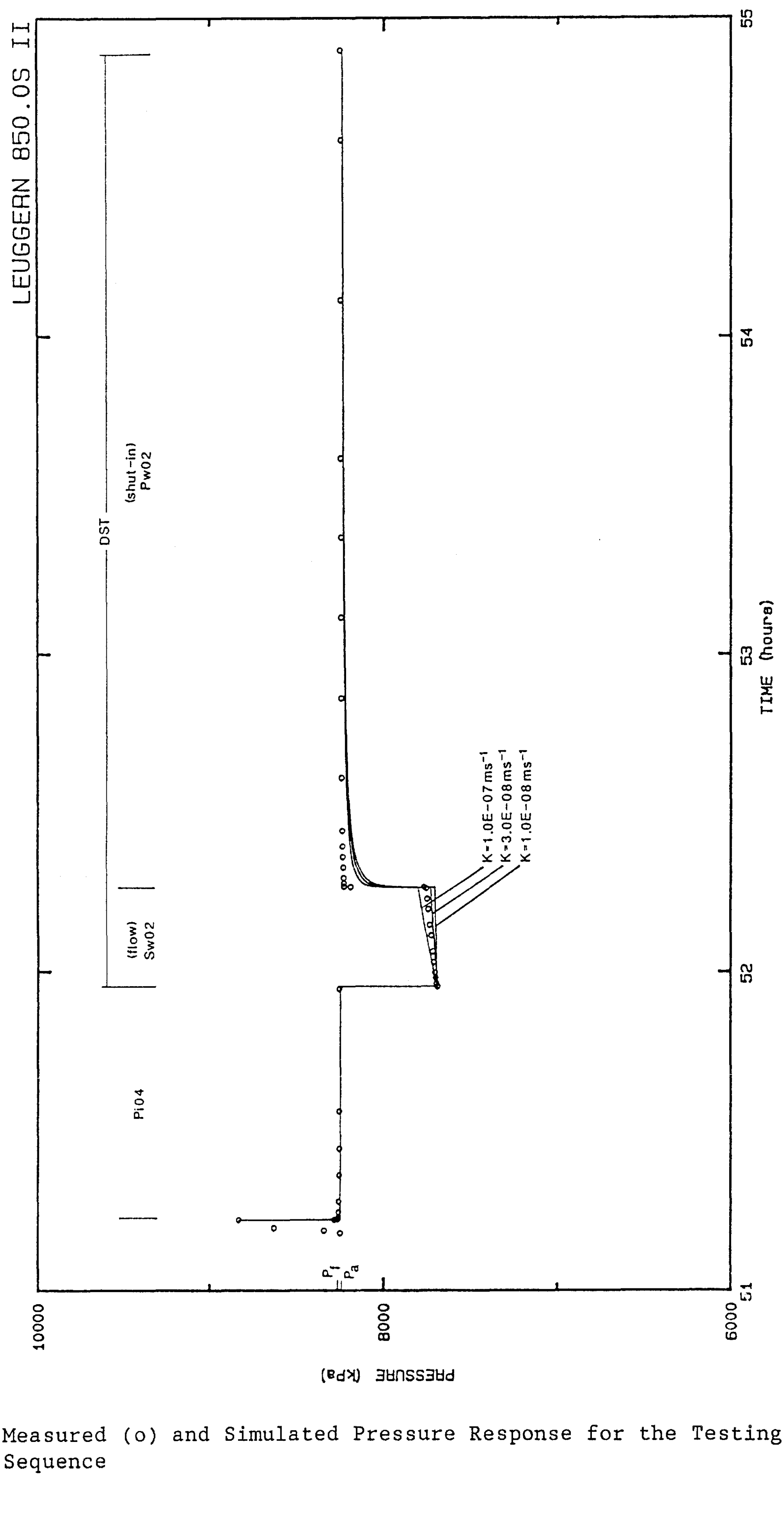


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 854.7S (850.00 m to 859.45 m)

Single packer test 854.7S tested the bottom 9.45 m of the interval covered by 850.0S testing. The test was an attempt to corroborate the theory that test results in the interval were influenced by borehole skin damage and are not indicative of formation parameters. In order to simulate this test, the testing from 850.0SI and 850.0SII was incorporated into a simplified pre-test pressure history. Test 850.0SI was simulated with a 26 hour period at an annulus pressure of 8338 kPa and 850.0SII was simulated by a constant pressure of 8328 kPa for about 15 hours. These simplifications are reasonable given the high hydraulic conductivity of the interval. The final flow period, Sw02, from the 850.0SII DST was also included in the pre-test history. The 6 hour drilling overpressure was not included in order to simplify the history period. Its effect is considered negligible when compared to the subsequent, longer constant pressure periods and the slug test. The packer compliance period was also included in the simulated pressure history.

The testing sequence was comprised of two pulse injections (Pi01 and Pi02) and a drill-stem test (Sw01 and Pw01). The pulse injection tests recovered too quickly to provide better than an order-of-magnitude estimate of hydraulic conductivity. The DST flow sequence, Sw01, although of short duration, permitted a good estimation of hydraulic conductivity. Thermal effects were not included due to the high hydraulic conductivity of the interval.

The best-fit GTFM simulation indicates a formation pressure at P2 depth of 8335 kPa, a hydraulic conductivity of 6.0E-09 ms^{-1} and a specific storage of 2.2E-07 m^{-1}. Figure 1 is a plot showing the best-fit simulation as well as the sensitivity to varying hydraulic conductivity. It can be seen that the Sw01 pressure response is insensitive to changes in K below 1.0E-09 ms^{-1}. Sensitivity analysis performed on formation pressure showed that simulated values from 8320 to 8350 kPa produce an acceptable fit to the measured pressure response. The simulated response is relatively insensitive to variations in specific storage by up to one order of magnitude from the base case value of 2.2E-07 m^{-1}.

A formation pressure representative of the center of the interval was calculated to be 8428 kPa using the true vertical depth between the P2 transducer and the center of the interval, the interpreted formation pressure at P2 depth, and an in-situ fluid density of 997 kgm^{-3}. This corresponds to an equivalent freshwater head at the center of the interval of 361.6 m ASL.

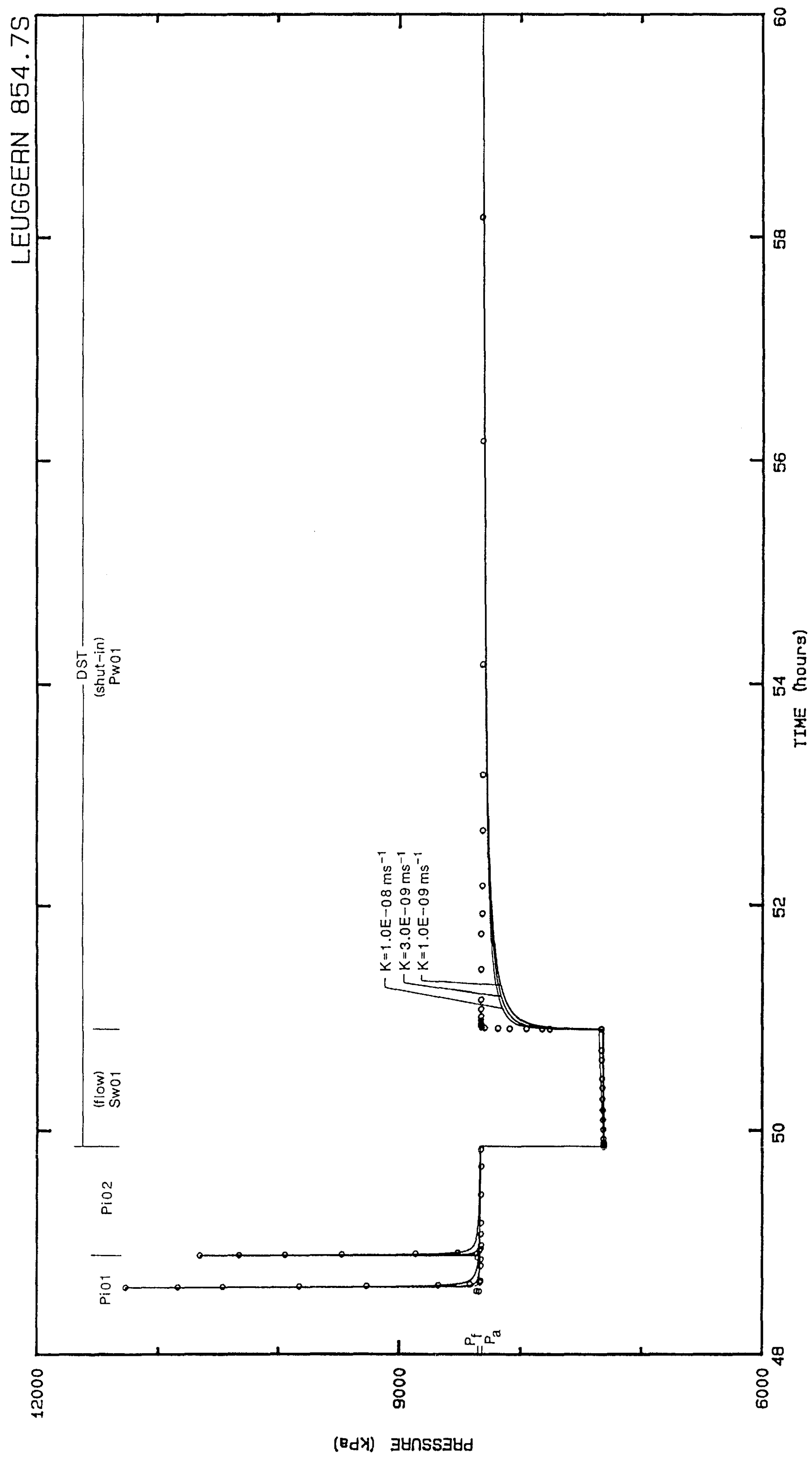


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 869.8H (857.35 m to 882.32 m)

H-log testing in this interval was performed on 6 January, 1985, as a part of H-log sequence #4, in order to determine a representative formation hydraulic conductivity. The simulated pre-test borehole pressure history includes a 21 hour drilling period with a 300 kPa overpressure, a 59.8 day open borehole period at an annulus pressure of 8382 kPa, and a 91 minute packer compliance period.

The testing sequence consisted of the following tests: a pulse injection (Pi01), a pulse withdrawal (Pw01), a drill-stem test (Sw01 and Pw01), and a final slug withdrawal (Sw02). Some uncertainty is associated with the shut-in pressures at the start of the pulse tests. Data from field reports were inconclusive; it is possible that the Pi01 shut-in pressure was as high as 9700 kPa and the Pw01 shut-in pressure was as high as 7323 kPa. For the GTFM simulations best estimates of 9400 and 6735 kPa were used. The formation pressure (at true P2 depth) was estimated from values determined in single packer tests 850.0SI, 850.0SII, and 854.7S.

The best-fit GTFM simulation, shown in Figure 1, indicates a hydraulic conductivity for this interval of 1.0E-10 ms^{-1} and a specific storage of 2.2E-07 m^{-1}. This hydraulic conductivity gives a reasonable match to the two initial pulse tests. The base case value was selected for specific storage because of the relative insensitivity of the simulated response to changes in the specific storage in this interval.

The sensitivity of the response to variations in the pulse shut-in pressures was investigated. A simulation was run using the maximum shut-in pressures for Pi01 (9700 kPa) and Pw01 (7323 kPa). Use of these shut-in pressures produced a slightly improved fit for both tests but the effects were not significant enough to change the best-fit estimates for the hydraulic conductivity or specific storage.

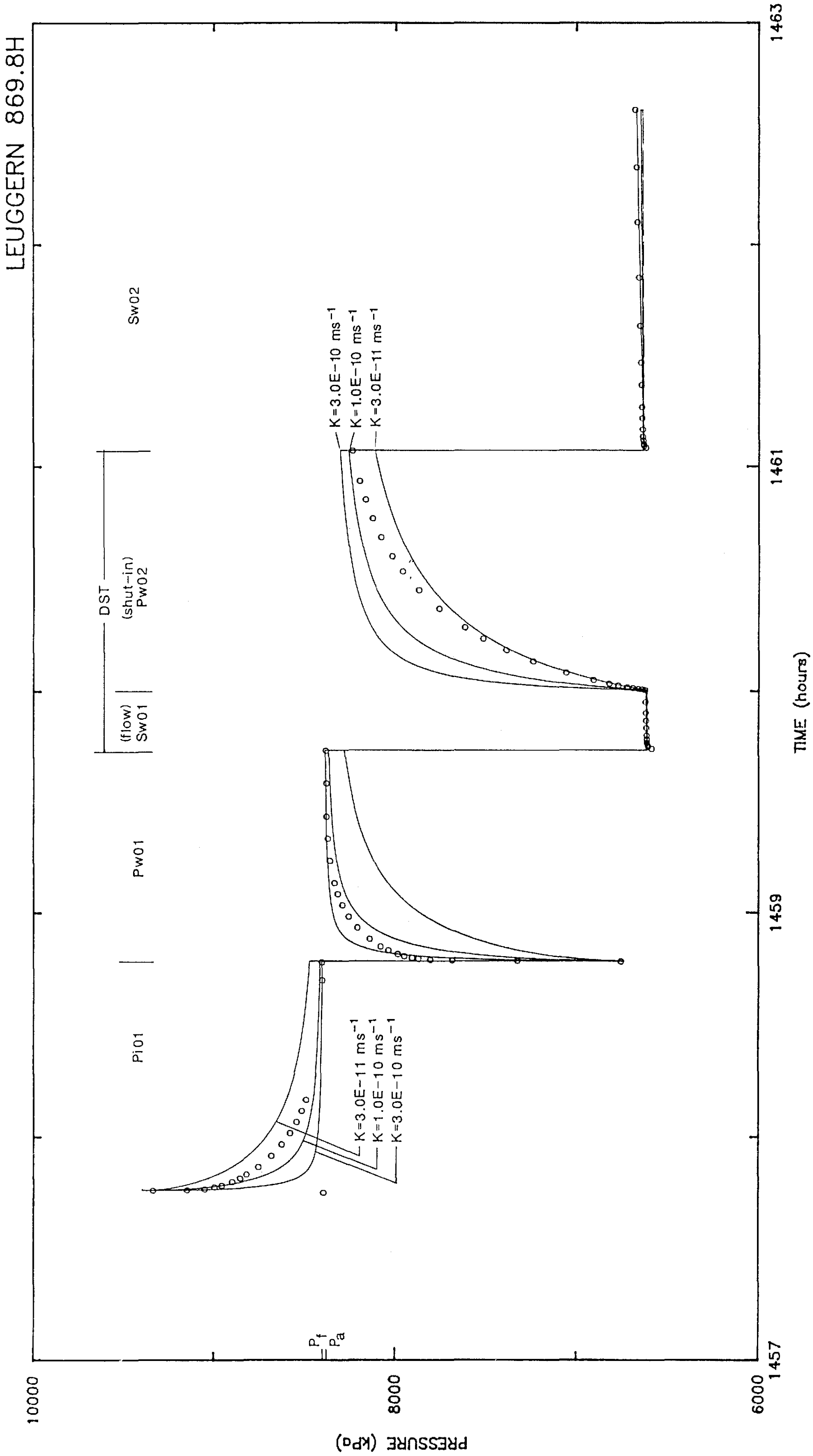


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 893.9H (881.38 m to 906.35 m)

Test 893.9H was performed on 6 January, 1985, as a part of H-log sequence #4, to determine a hydraulic conductivity representative of the interval. The pre-test borehole pressure history was simulated with a 21.5 hour drilling period, a 57.7 day open borehole period at an annulus pressure of 8613 kPa, and a 66 minute packer compliance period.

The testing sequence consisted of the following tests: a pulse injection (Pi01), a pulse withdrawal (Pw01), a drill-stem test (Sw01 and Pw01), and a slug withdrawal (Sw02). The temperature remained constant for the duration of testing, therefore, thermal effects were not included in the simulation. The formation pressure (at true P2 depth) was estimated to be 8630 kPa based on the values determined in single packer tests 850.0SI, 850.0SII, and 854.7S.

The best-fit GTFM simulation, using a formation pressure of 8630 kPa, yielded a hydraulic conductivity of 3.0E-11 ms^{-1} and a specific storage of 2.2E-07 m^{-1}. As can be seen in Figure 1 these best-fit parameters give a reasonable fit to the two pulse withdrawal test sequences, but do not adequately match the late time data from Pi01. In particular, the end pressure value of Pi01 (8599 kPa) is lower than the assumed P_f (8630 kPa). A simulation was run with a formation pressure of 8570 kPa, however, because of the long pre-test open borehole period, the fit was only slightly improved and the best-fit hydraulic conductivity did not change. The base case specific storage value of 2.2E-07 m^{-1} was selected because of the relative insensitivity of the simulated response to changes in the specific storage in this interval.

Despite the poor fit to the measured Pi01 response, the interpreted hydraulic conductivity of 3.0E-11 ms^{-1} is still considered acceptable to within an order of magnitude given the good fit to Pw01 and Pw02.

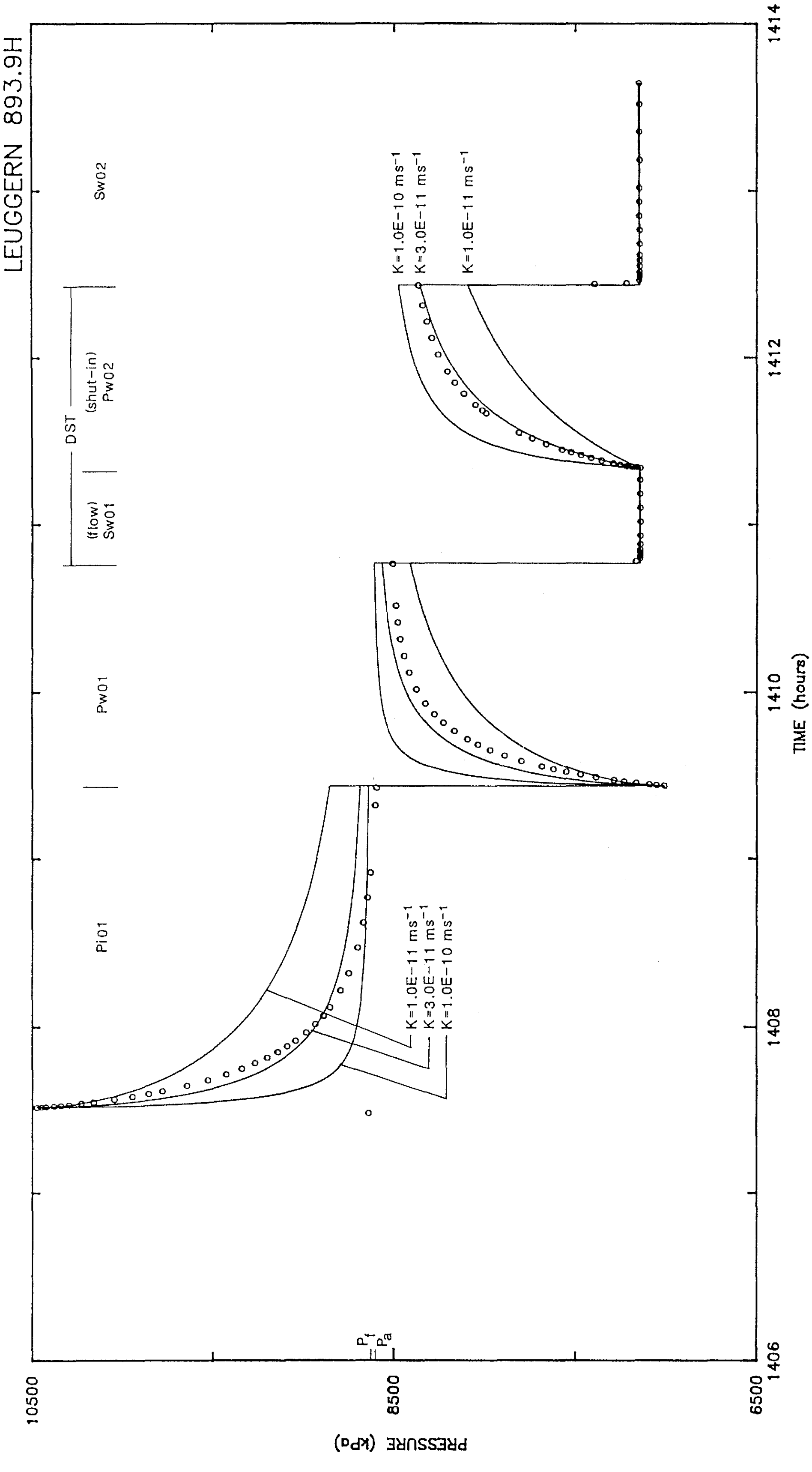


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 912.5S (905.85 m to 919.15 m)

Single packer test 912.5S began on 10 November, 1984, 1.5 days after the mid-point of drilling. The pre-test borehole pressure history was simulated with a 100 kPa drilling overpressure for 24 hours, an open borehole period at an annulus pressure of 8878 kPa for 13 hours, and a 1 hour packer compliance period.

A pulse injection test (Pi01), a pulse withdrawal test (Pw01), and a drill-stem test (Sw01 and Pw02) were performed in order to determine a representative formation pressure and hydraulic conductivity for the interval. Pulse injection test Pi01 was allowed to recover for nearly 15 hours providing a good opportunity to estimate formation pressure. Pw01 had only a 1 hour recovery period and did not reach a static pressure. The drill-stem test consisted of a 64 minute flow period and a 4 hour shut-in pressure recovery.

The best-fit simulated pressure response, based on a match with Pi01 and Pw01, corresponded to a hydraulic conductivity of about 4.0E-11 ms^{-1}, a formation pressure at P2 depth of 8910 kPa and a specific storage of 2.2E-07 m^{-1}. Figure 1 provides a comparison of the best-fit simulated response with the measured response and also shows the result of varying hydraulic conductivity. The best-fit parameters from Figure 1 yield a Pw02 response that is faster than measured. Since no single set of formation parameters can provide a good match for both pulse withdrawal segments the Pi01/Pw01 tests were utilized to determine the best-fit hydraulic conductivity.

A formation pressure representative of the center of the interval was calculated to be 8983 kPa using the true vertical depth between the P2 transducer and the center of the interval, the interpreted calibrated formation pressure at P2 depth, and an in-situ fluid density of 995 kgm^{-3}. The equivalent freshwater head corresponding to the pressure at the interval center is 363.0 m ASL.

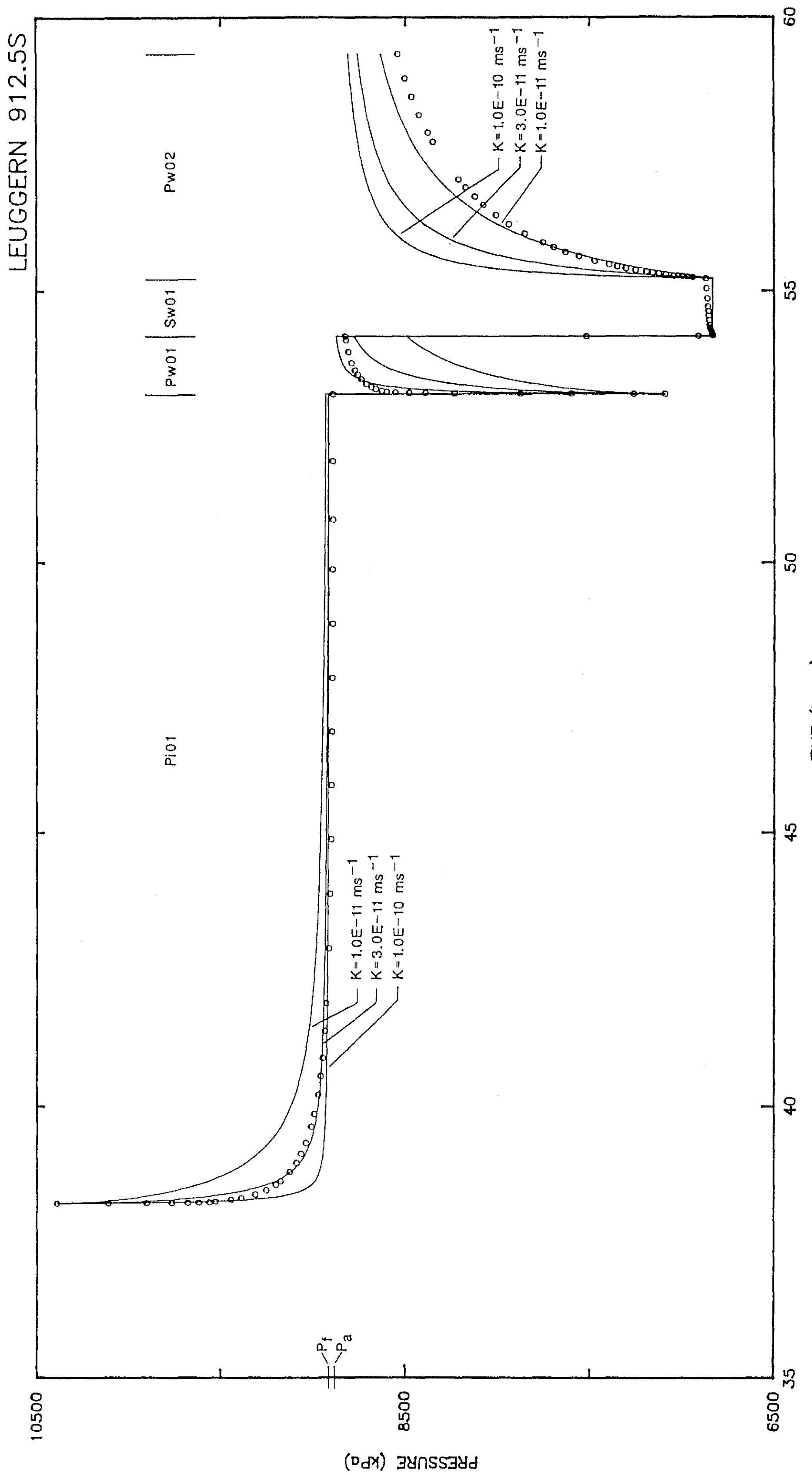


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 918.4H (905.95 m to 930.92 m)

H-log testing was performed in this interval on 5 January, 1985, as a part of H-log sequence #4, in order to obtain a representative formation hydraulic conductivity. Pressures in this interval were affected by two earlier tests: 912.5S (905.85 to 919.15 m) on 10 to 11 November, 1984 and 923.0D (916.20 to 929.74 m) from 25 November to 7 December, 1984. Test 912.5S was performed in the middle of the drilling period for this interval. Due to the long open borehole period (55.8 days) between the middle of drilling and the start of testing, the influence of the drilling overpressure and test 912.5S were not incorporated into the borehole pressure history preceding test 918.4H.

The complete simulated pre-test borehole pressure history includes a 14.5 day open borehole period at an annulus pressure of 8847 kPa prior to test 923.0D, a 12 day period at a pressure of 5000 kPa representative of 923.0D sampling, a second, 29.1 day open borehole period at annulus pressure (8847 kPa), and a 14 minute pulse injection sequence re-creating an aborted attempt at Pi01. The packer compliance period was combined with the second open borehole period for simplicity. Similarly a short flow period after the aborted Pi01 attempt was incorporated into the pulse injection sequence.

The testing sequence consisted of the following tests: a pulse injection (Pi01), a pulse withdrawal (Pw01), a drill-stem test (Sw01 and Pw01), and a slug withdrawal (Sw02). The formation pressure (at true P2 depth) was estimated based on values determined in single packer tests 705.7S, 850.0SI, 850.0SII and 912.5S.

GTFM simulations were run using hydraulic conductivities ranging from 3.0E-12 to 3.0E-10 ms^{-1} and specific storages ranging from 2.0E-05 to 4.0E-08 m^{-1}. Figure 1 shows the results for the best-fit hydraulic conductivity of 1.0E-11 ms^{-1} and a specific storage of 2.0E-05 m^{-1}. The estimated formation compressibility of 2.0E-09 Pa^{-1}, which results in this high value for specific storage, is at the upper limit of the acceptable range of compressibilities for crystalline rock. GTFM runs using a lower value for specific storage (2.2E-07 m^{-1}) resulted in a somewhat poorer fit, with the simulated Pi01 response approaching a pressure about 50 kPa lower than the measured Pi01 pressure response and a best-fit K of about 3.0E-11 ms^{-1}. Since the flow responses during Sw01 and Sw02 indicate a somewhat higher hydraulic conductivity, the last mentioned S_s and K values are recommended.

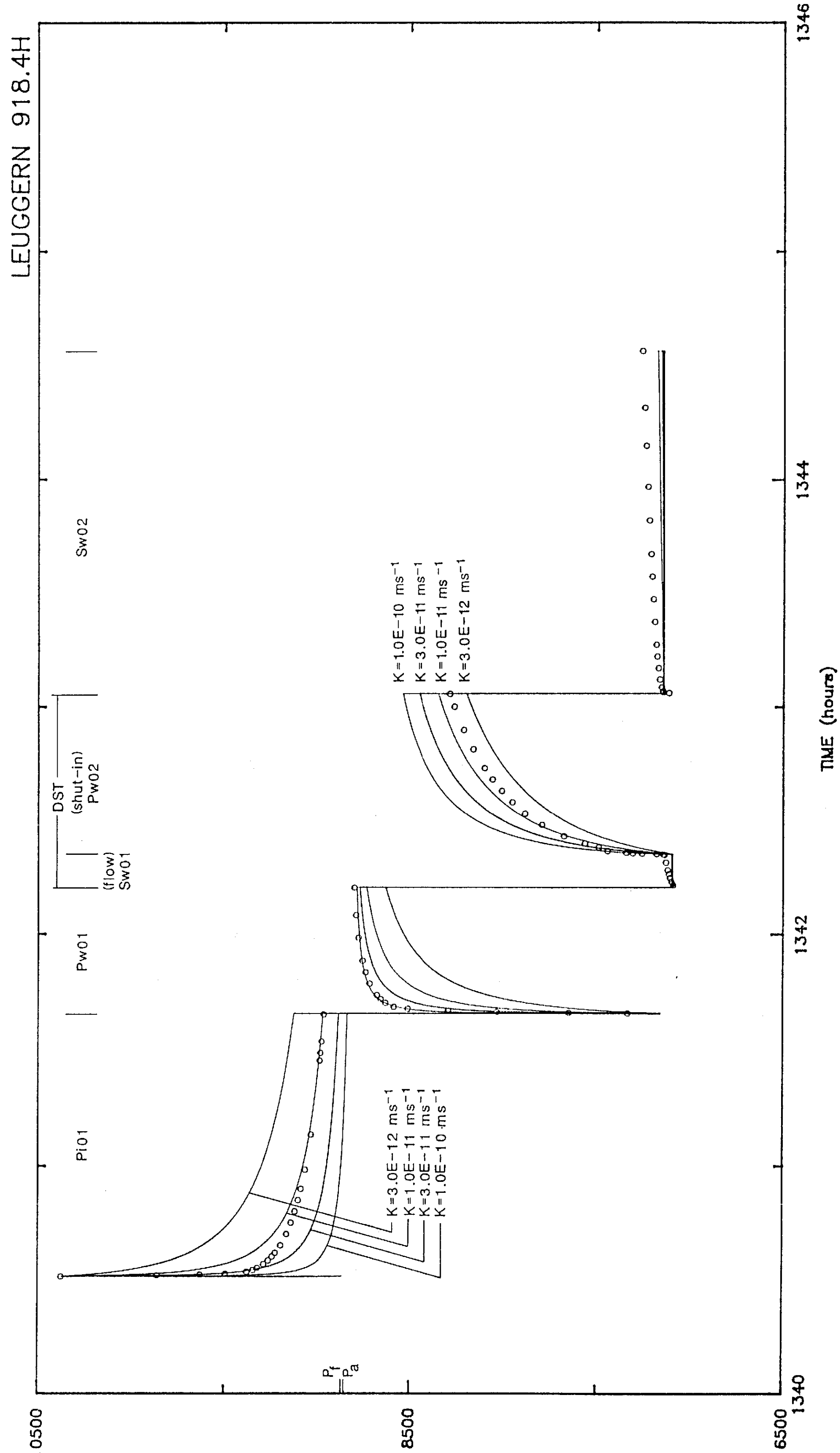


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence at a Formation Specific Storage of 2.0E-05 m^{-1}

Test 923.0D (916.20 m to 929.74 m)

This double packer test was conducted on 25 November, 1984, 13.1 days after the mid-point of the drilling period. Hydraulic testing was performed to determine a representative formation hydraulic conductivity. Following the hydraulic testing period, the interval was swabbed for 13.3 days in order to obtain samples of the formation fluid. The complete simulated pre-test pressure history for this interval includes an 8.4 hour drilling period at 425 kPa above annulus pressure, a 12.7 day open borehole period at an annulus pressure of 8952 kPa, a 97 minute packer compliance period at 8982 kPa, and a 46 minute shut-in period during which the pressure decreased from 8982 to 8967 kPa.

A drill-stem test was the only hydraulic test performed in this interval. It consisted of a 21 minute flow period (Sw01) and a 61 minute pressure buildup under shut-in conditions (Pw01). The likely influences of history on the pressure recovery of Pw01 make it impossible to obtain a confident estimate of formation pressure from this test. An assumed formation pressure of 8965 kPa (at true P2 depth) was interpolated from values determined in single packer testing of surrounding intervals. The measured temperature remained constant throughout the testing sequence, therefore, thermal effects were not included in the simulations.

A suite of simulations where conducted using a specific storage of 2.0E-06 m^{-1}. The best-fit hydraulic conductivity for the DST sequence is 1.0E-11 ms^{-1}. A specific storage of 2.0E-06 m^{-1} was selected over the base case value of 2.2E-07 m^{-1} because it produced a pressure response with a shape more characteristic of the measured pressure response. Simulations showed that by varying the specific storage by one order of magnitude the best-fit hydraulic conductivity changed by a factor of less than 2.

The sampling exercise which followed the testing sequence at this depth in the borehole consisted of a period of formation cleaning and sampling by bailer during which 6.3 m^3 of fluid were removed to reduce drilling fluid contamination in the zone. The system volume (interval and tubing) was 313 liters. During the bailing activity, formation fluid samples were collected by Preussag from the bailer water.

During the bailing period, the pressure was recorded at the sensor carrier. This enabled an interpretation of the interval pressure response during the fluid removal. Twenty-seven of the bailer runs were chosen for interpretation with GTFM to provide an estimate of hydraulic conductivity for the zone. Figure 1 shows the measured pressure data collected from 25 November, 1984 through 1 December, 1984 together with the simulated pressure response. Each swab was treated as a separate slug withdrawal test with the starting pressure for each test corresponding to the measured pressure from the swabbing record log. When a swab was removed from the tubing string it was assumed that there was no return of fluid to the test interval from the bailer.

The slug withdrawal simulations were completed using the range of hydraulic conductivity 1.0E-09, 3.0E-10, and 1.0E-10 ms^{-1} and a formation specific storage of 2.0E-06 m^{-1} corresponding to the specific storage chosen for the earlier simulations in this interval. The best fit to the sequence of measured pressures is obtained using a hydraulic conductivity of about 7.0E-10 ms^{-1} at the specific storage value of 2.0E-06 m^{-1}. This hydraulic conductivity is greater than the value of 1.0E-11 ms^{-1} interpreted from the DST conducted on 25 November, 1984. The interpretation of the DST is valid and the lower hydraulic conductivity could represent the test zone in the immediate vicinity of the borehole (<1m from the wellbore) at the time of testing. The apparent increase in permeability of about two orders of magnitude of the formation during the swabbing period could be due, at least in part, to the flow of fluid from the formation to the borehole and the opening of interstices in the rock adjacent to the borehole, and to the impact of the flow test on a larger volume of rock corresponding to a more laterally extensive and more permeable test zone.

Given the consistent 7.0E-10 ms^{-1} response of the formation to the underpressure caused by swabbing and the impact of a larger volume of formation during these flow-recovery periods, a hydraulic conductivity of 7.0E-10 ms^{-1} is reported for this interval at a specific storage of 2.0E-06 m^{-1}.

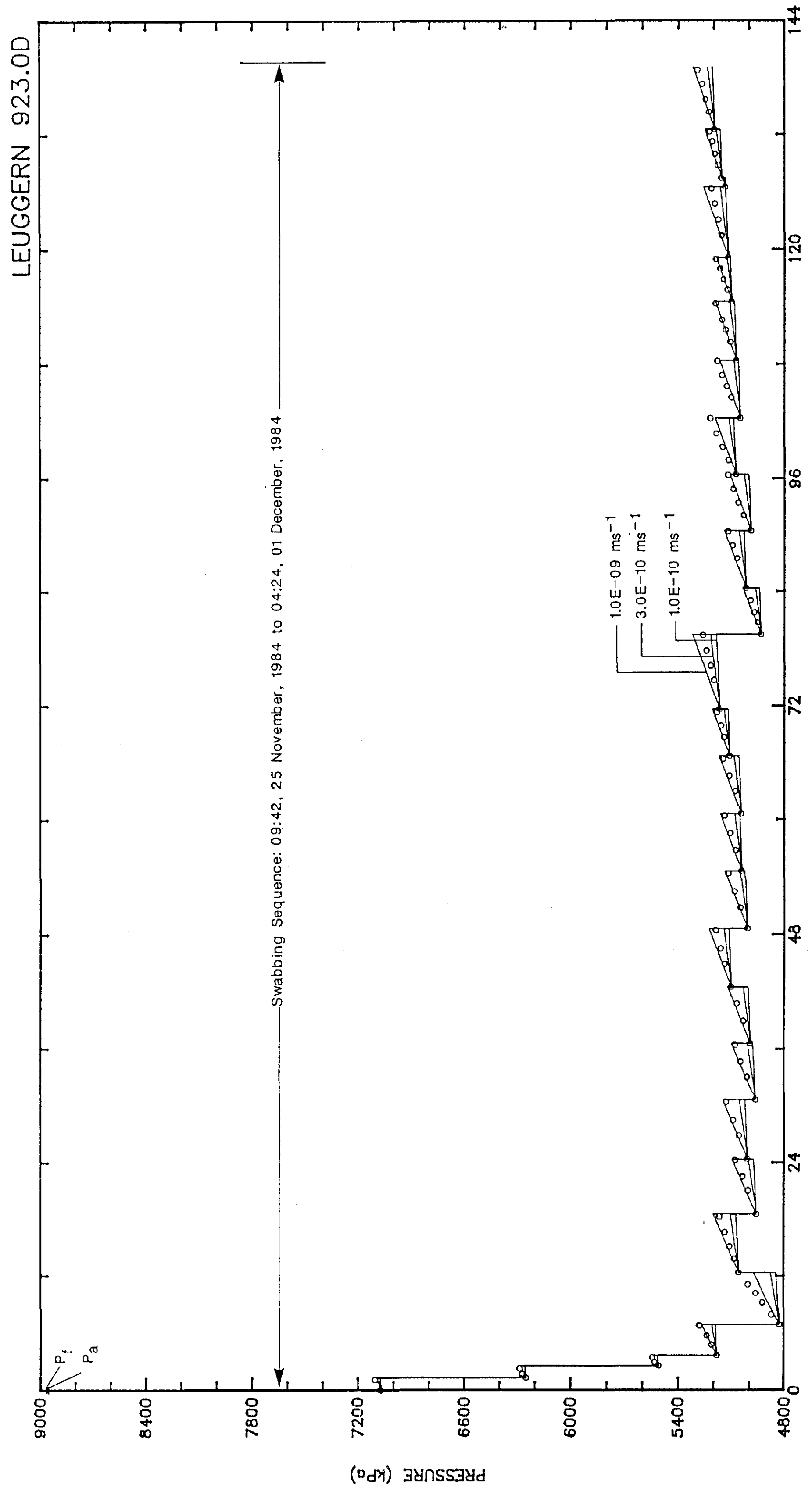


Figure 1: Measured (o) and Simulated Pressure Response for the Swabbing Sequence to 01 December, 1984

Test 940.8H (928.30 m to 953.27 m)

Test 940.8H was performed on 5 January, 1985, as a part of H-log sequence #4, in order to obtain a representative formation hydraulic conductivity. The simulated pre-test pressure history includes a 14 hour drilling overpressure of 400 kPa, a 52.8 day open borehole period at an annulus pressure of 9057 kPa, and a 90 minute packer compliance period.

H-log 940.8H consisted of 2 tests: a 2.7 hour pulse injection test (Pi01) and a 2.2 hour slug withdrawal test (Sw01). The formation pressure (at true P2 depth) was estimated to be 9075 kPa based on values determined in single packer tests between 700 and 900 m depth. The GTFM simulations for this interval are likely to be insensitive to formation pressure because of the long open borehole period at annulus pressure.

The estimated shut-in pressure for Pi01 of 11128 kPa may be an overestimate. Based on the measured pressure response, the shut-in pressure appears to be closer to 10985 kPa, indicating a shut-in squeeze of about 150 kPa. This difference in Pi01 shut-in pressures is considered to have a negligible effect on the interpreted hydraulic conductivity because of the small magnitude of the squeeze relative to the pulse.

All hydraulic parameters were selected based on the best fit of the simulated pressure response to the measured Pi01 pressure response. The best-fit simulation is shown in Figure 1. It indicates an interval hydraulic conductivity of between 3.0E-12 and 1.0E-11 ms^{-1} and a specific storage of 2.2E-07 m^{-1}. The recommended K for this interval is 6.0E-12 ms^{-1} at this S_s value. Additional simulations showed the effect of varying the specific storage by one order of magnitude was equivalent to changing the hydraulic conductivity by only a factor of 2 or 3. For this reason the base case specific storage of 2.2E-07 m^{-1} was used in simulations.

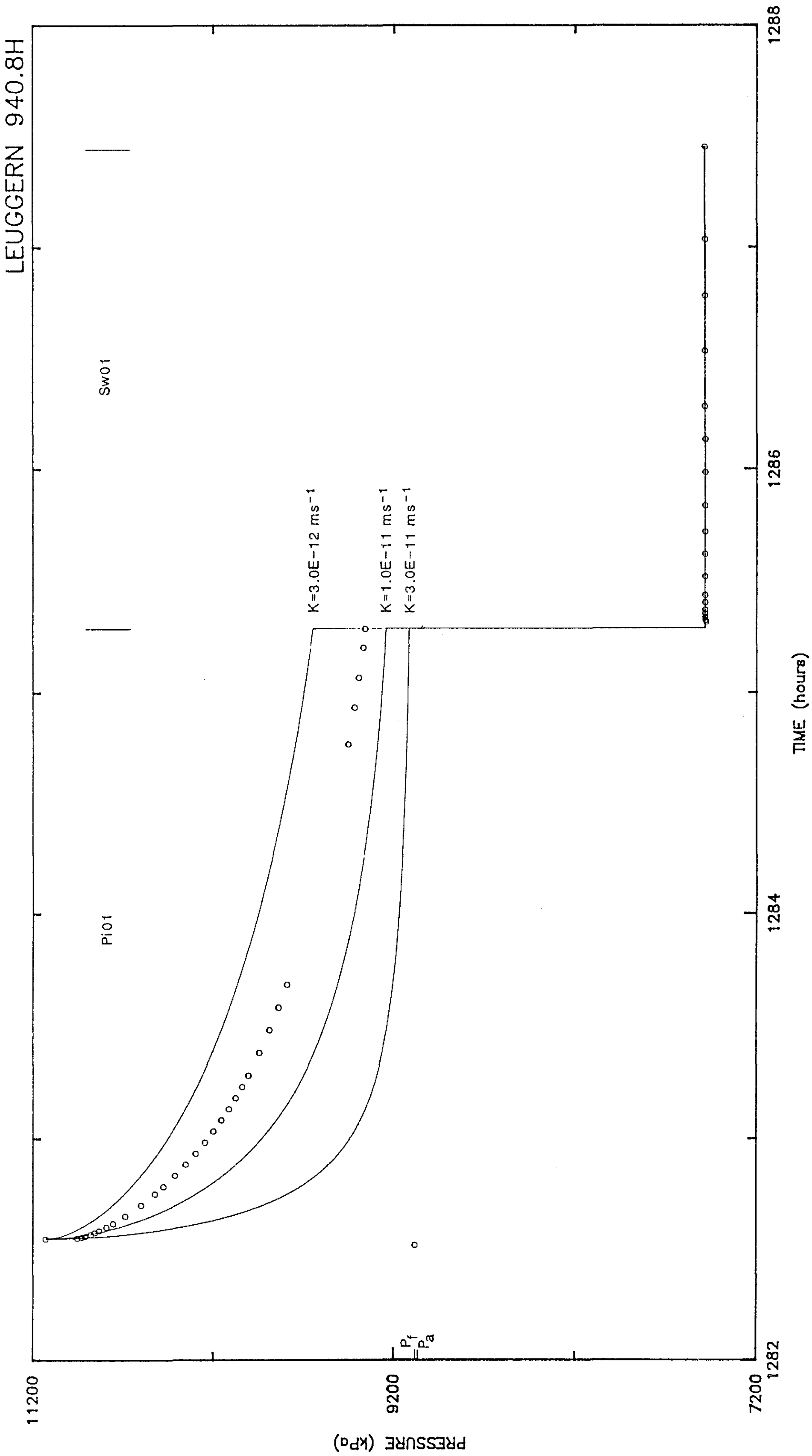


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 964.4H (951.95 m to 976.92 m)

This interval was tested, as a part of H-log sequence #4, on 5 January, 1985 in order to obtain a representative formation hydraulic conductivity. The complete simulated pre-test pressure history includes a 17 hour drilling overpressure of 400 kPa above annulus pressure, a 51.1 day open borehole period at an annulus pressure of 9281 kPa, and a 79 minute packer compliance period.

The testing sequence was comprised of 2 tests: a 2.7 hour pulse injection test (Pi01) and a 2.6 hour slug withdrawal test (Sw01). The formation pressure (at true P2 depth) was estimated to be 9300 kPa based on values determined in single packer tests performed between 700 and 900 m depth. The formation pressure assumed for this interval has a negligible effect on the simulated pressure response because of the long pre-test open borehole period at annulus pressure. The temperature remained constant during Pi01 so thermal effects were not simulated. A temperature rise of 0.5°C was measured by the T2 temperature probe during Sw01, however, because of the open shut-in during slug tests, pressure fluctuations resulting from temperature changes are quickly dissipated.

The best-fit simulation is shown in Figure 1. It indicates an interval hydraulic conductivity of between 1.0E-12 and 3.0E-12 ms^{-1} and a specific storage of 2.2E-07 m^{-1}. Simulations were also performed using a specific storage of 4.0E-08 m^{-1} and resulted in a best-fit hydraulic conductivity of about 2.5E-12 ms^{-1}. This indicates that the effect of varying specific storage by one order of magnitude is equivalent to changing the hydraulic conductivity by a factor of 2.

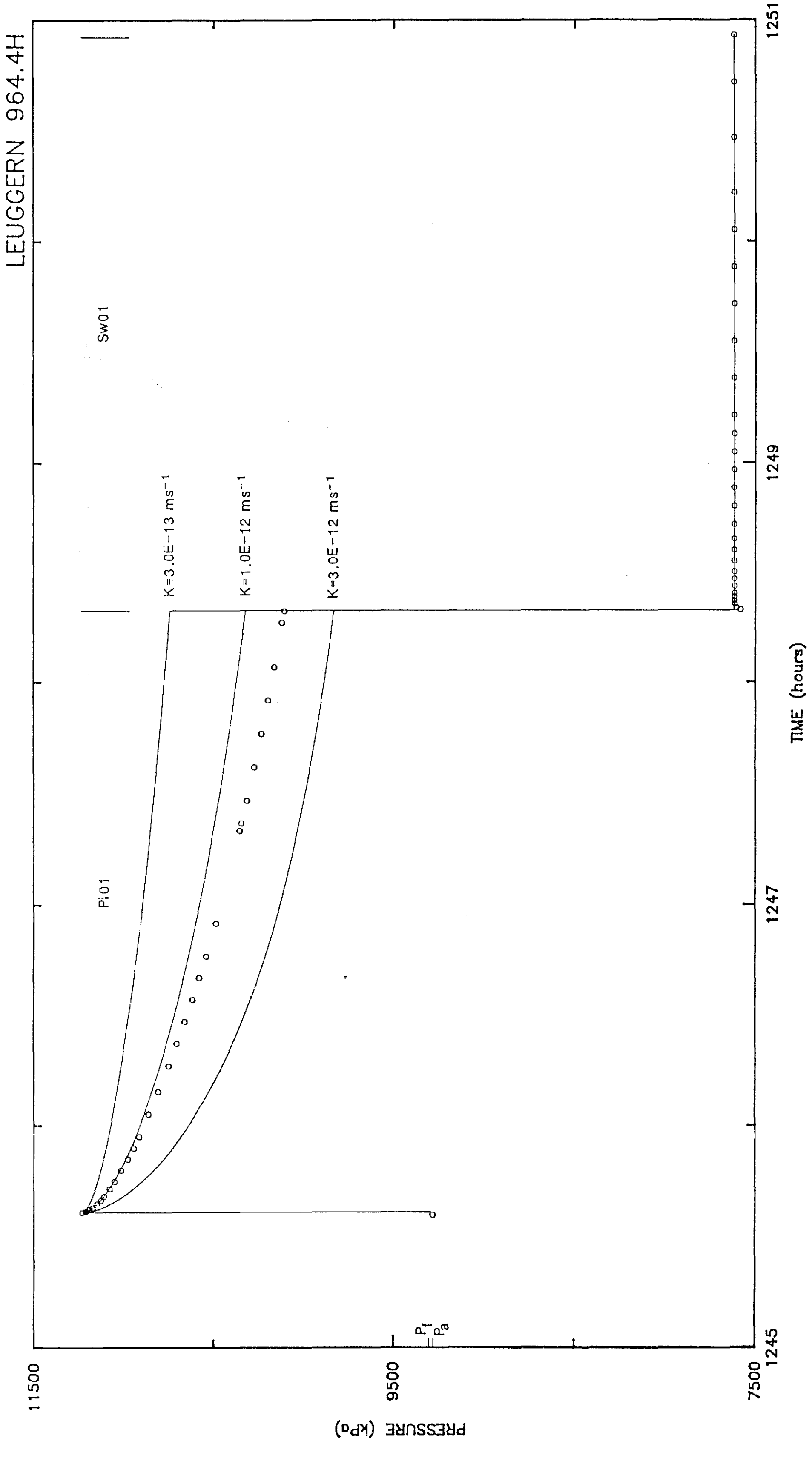


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 986.0H (973.55 m to 998.52 m)

This interval was tested on 4 January, 1985, as a part of H-log sequence #4, in order to obtain a representative hydraulic conductivity. The interval pressure history may have been influenced by test sequence 1002.2H, which overlaps with the bottom 8.77 m of this interval. A GTFM simulation was run to test the influence of 1002.2H and the resulting change in 986.0H test sequence pressure response was less than 10 kPa. This is not significant when compared with the influence of changing the hydraulic conductivity by one half order of magnitude. Therefore, omitting test 1002.2H from the pre-test pressure history will not affect the half order of magnitude best-fit estimate of hydraulic conductivity. The simulated pre-test borehole pressure history includes a 17 hour drilling overpressure of 400 kPa, a 50.9 day open borehole period, and a 66 minute packer compliance period. The interval was exposed to annulus pressure of 9485 kPa during the open borehole period between drilling and testing.

The test sequence was comprised of the following 3 tests: a 3.1 hour pulse injection (Pi01), a 2.5 hour slug withdrawal (Sw01), and a 0.8 hour pulse withdrawal (Pw01). The formation pressure (at true P2 depth) was estimated by extrapolating from the values determined in single packer tests of the upper 900 m of the borehole. The temperature remained constant during Pi01 so thermal effects were not included.

The best-fit simulation, shown in Figure 1, indicates a hydraulic conductivity of 3.0E-13 ms^{-1} and a specific storage of 2.2E-07 m^{-1}. The best-fit simulation gives a near perfect fit to all 3 test sequences. An analysis of the effect of varying the specific storage for this zone of very low hydraulic conductivity (less than 1.0E-12 ms^{-1}) indicates that varying the specific storage by one order of magnitude is equivalent to changing the hydraulic conductivity by a factor of 3 to 4.

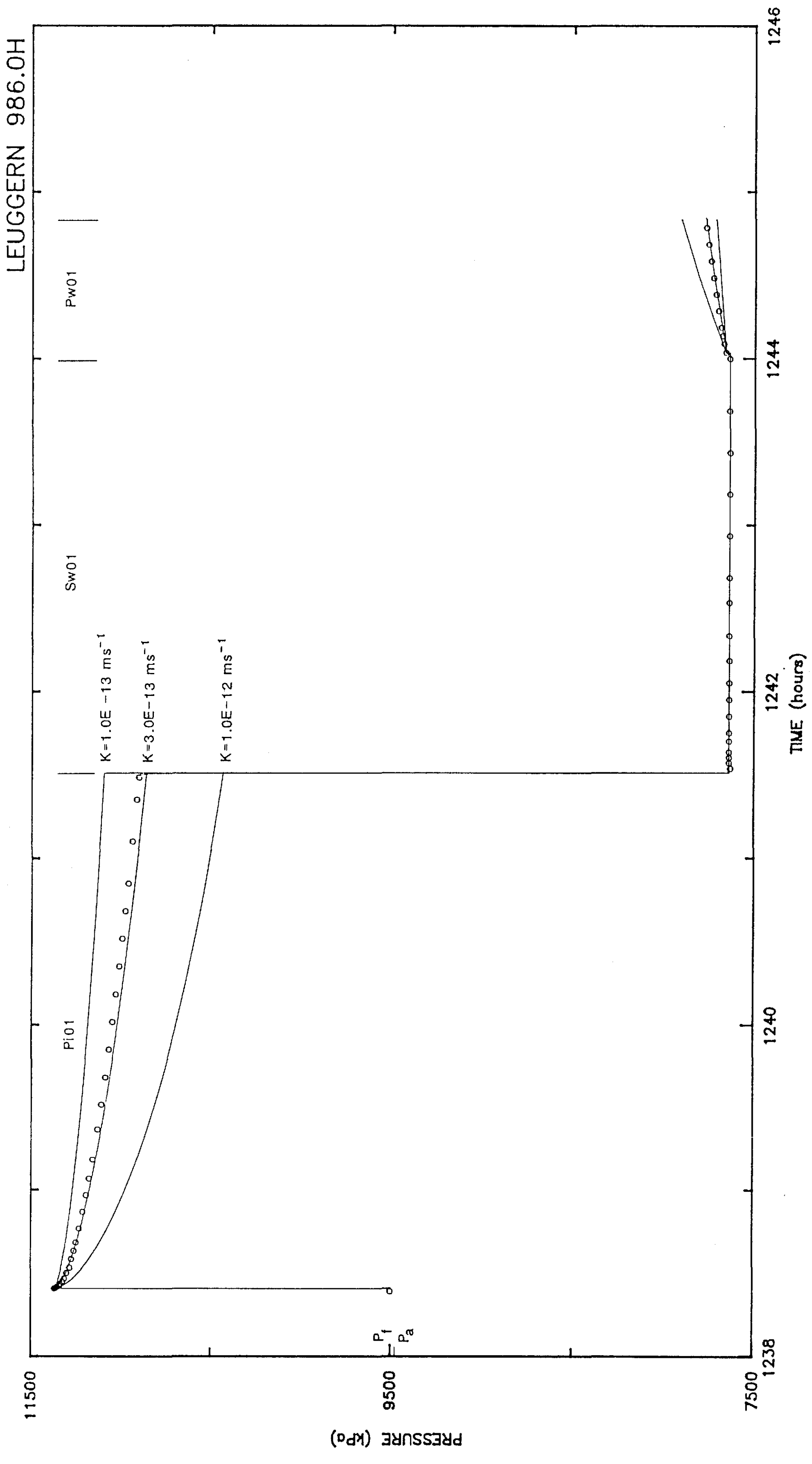


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 1002.2H (989.75 m to 1014.72 m)

This interval was tested, as a part of H-log sequence #4, on 4 January, 1985 in order to obtain a representative formation hydraulic conductivity. The complete simulated pre-test pressure history includes a 16 hour drilling period with a 400 kPa overpressure, a 48.6 day open borehole period at an annulus pressure of 9638 kPa, and a 79 minute packer compliance period.

The testing period was comprised of a 2.8 hour pulse injection test (Pi01) and a 3.6 hour slug withdrawal test (Sw01). The formation pressure (at true P2 depth) was estimated to be 9655 kPa based on values determined from single packer tests in this borehole. The GTFM simulations for this interval are insensitive to the assumed formation pressure because of the long open borehole period at annulus pressure. The temperature remained constant during Pi01 so thermal effects were not simulated.

The best-fit simulation, shown in Figure 1, indicates an interval hydraulic conductivity of between 3.0E-13 and 1.0E-12 ms^{-1} and a specific storage of 2.2E-07 m^{-1}. A sensitivity analysis of specific storage showed that the effect of varying specific storage by one order of magnitude is equivalent to changing the hydraulic conductivity by a factor of 3.

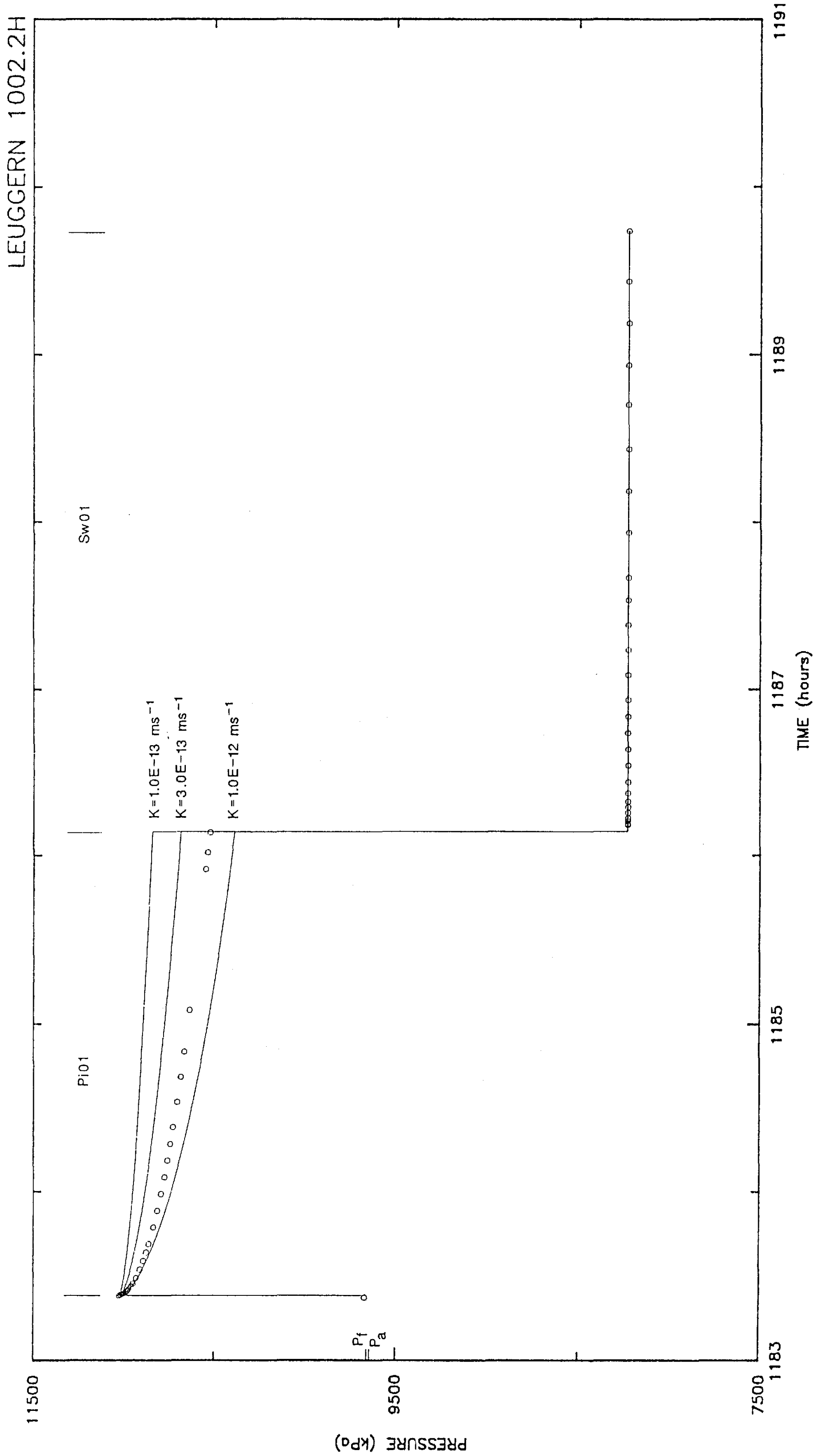


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 1026.6H (1014.10 m to 1039.07 m)

This interval was tested on 4 January, 1985, as a part of H-log sequence #4, in order to obtain a representative hydraulic conductivity. The simulated pre-test pressure history includes a 17 hour drilling overpressure of 400 kPa, a 46.8 day open borehole period at an annulus pressure of 9867 kPa, and a 73 minute packer compliance period.

Testing consisted of a 3.3 hour pulse injection test (Pi01) and a 1.3 hour slug withdrawal test (Sw01). The estimated formation pressure of 9885 kPa (at true P2 depth) is based on values determined from analysis of surrounding single packer tests. The temperature remained constant during testing so thermal effects were not simulated.

The best-fit simulation, shown in Figure 1, results in an interval hydraulic conductivity of between 1.0E-13 and 3.0E-13 ms^{-1} and a specific storage of 2.2E-07 m^{-1}. Simulations using different specific storage values showed that the effect of varying the specific storage by one order of magnitude was roughly equivalent to changing the hydraulic conductivity by a factor of 3. The base case specific storage value was selected in the absence of any test data that would provide a more reliable estimate. Given the uncertainty in the true specific storage and the aforementioned sensitivity, the best-fit hydraulic conductivity should be considered to have an uncertainty of at least one half order of magnitude.

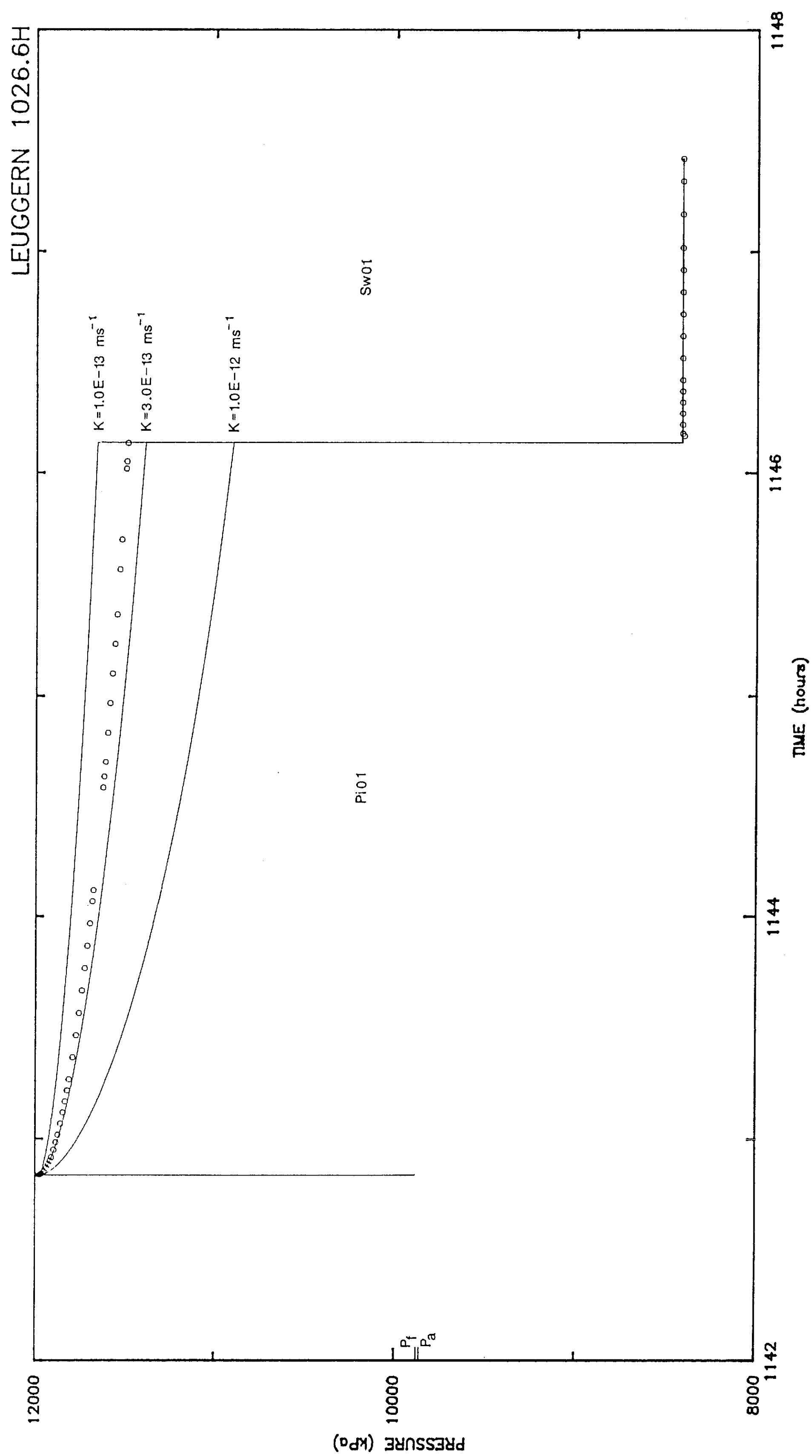


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 1046.0H (1033.55 m to 1058.52 m)

This interval was tested on 3 January, 1985, as a part of H-log sequence #4, in order to determine a representative hydraulic conductivity. The simulated pre-test pressure history includes a 20.5 hour drilling overpressure of 400 kPa, a 45.2 day open borehole period at an annulus pressure of 10049 kPa, and a 71 minute packer compliance period.

H-log 1046.0H consisted of the following tests: a 91 minute pulse injection test (Pi01), a 55 minute pulse withdrawal test (Pw01), a 114 minute slug withdrawal test (Sw01), and a final 16 minute buildup period (Pw02). The exact time of shut-in for the buildup period is uncertain because the data acquisition computer was not collecting data at the time. The shut-in time was estimated by interpolating from the pressure recovery curve. The estimated formation pressure (at true P2 depth) of 10060 kPa is based on values determined in analysis of surrounding single packer tests. Thermal effects were not simulated as temperatures remained essentially constant throughout the testing period.

The results of simulations using a specific storage of 2.2E-07 m^{-1}, shown in Figure 1, indicate an interval hydraulic conductivity of between 3.0E-12 and 1.0E-11 ms^{-1} based on Pi01. Pw01 and Pw02 recovered faster than Pi01, a response characteristic of many of the test intervals where a pulse withdrawal immediately followed a pulse injection. The Pw01 and Pw02 pressure responses indicate a hydraulic conductivity about half an order of magnitude greater than Pi01. A good fit was obtained using the base case specific storage of 2.2E-07 m^{-1}. Sensitivity analysis showed that by varying the specific storage by one order of magnitude, the best-fit hydraulic conductivity changed by a factor of 3. A hydraulic conductivity of 1.0E-11 ms^{-1} is considered representative for the test interval.

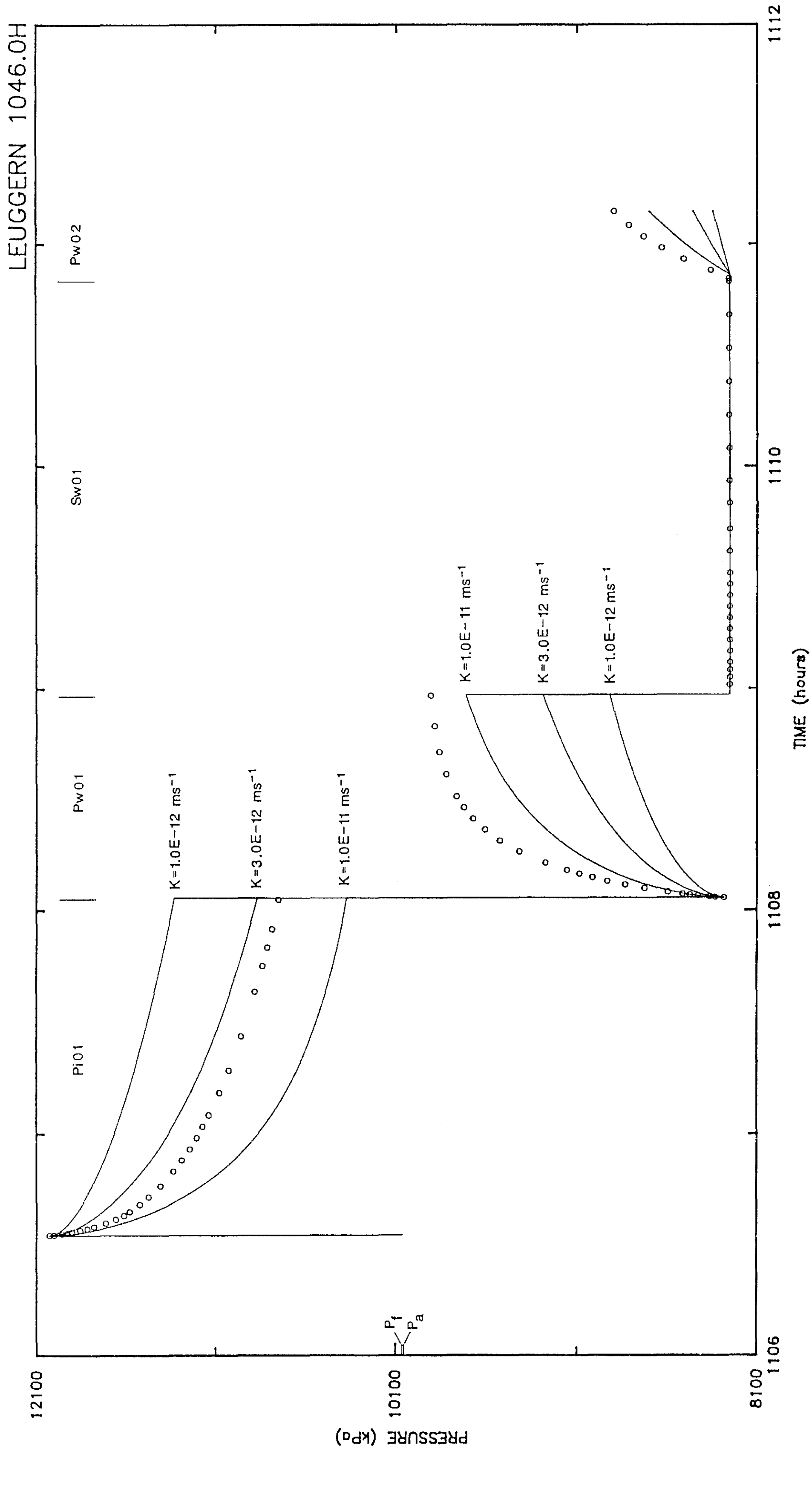


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 1064.6H (1052.15 m to 1077.12 m)

H-log testing was conducted in this interval on 5 January, 1985 in order to determine a representative formation hydraulic conductivity. The simulated pre-test pressure history includes a 29 hour drilling overpressure of 450 kPa, a 42.9 day open borehole period at an annulus pressure of 10222 kPa, and a 73 minute packer compliance period.

This testing sequence consisted of the 2 tests: a 2.4 hour pulse injection (Pi01) and a 1.6 hour slug withdrawal (Sw01). The estimated formation pressure at P2 depth of 10235 kPa is based on values determined from analysis of surrounding single packer test intervals. The temperature remained stable throughout testing so thermal effects were not included in the simulation.

GTFM simulation results are shown in Figure 1 for hydraulic conductivities ranging from 1.0E-12 to 1.0E-11 ms^{-1} and a specific storage of 4.0E-08 m^{-1}. The formation hydraulic conductivity, based on the best fit to the measured Pi01 response, is about 3.0E-12 ms^{-1}. The best-fit specific storage value provides a better fit to the early time Pi01 response than the base case value of 2.2E-07 m^{-1}. Sensitivity analysis showed that by varying the specific storage by one order of magnitude, the best-fit hydraulic conductivity is only changed by a factor of 3. The selection of a specific storage value for this interval that is one order of magnitude lower than the base case value is justified by the improved fit it provides, the small effect it has on the best-fit hydraulic conductivity, and the uncertainty in specific storage values in the crystalline rock at Leuggern.

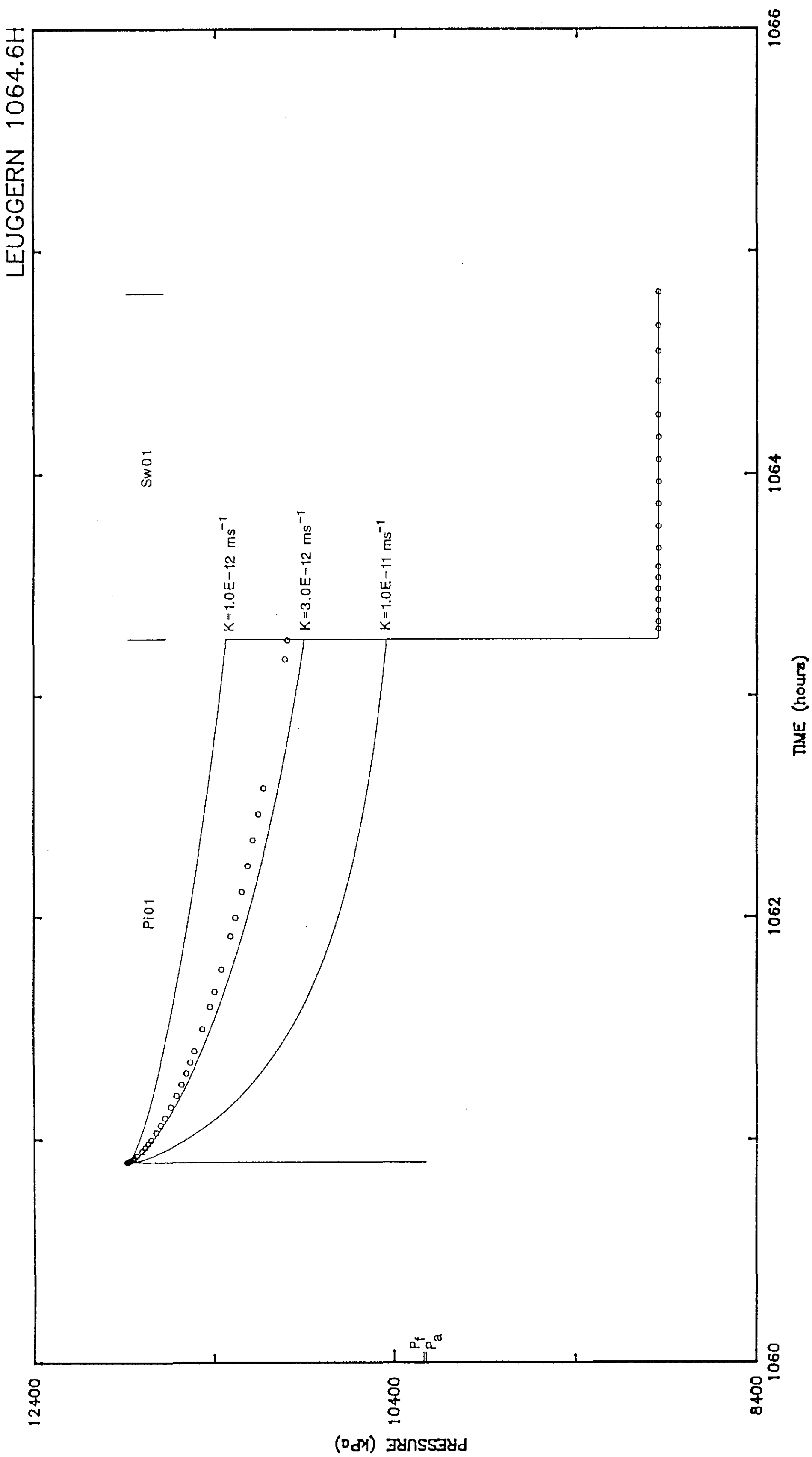


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 1082.9H (1070.40 m to 1095.37 m)

Testing in this interval was performed on 3 January, 1985, as a part of H-log sequence #4, in order to determine a representative hydraulic conductivity. The simulated pre-test pressure history includes a 26 hour drilling period with a 450 kPa overpressure, a 42.0 day open borehole period at an annulus pressure of 10392 kPa, and a 78 minute packer compliance period.

Test sequence 1082.9H was comprised of the following 3 hydraulic tests: a 1.7 hour pulse injection test (Pi01), a 1.5 hour pulse withdrawal test (Pw01), and a 1.3 hour slug withdrawal test (Sw01). The estimated formation pressure (at P2 depth) of 10405 kPa is based on values determined from analysis of surrounding single packer tests. Thermal effects were not simulated as temperature remained essentially constant throughout the testing period.

Formation parameters were selected based on the best fit of the simulated Pi01 pressure response to the measured response. Simulation results, shown in Figure 1, indicate an interval hydraulic conductivity of 3.0E-11 ms^{-1} and a specific storage of 2.2E-07 m^{-1}. The Pw01 response indicates an interval hydraulic conductivity of about half an order of magnitude greater than Pi01. A good fit was obtained using the base case specific storage of 2.2E-07 m^{-1}. Sensitivity analysis showed that by varying the specific storage by one order of magnitude, the best-fit hydraulic conductivity changed by a factor of 3.

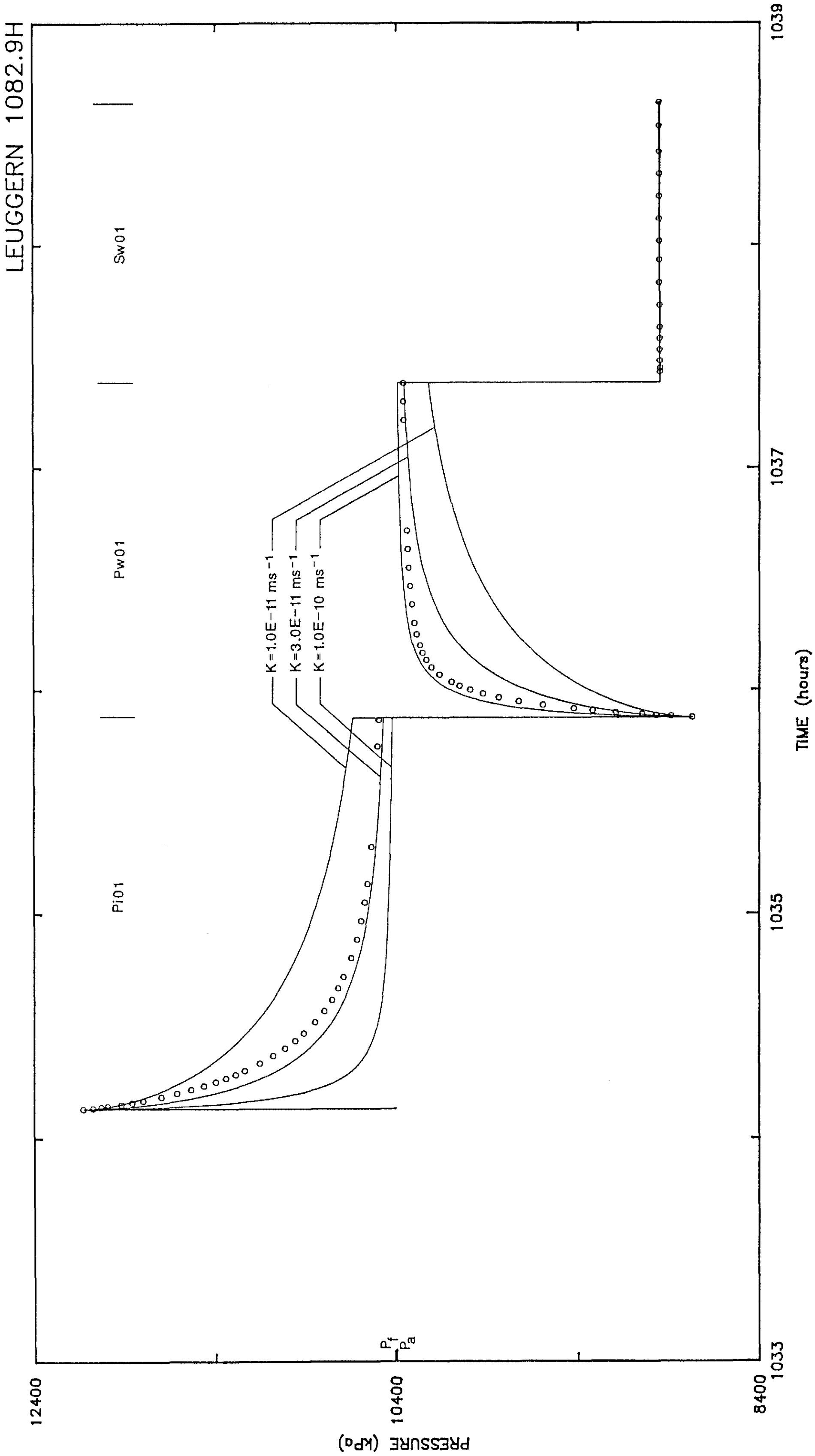


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 1102.1H (1089.60 m to 1114.57 m)

Test 1102.1H was performed on 2 January, 1985, as a part of H-log sequence #4, in order to obtain a representative estimate hydraulic conductivity of the crystalline rock in the interval. The testing period included 2 tests: a 3.8 hour pulse injection (Pi01) and a 2.2 hour slug withdrawal (Sw01).

The drilling history was simulated with 2 sequences; an open borehole at an annulus pressure of 10570 kPa from the end of the first drilling period to the start of the second, and the second drilling period at 450 kPa overpressure. The simulated pre-test pressure history includes the 2 drilling sequences followed by a 25.0 day open borehole period at annulus pressure and a 76 minute packer compliance period. The assumed formation pressure at P2 depth of 10590 kPa is extrapolated from values determined from the analysis of surrounding single packer tests. Thermal effects were not simulated as temperatures remained essentially constant throughout the testing period.

Simulation results are shown in Figure 1. The selected hydraulic parameters of the formation are a hydraulic conductivity of 2.0E-12 ms^{-1} and a specific storage of 4.0E-08 m^{-1}. The specific storage of 4.0E-08 m^{-1} was selected over the base case value of 2.2E-07 m^{-1} because it resulted in a better fit of the simulated early-time Pi01 response to the measured response. By choosing a specific storage value one order of magnitude lower than the base case value, the best-fit hydraulic conductivity is increased by a factor of only 3.

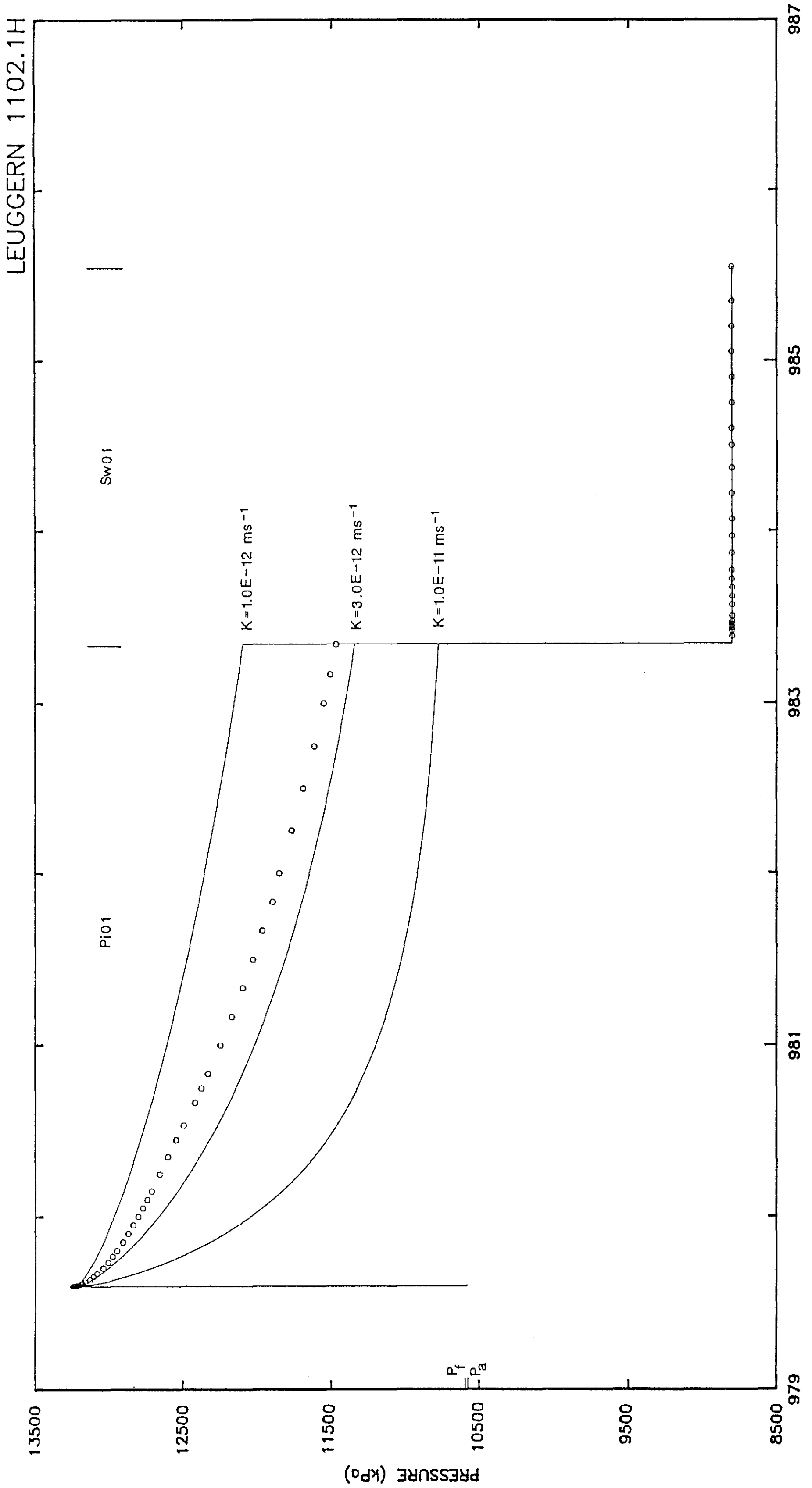


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 1125.1HI (1112.59 m to 1137.56 m)

Test 1125.1HI was performed on 1 to 2 January, 1985, as a part of H-log sequence #4, in order to determine a representative hydraulic conductivity. The measured pressure response showed an abrupt change in slope that was considered to be tool related so a second test, test 1125.1HII, was done on 14 to 15 March, 1985. The simulated pre-test pressure history for this interval includes a 16.7 hour drilling period with a 425 kPa drilling overpressure, a 22.7 day open borehole period at an annulus pressure of 10768 kPa, and a 69 minute packer compliance period.

Test 1125.1HI included a 3.1 hour pulse injection test (Pi01) and a 3.8 hour slug withdrawal test (Sw01). From the measured pressure response it can be seen that a slope change occurred about 5 minutes into the Pi01 pressure recovery. A similar slope change occurred in the preceding H-log test, 1149.8HI. This slope change could be attributable to either boundary effects or problems with the test tool. Retests of these two intervals did not reproduce the slope change indicating that it was probably caused by problems with the test equipment. Test 1125.1HI was still considered analyzable, and provides support for the formation parameters determined from 1125.1HII.

The estimated formation pressure of 10800 kPa is extrapolated from values determined from the analysis of surrounding single packer tests. The temperature decreased by only 0.1°C during testing so thermal effects were not simulated.

Two sets of GTFM simulations were run. For the first set, shown in Figure 1, the simulated Pi01 test started at shut-in (p=12773 kPa, t=561.9 hours) and the hydraulic conductivity was varied from 1.0E-12 to 1.0E-11 ms^{-1}. For the second set, the simulated Pi01 test started at the slope change (p=12532 kPa, t=562.0 hours) and the hydraulic conductivity was varied from 3.0E-13 to 3.0E-12 ms^{-1}. In both cases the assumed specific storage was 2.2E-07 m^{-1} and the best fit of the simulated late-time Pi01 pressure to the measured pressure was obtained using a hydraulic conductivity within half an order of magnitude of 1.0E-12 ms^{-1}. The results of these simulations support the findings of 1125.1HII, which has a best-fit hydraulic conductivity of 1.0E-12 ms^{-1} and an assumed specific storage of 2.2E-07 m^{-1}.

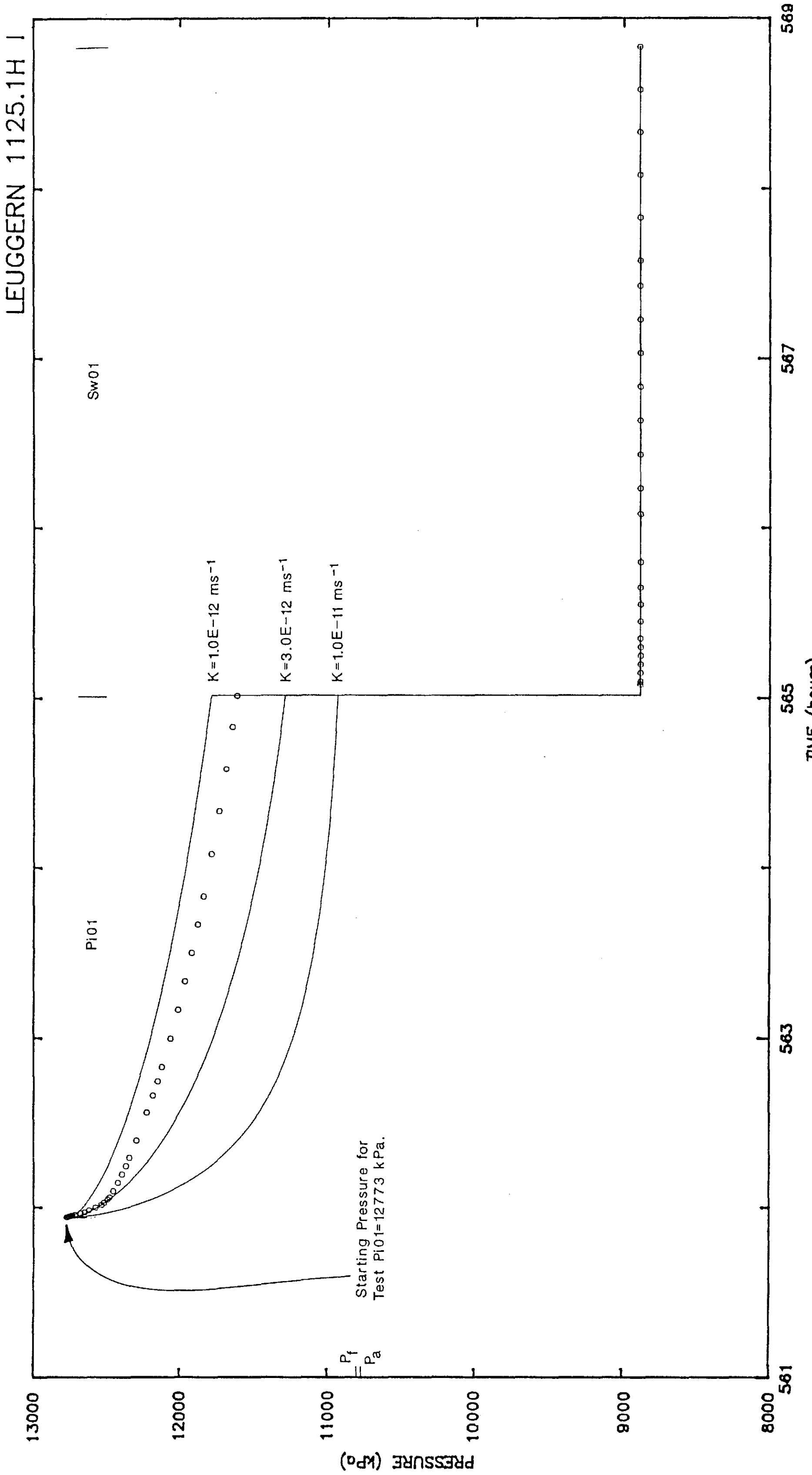


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 1125.1HII (1112.59 m to 1137.56 m)

Test 1125.1HII was a retest of the same interval tested during 1125.1HI. The measured pressure response of 1125.1HI showed an abrupt change in slope that was considered to be tool related so the retest, 1125.1HII, was performed on 14 to 15 March, 1985 in an effort to obtain a more confident estimate of hydraulic conductivity. The simulated pre-test pressure history includes a 16.7 hour drilling period with a 425 kPa drilling overpressure, a 22.7 day open borehole period at an annulus pressure of 10768 kPa prior to test 1125.1HI, the Sw01 sequence from 1125.1HI simulated at a constant pressure of 8878 kPa, a second open borehole period at annulus pressure for 72.6 days, and a 64 minute packer compliance period from the start of testing at 1125.1HII.

Test 1125.1HII consisted of 3 hydraulic tests: an 11.9 hour pulse injection test (Pi01), a 2.4 hour pulse withdrawal test (Pw01), and a 2.1 hour slug withdrawal test (Sw01). The slope change that occurred during 1125.1HI is not present in this test. This seems to indicate that the 1125.1HI pressure response was affected by tool problems and may not have been characteristic of the crystalline rock in this interval. The estimated formation pressure of 10800 kPa is extrapolated from values determined from the analysis of surrounding single packer tests. Thermal effects were not included in the simulation.

Figure 1 shows GTFM simulation results for hydraulic conductivities ranging from 3.0E-13 to 3.0E-12 ms^{-1}. The best-fit formation parameters, based on a match to the measured Pi01 pressure data, are a hydraulic conductivity of 1.0E-12 ms^{-1} and a specific storage of 2.2E-07 m^{-1}. These best-fit parameters are the same as the formation parameters determined from test 1125.1HI.

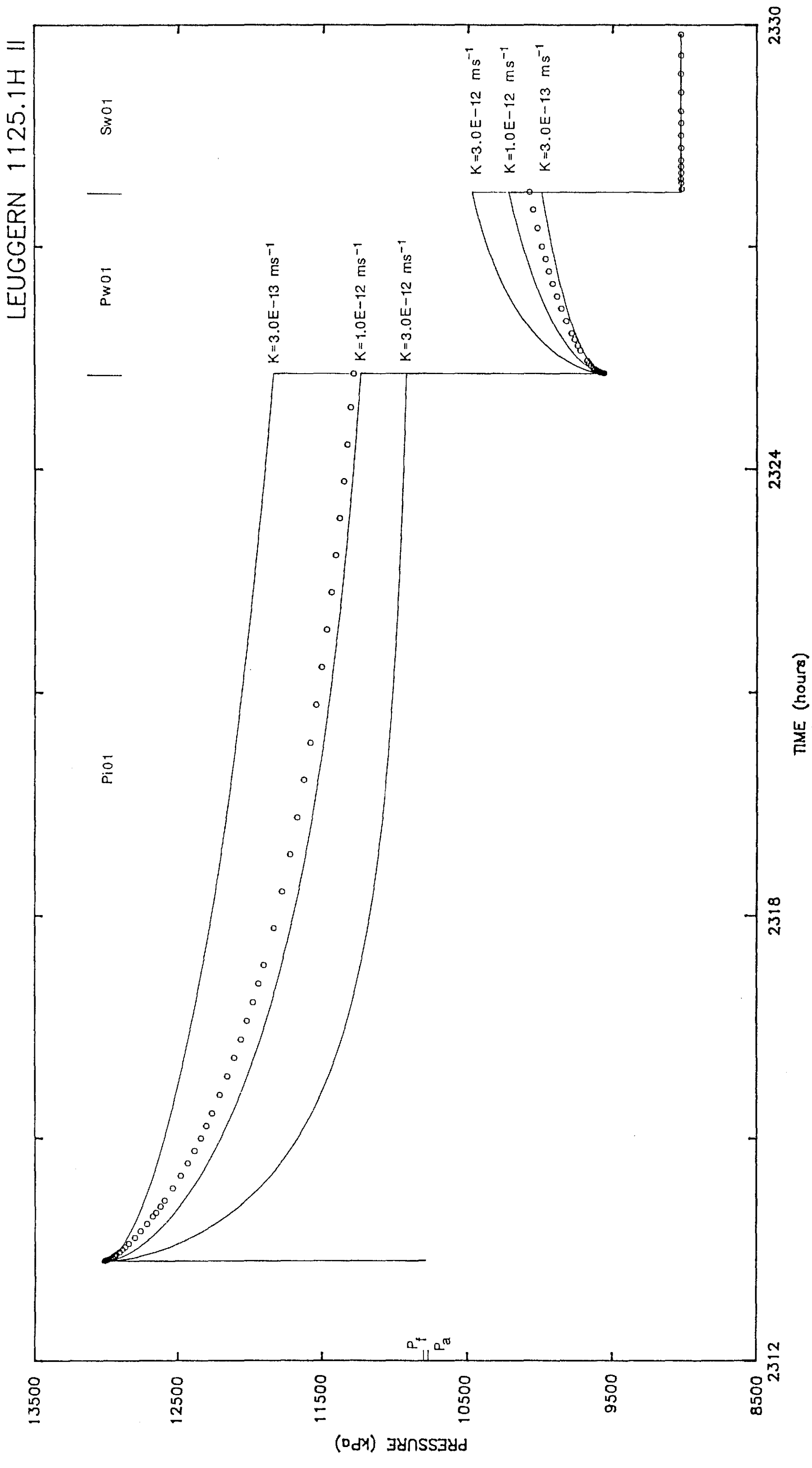


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 1128.9S (942.76 m to 1315.05 m)

This single packer test was performed on 26 December, 1984 immediately prior to the H-log sequence #4. The purpose of this test was to determine a formation hydraulic conductivity representative of the 327.29 m long test interval. To simplify pre-test history, the simulated mid-point of drilling was set to coincide with the start of the second drilling period. The simulated pre-test pressure history for the interval includes a 15.5 day drilling period at 425 kPa above annulus pressure, a 2.5 day open borehole period at an annulus pressure of 9191 kPa, an 83 minute packer compliance period, and a 16 minute aborted pulse injection test.

The testing sequence consisted of the following tests: a 1.0 hour pulse injection (Pi01), a 1.2 hour pulse withdrawal (Pw01), a 1.6 hour drill-stem test (14 minute flow period (Sw01) followed by pressure buildup under shut-in conditions (Pw02)), and a 2.8 hour slug withdrawal (Sw02). An assumed formation pressure of 9215 kPa (at true P2 depth) was interpolated from values determined in single packer testing of surrounding intervals. The measured temperature remained constant throughout the testing sequence, therefore, thermal effects were not included in the simulations.

Simulations were run using a specific storage of 2.2E-07 m^{-1} and hydraulic conductivities ranging from 1.0E-11 to 1.0E-10 ms^{-1}. The results of these simulations are shown in Figure 1. From the simulated pressure responses, a hydraulic conductivity of 5.0E-11 ms^{-1} would provide the best match to the measured pressure responses. A sensitivity study demonstrated that by varying the specific storage by one order of magnitude, the best-fit hydraulic conductivity changed by a factor of 2 or 3.

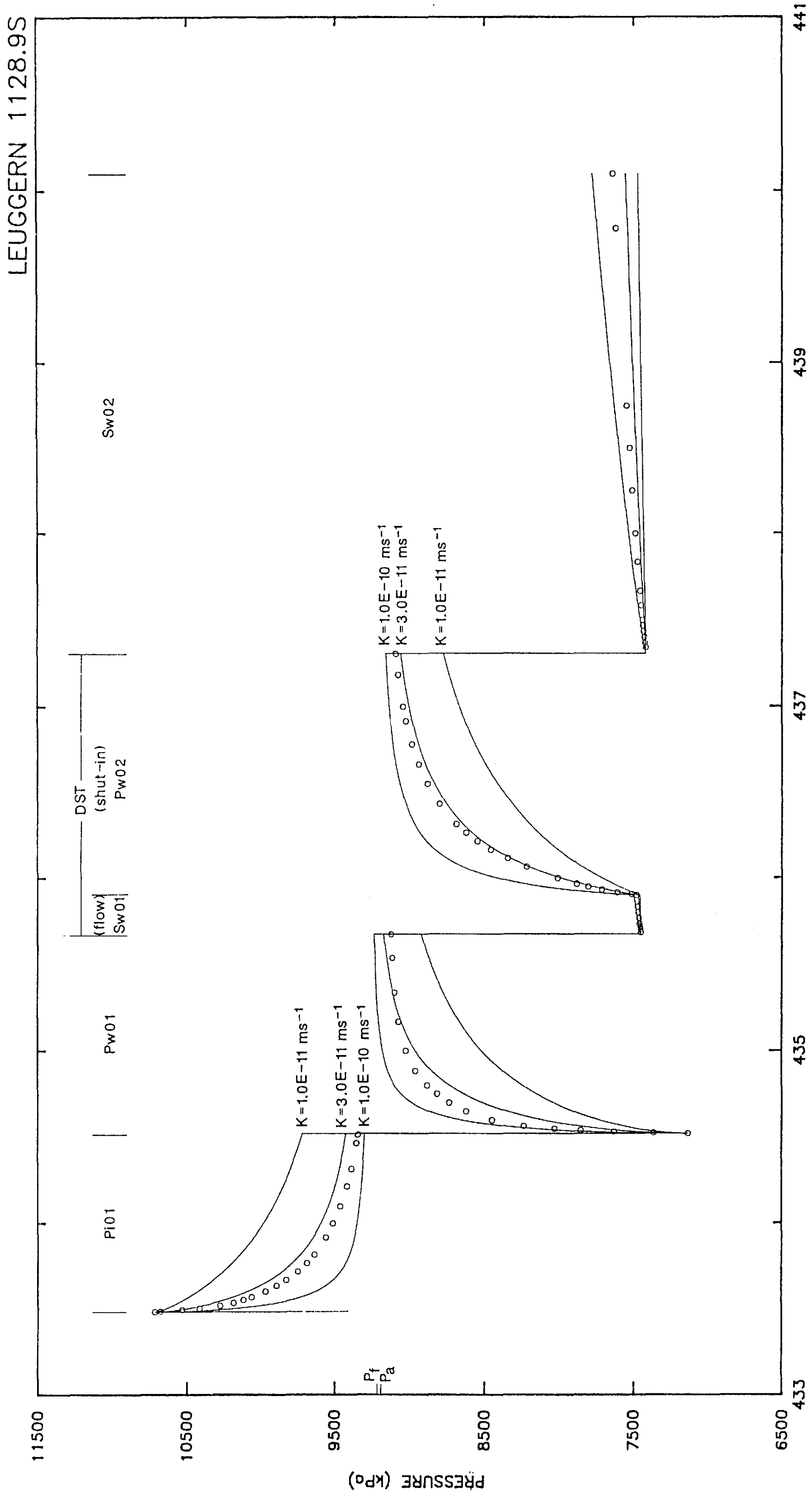
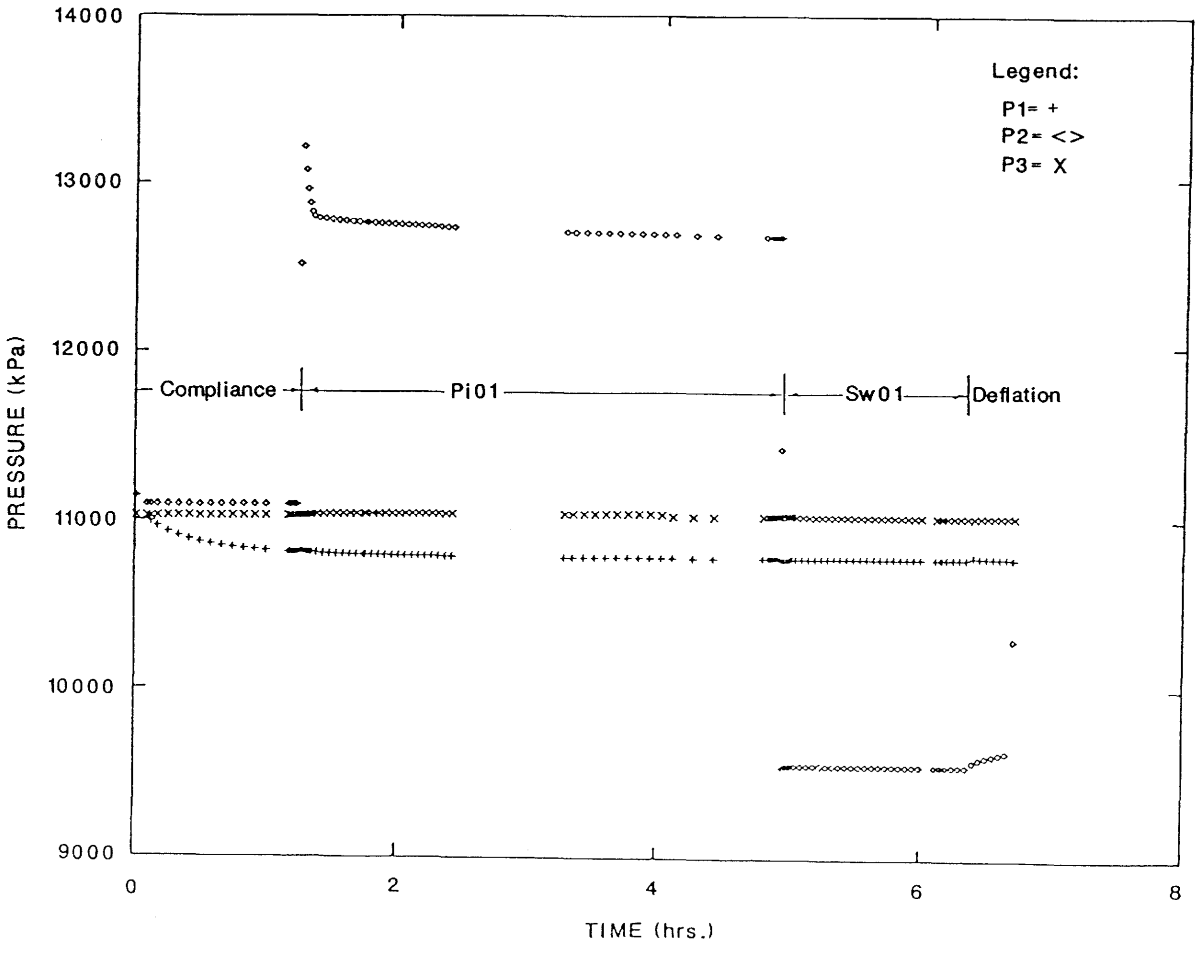


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 1149.8HI (1137.31 m to 1162.28 m)

Test sequence 1149.8HI was performed on 1 January, 1985 to determine a representative formation hydraulic conductivity. Testing consisted of a pulse injection test followed by a slug withdrawal test. An abrupt change in the slope of the pulse injection pressure response (Pi01) occurred about 6 minutes after shut-in as can be seen in the figure below. A similar response occurred in the subsequent H-log test 1125.1HI.

This interval was retested on 14 March, 1985 (1149.8HII) and the slope change in the pressure response was not evident. Therefore, the slope change was considered to be tool-related and the data from this test was not analyzed. Formation parameters interpreted for this interval are based on the simulation results of test 1149.8HII.



1149.8HII (1137.31 m to 1162.28 m)

Test 1149.8HII was performed on 14 March, 1985 in order to obtain a representative estimate of hydraulic conductivity of the crystalline rock in the interval. This is a retest of the same interval covered in test 1149.8HI. The simulated pretest pressure history includes a 93.5 day open borehole period at annulus pressure followed by a 1.3 hour packer compliance period.

The testing period included two tests: a 3.6 hour pulse injection (Pi01) followed by a 2.1 hour slug withdrawal (Sw01). Test Sw01 was not simulated due to the negligible pressure recovery (1 kPa). The assumed formation pressure at P2 depth of 11000 kPa is approximately equal to the annulus pressure used in the borehole history. Sensitivity studies indicated that the simulated pressure response is relatively insensitive to changes in assumed formation pressure. Thermal effects were not included in the simulation as temperatures remained essentially constant throughout the testing period.

Results of the Pi01 simulations are shown in Figure 1. The selected hydraulic parameters for the test interval are a hydraulic conductivity of 3.0E-13 ms^{-1} and a specific storage of 2.2E-07 m^{-1}.

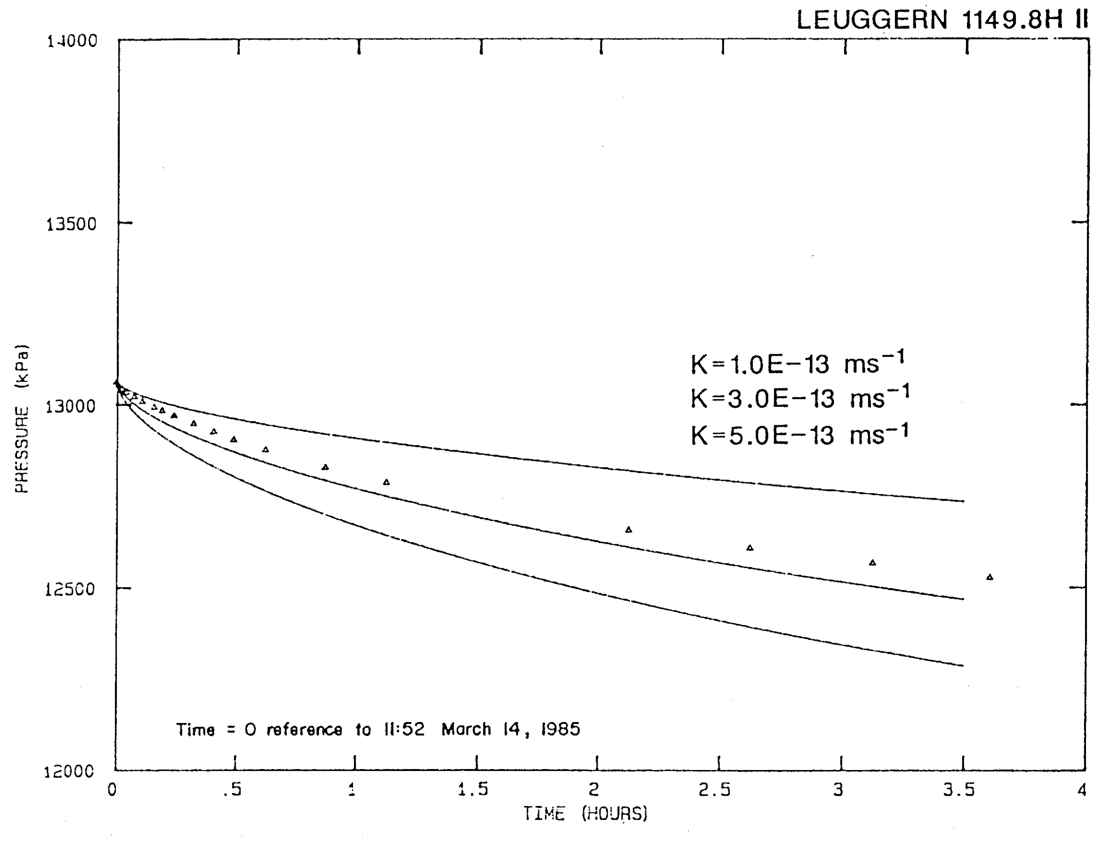


Figure 1: Measured (△) and Simulated Pressure Response for Test Pi01

Test 1174.5H (1162.03 m to 1187.00 m)

Test 1174.5H was performed on 1 January, 1985, as part of H-log sequence #4, in order to obtain a representative estimate of hydraulic conductivity of the crystalline rock in this interval. The simulated pretest pressure history includes a 18.75 day open borehole period at annulus pressure followed by a short packer compliance period.

The testing period included three tests: a 2.4 hour pulse injection (Pi01) followed by a 2.21 hour pulse withdrawal (Pw01) followed by a 2.7 hour slug withdrawal (Sw01). Test Sw01 was not simulated due to the negligible pressure recovery. Thermal effects were not included in the simulation as temperatures remained essentially constant throughout the testing period.

Although the primary goal of the analysis was determination of hydraulic conductivity, lack of information with respect to estimated formation pressure required that an assumed reference pressure be determined through sensitivity studies on Pi01. A best-fit assumed reference pressure of 10570 kPa was determined from the studies.

Results of the simulations are shown in Figure 1 (Pi01) and Figure 2 (Pw01). The selected hydraulic parameters for the test interval are a hydraulic conductivity of 1.0E-11 ms^{-1} (based primarily on the Pi01 fit) and the base case specific storage of 2.2E-07 m^{-1}.

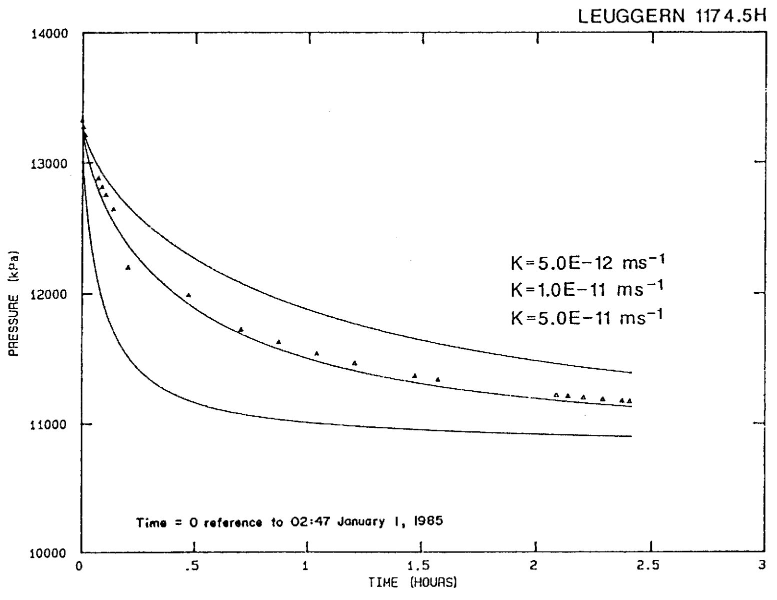


Figure 1: Measured (△) and Simulated Pressure Response for Test Pi01

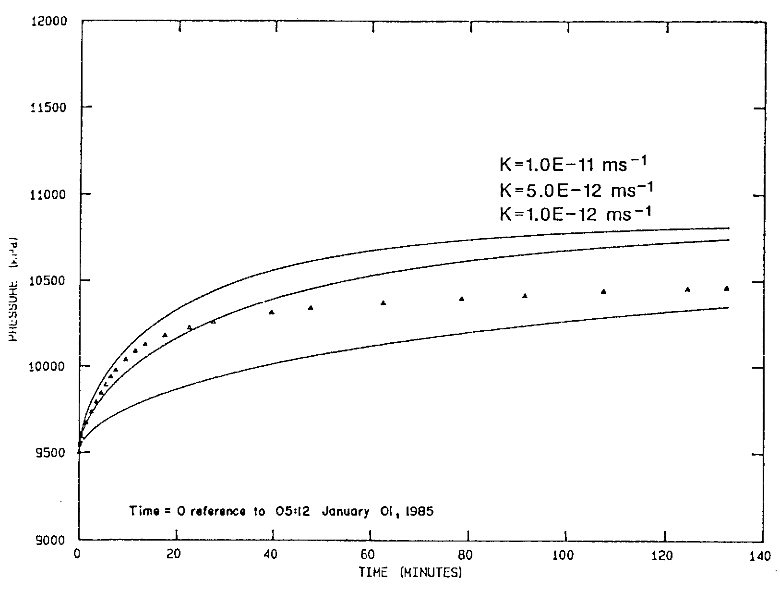


Figure 2: Measured (△) and Simulated Pressure Response for Test Pw01

Test 1191.6H (1179.15 m to 1204.12 m)

Test 1191.6H was performed on 31 December, 1984, as part of H-log sequence #4, in order to obtain a representative estimate of hydraulic conductivity of the crystalline rock in this interval. The simulated pretest pressure history includes a 12.3 day open borehole period at annulus pressure followed by a sequence of pressures reflecting approximately 2.5 days of testing at intervals 1123.1S, 1128.9S, and 1192.5D and subsequent swabbing events.

The testing period included four tests: a 1.25 hour pulse injection (Pi01) followed by a 0.25 hour slug withdrawal (Sw01) followed by a 1.1 hour build-up (Pw01) and concluding with a 1.2 hour slug withdrawal (Sw02). Tests Sw01 and Pw01 were conducted in sequence as a DST test (DST01). Test Sw02 was not simulated due to the negligible pressure recovery. Thermal effects were not included in the simulation as temperatures remained essentially constant throughout the testing period.

Concerning formation pressure, this test was interpreted using an assumed reference pressure of 10800 kPa determined through sensitivity studies.

Results of the simulations are shown in Figures 1 and 2 (Pi01 and Pw01, respectively). Results for Sw01 are not shown as the test was considered to be of too short duration to yield meaningful results. The selected hydraulic parameters for the test interval are a hydraulic conductivity of 5.0E-11 ms^{-1} and the base case specific storage of 2.2E-07 m^{-1}.

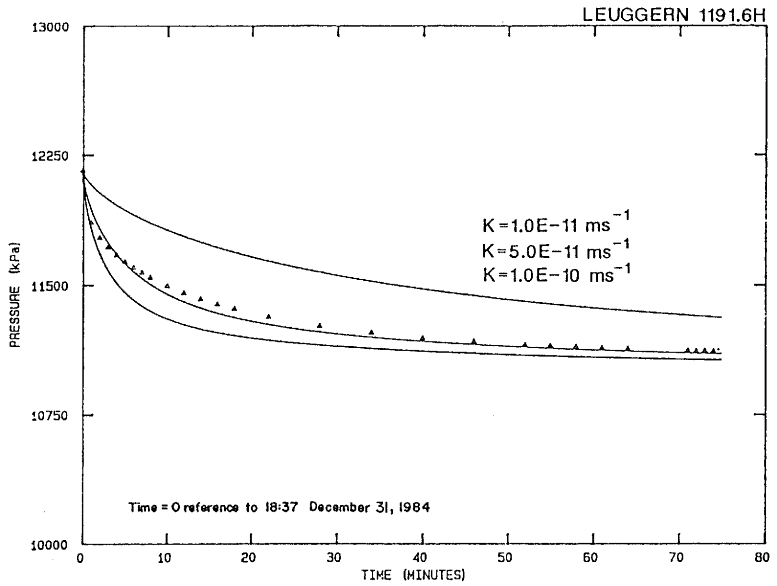


Figure 1: Measured (△) and Simulated Pressure Response for Test Pi01

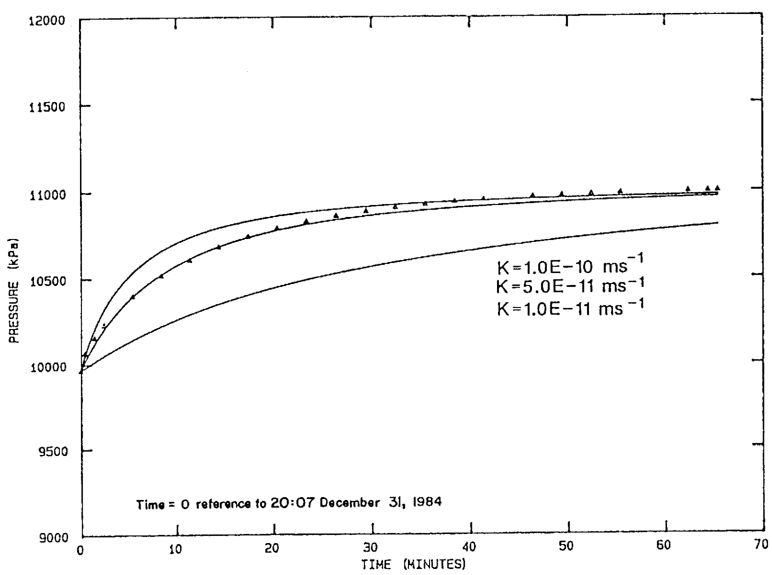


Figure 2: Measured (△) and Simulated Pressure Response for Test Pw01

Test 1192.5D (1176.21 m to 1208.79 m)

Double-packer test 1192.5D was performed on 27 December, 1984 to obtain a representative estimate for the hydraulic conductivity of the crystalline rock in this interval. The simulated pretest pressure history includes a 12 day open borehole period at annulus pressure followed by a short packer compliance period.

Testing in the interval consisted of a 39 minute pulse injection (Pi01) test followed by a 34 minute pulse withdrawal (Pw01) followed by a DST test of 1.7 hour duration (16 minutes for flow period Sw01, remainder for build-up period Pw02) and concluding with a 2.4 hour slug withdrawal (Sw02). Thermal effects were not simulated as temperature did not vary significantly over the duration of the tests.

Results of the pulse tests are shown in Figures 1 through 3 (Pi01, Pw01, and Pw02, respectively). The reference formation pressure of 11290 kPa was determined through sensitivity studies. Results for the slug withdrawal tests are not shown due to the insignificant pressure response (both measured and simulated) during the tests. The selected hydraulic parameters for the test interval are a hydraulic conductivity of 1.0E-10 ms^{-1} at a base case specific storage of 2.2E-07 m^{-1}.

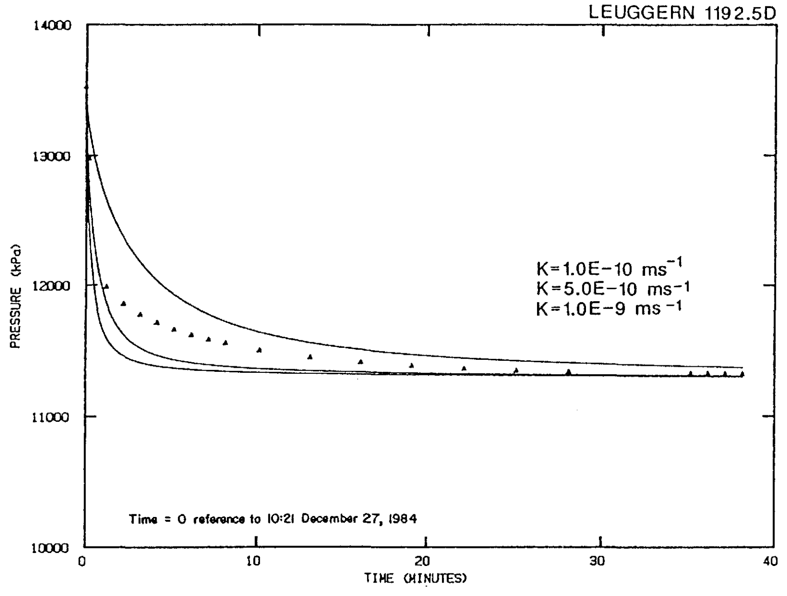


Figure 1: Measured (△) and Simulated Pressure Response for Test Pi01

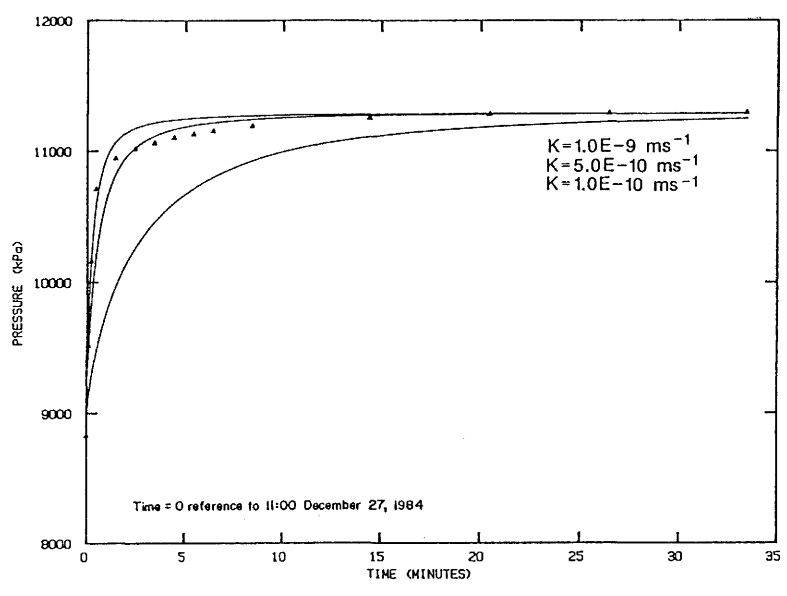


Figure 2: Measured (△) and Simulated Pressure Response for Test Pw01

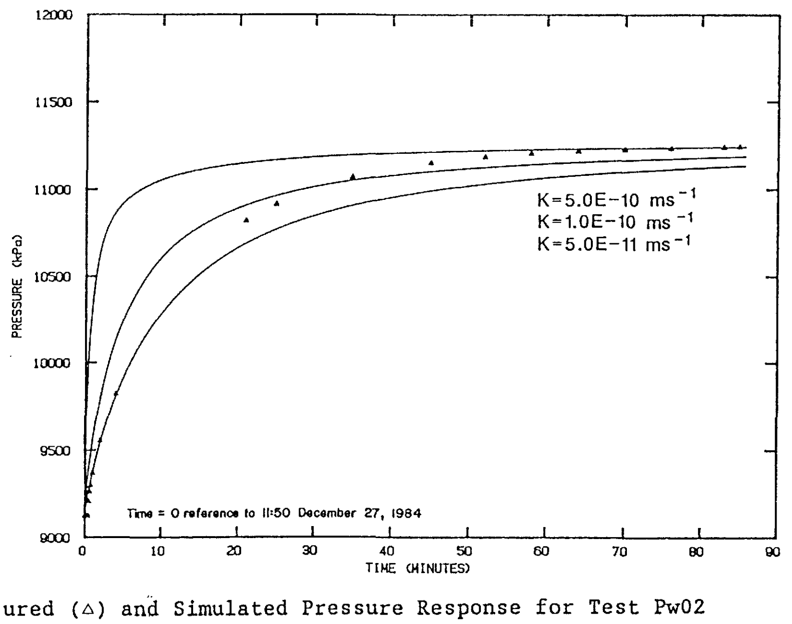


Figure 3: Measured (△) and Simulated Pressure Response for Test Pw02

Test 1203.2D (1179.32 m to 1227.15 m)

Double-packer test 1203.2D was performed on 28 to 29 March, 1985 to obtain a representative estimate of hydraulic conductivity of the crystalline rock in this interval. Pretest borehole history was complicated by a number of testing events occurring in overlapping intervals (tests 1192.5D, 1191.6H, and 1215.0H). To simplify the analyses, the simulated pretest pressure history was started at the end of the swabbing period concluding the 1192.5D test. The simplified simulated pretest history includes an 88.8 day open borehole period at annulus pressure followed by a 1.4 hour packer compliance period.

Testing in the interval consisted of a 53 minute pulse injection (Pi01) test followed by a 51 minute pulse withdrawal (Pw01) and concluding with a 14.4 hour slug withdrawal (Sw01). The long history period makes the analyses insensitive to formation pressure. Therefore, the reference pressure used in the analyses was set equal to the annulus pressure. Thermal effects were simulated as significant temperature variations were encountered over the testing period.

Results of the pulse tests are shown in Figures 1 and 2 (Pi01 and Pw01, respectively). Slug withdrawal test results are not shown due to the insignificant pressure response (both measured and simulated) during the test. The selected hydraulic parameters for the test interval are a hydraulic conductivity of 1.0E-10 ms^{-1} at a base case specific storage of 2.2E-07 m^{-1}.

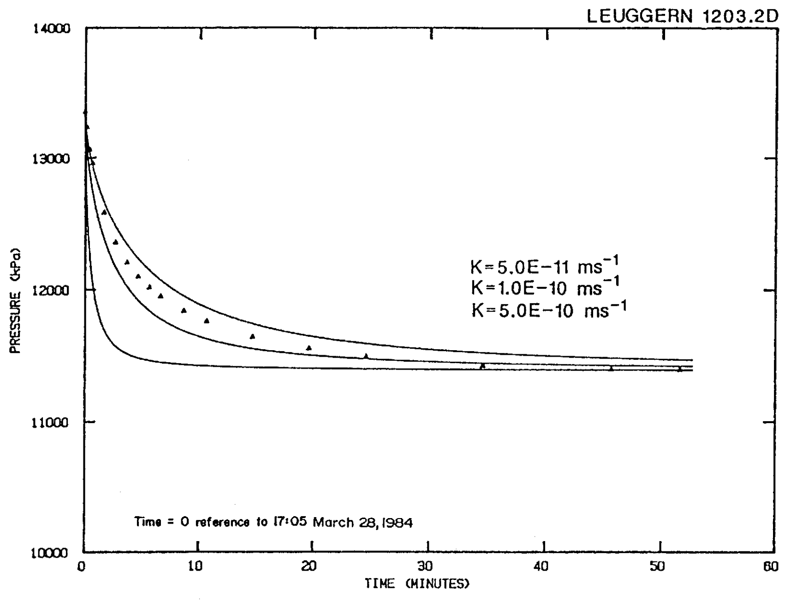


Figure 1: Measured (△) and Simulated Pressure Response for Test Pi01

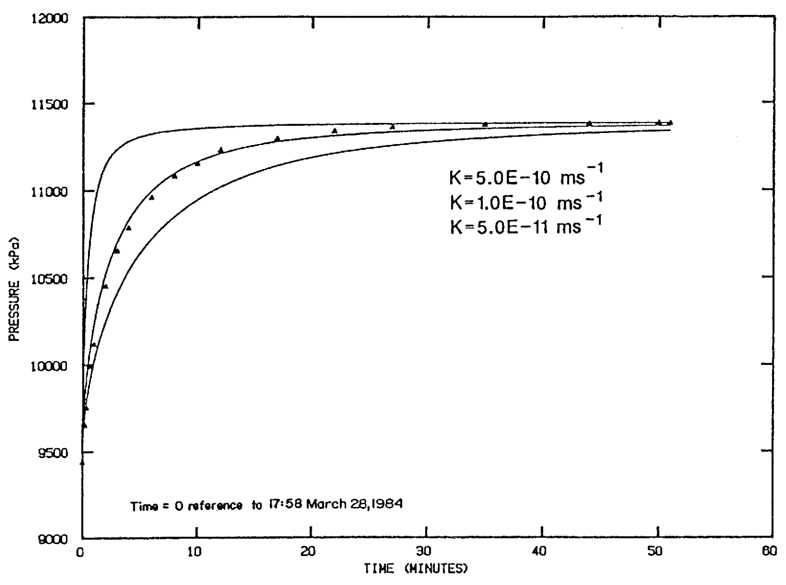


Figure 2: Measured (△) and Simulated Pressure Response for Test Pw01

Test 1215.0H (1202.55 m to 1227.52 m)

Test 1215.0H was performed on 31 December, 1984, as part of H-log sequence #4, in order to obtain a representative estimate of hydraulic conductivity of the crystalline rock in this interval. The simulated pretest pressure history includes a 15 day open borehole period at annulus pressure followed by a 0.6 hour packer compliance period.

The testing period consisted of four tests: a 1.9 hour pulse injection (Pi01) followed by a 1.2 hour pulse withdrawal (Pw01) followed by a 2.3 hour DST test (DST01). The DST test included a 1.1 hour flow period (Sw01) and a 1.2 hour build-up period (Pw01). The assumed reference pressure of 10900 kPa was determined by averaging the final pressures of tests Pi01 and Pw01 which provided a reasonable fit of simulated pressures to the measured late-time pressure data. Thermal effects were not included in the simulation as temperatures remained essentially constant throughout the testing period.

Results of the simulations are shown in Figure 1 (Pi01) and Figure 2 (Pw01). The DST test was not simulated as the results for the Pi01 and Pw01 tests were felt to be sufficient for determination of hydraulic conductivity. The selected hydraulic parameters for the test interval are a hydraulic conductivity of 5.0E-11 ms^{-1} (based primarily on the Pi01 fit) and the base case specific storage of 2.2E-07 m^{-1}.

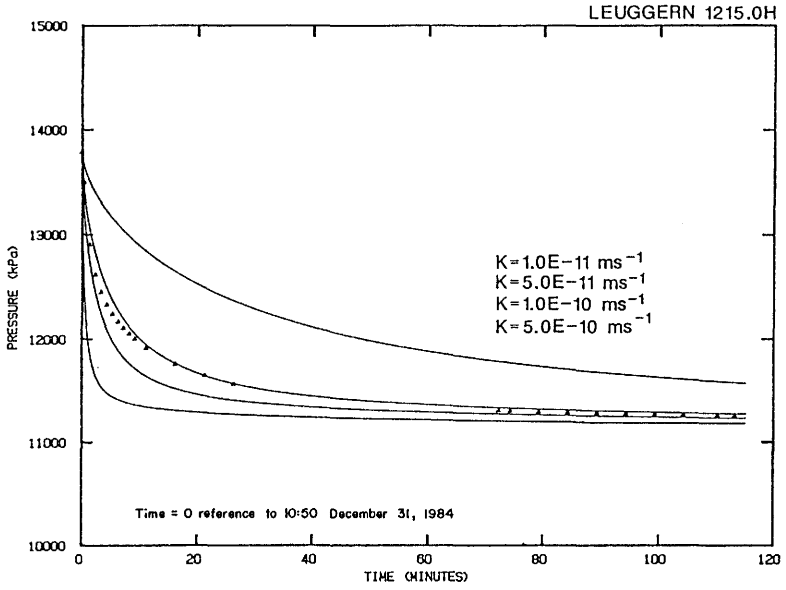


Figure 1: Measured (△) and Simulated Pressure Response for Test Pi01

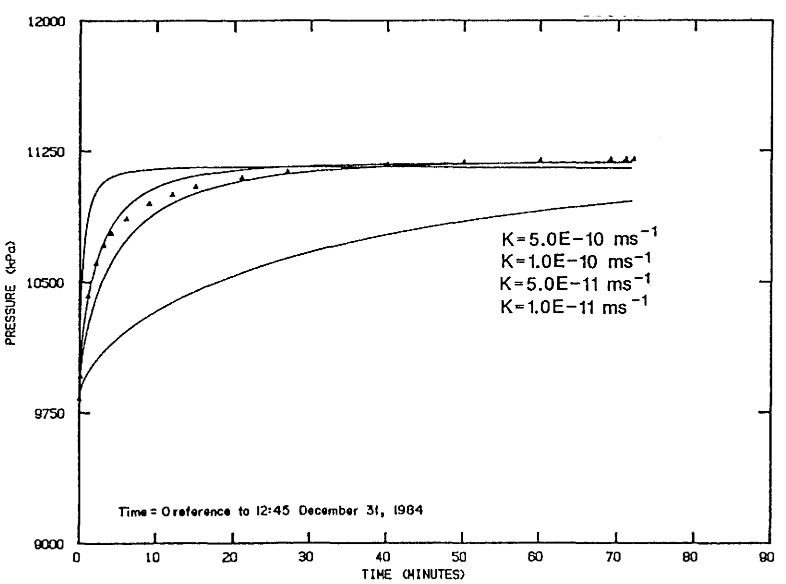


Figure 2: Measured (△) and Simulated Pressure Response for Test Pw01

Test 1238.6H (1226.13 m to 1251.10 m)

Test 1238.6H was performed on 31 December, 1984, as part of H-log sequence #4, in order to obtain a representative estimate of hydraulic conductivity of the crystalline rock in this interval. The simulated pretest pressure history includes a 7.75 day open borehole period at annulus pressure followed by a sequence of pressure oscillations reflecting approximately 4.0 days of testing (other intervals) and swabbing events.

The testing period included three tests: a 1.3 hour pulse injection (Pi01) followed by a 1.4 hour pulse withdrawal (Pw01) followed by a 1.75 hour slug withdrawal (Sw01). Test Sw01 was not simulated due to the negligible pressure recovery. Thermal effects were not included in the simulation as temperatures remained essentially constant throughout the testing period. A best-fit assumed reference pressure of 11750 kPa was determined from sensitivity studies on Pi01.

Results of the simulations for Pi01 and Pw01 are shown in Figures 1 and 2, respectively. The selected hydraulic parameters for the test interval are a hydraulic conductivity of 3.0E-11 ms^{-1} and the base case specific storage of 2.2E-07 m^{-1}.

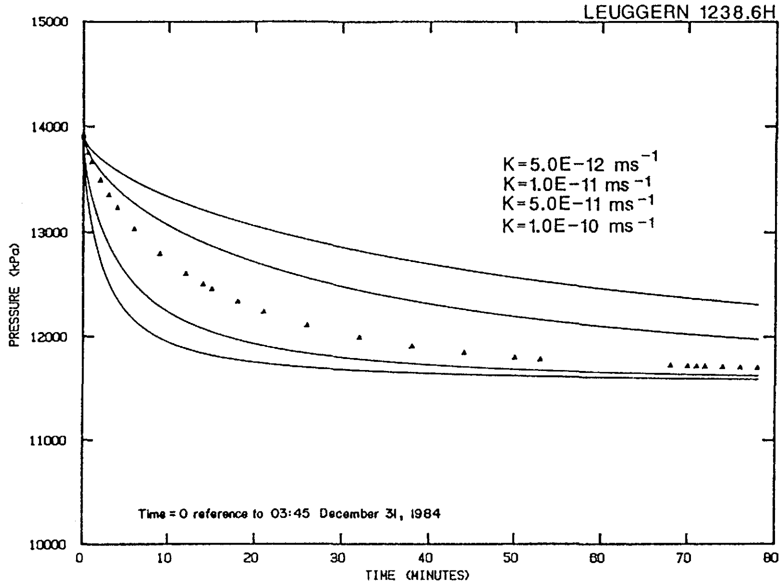


Figure 1: Measured (△) and Simulated Pressure Response for Test Pi01

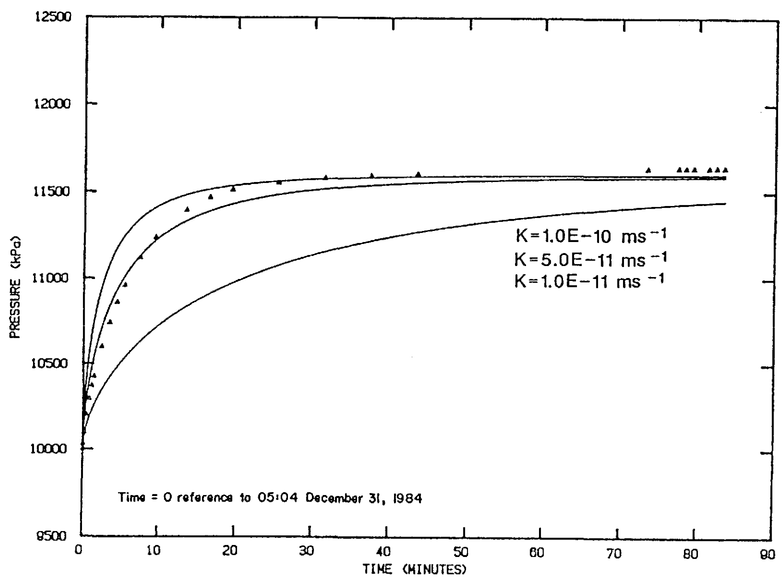


Figure 2: Measured (△) and Simulated Pressure Response for Test Pw01

Test 1263.3H (1250.85 m to 1275.82 m)

Testing in this interval was completed on 30 December, 1984, as a part of H-log sequence #4, in order to determine a representative hydraulic conductivity. The simulated pre-test pressure history includes a 26 hour drilling period with a 425 kPa overpressure, a 9.8 day open borehole period at an annulus pressure of 12052 kPa, and a 71 minute packer compliance period.

The testing sequence was comprised of 2 tests: a 2.1 hour pulse injection (Pi01) and a 2.3 hour slug withdrawal (Sw01). An estimated formation pressure at P2 depth of 12090 kPa was interpolated from values determined in the single packer test analyses. The temperature remained relatively constant throughout the testing phase and so thermal effects were not included in the simulations.

The results of GTFM simulations for a suite of hydraulic conductivities are shown in Figure 1. The best fit is obtained using a hydraulic conductivity of 1.0E-11 ms^{-1} and a specific storage of 4.0E-08 m^{-1}. Sensitivity analysis showed that varying the specific storage by one order of magnitude changes the best-fit hydraulic conductivity by a factor of 2 or less. In this interval a specific storage of 4.0E-08 m^{-1} was selected to produce a better match to the measured pressure response than was obtained using the base case value of 2.2E-07 m^{-1}.

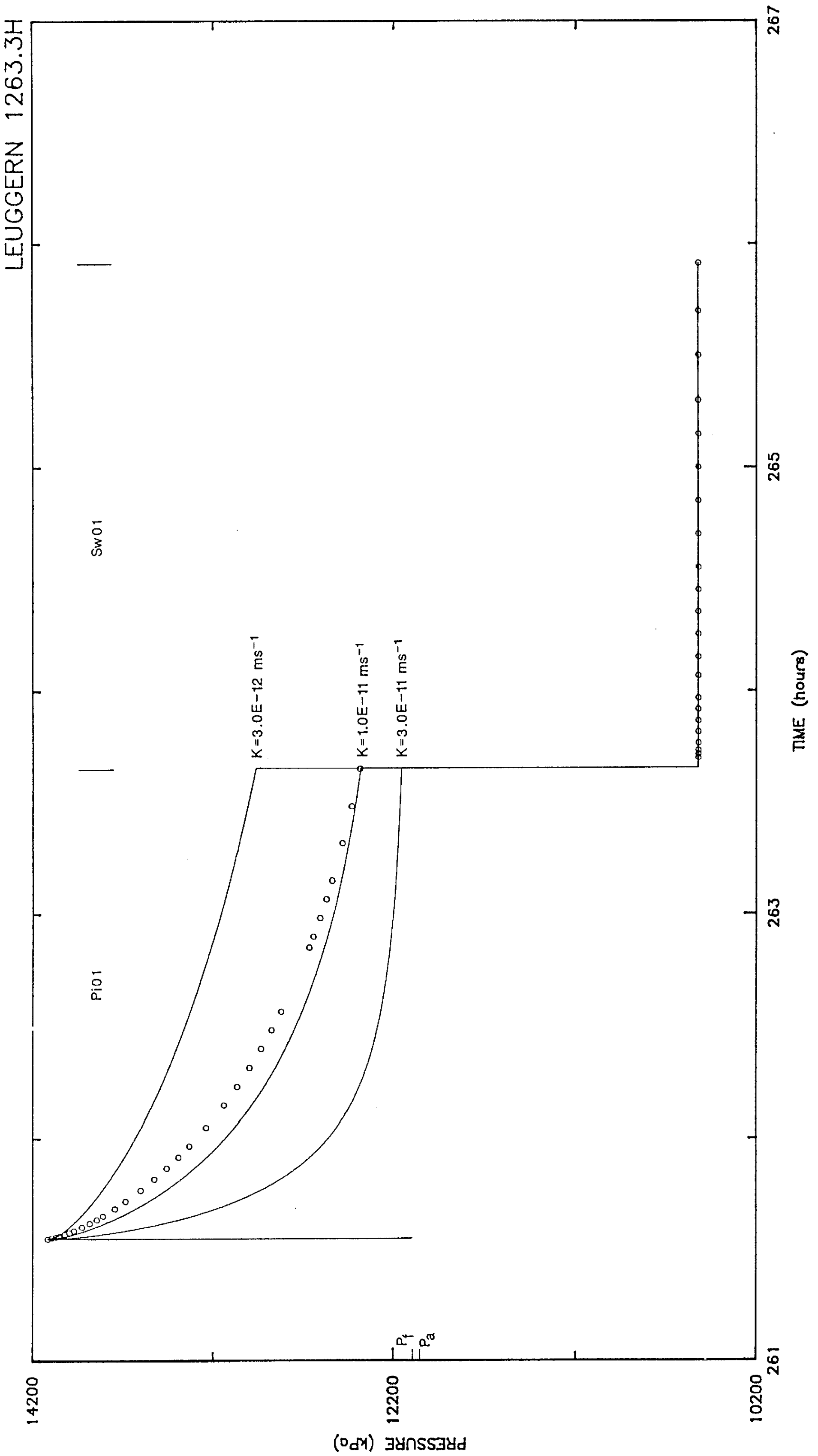


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 1283.8H (1271.35 m to 1296.32 m)

Test 1283.8H, the first test in H-log sequence #4, was performed on 30 December, 1984 in order to obtain a representative formation hydraulic conductivity. The simulated pre-test pressure history for this interval includes an 18 hour drilling overpressure of 450 kPa, an 8.3 day open borehole period at an annulus pressure of 12243 kPa, and an 88 minute packer compliance period.

The testing period consisted of 2 tests: a 3.9 hour pulse injection (Pi01) and a 1.1 hour slug withdrawal (Sw01). An abrupt change in the slope of the measured Pi01 pressure response curve occurred between 1.5 and 7 minutes after shut-in, during a 5.5 minute lapse in data collection. This is considered to be an equipment related problem, similar to the observed responses from tests 1125.1HI and 1149.8HI, although it was not confirmed by a retest. Consequently, analysis of test Pi01 assumed a shut-in pressure of 14021 kPa at 11:17:00, 30 December, 1984, which corresponds with the first pressure reading after the slope change. The formation pressure (at true P2 depth) was estimated based on values determined from single packer tests of surrounding intervals. Thermal effects were not included in the simulation.

A suite of GTFM simulations using a specific storage of 2.2E-07 m^{-1} are shown in Figure 1. The interpreted hydraulic conductivity, based on the best fit of the simulated Pi01 pressure response to the measured pressure response, is about 2.0E-14 ms^{-1}. The best-fit value, because it is so low, is fairly sensitive to specific storage. Additional simulations showed that by varying the specific storage by one order of magnitude, the best-fit hydraulic conductivity changed by as much as a factor of 4. The hydraulic conductivity determined for this interval is much lower than surrounding intervals, and given the uncertainty with Pi01 caused by the slope change in the measured response, it must be considered questionable.

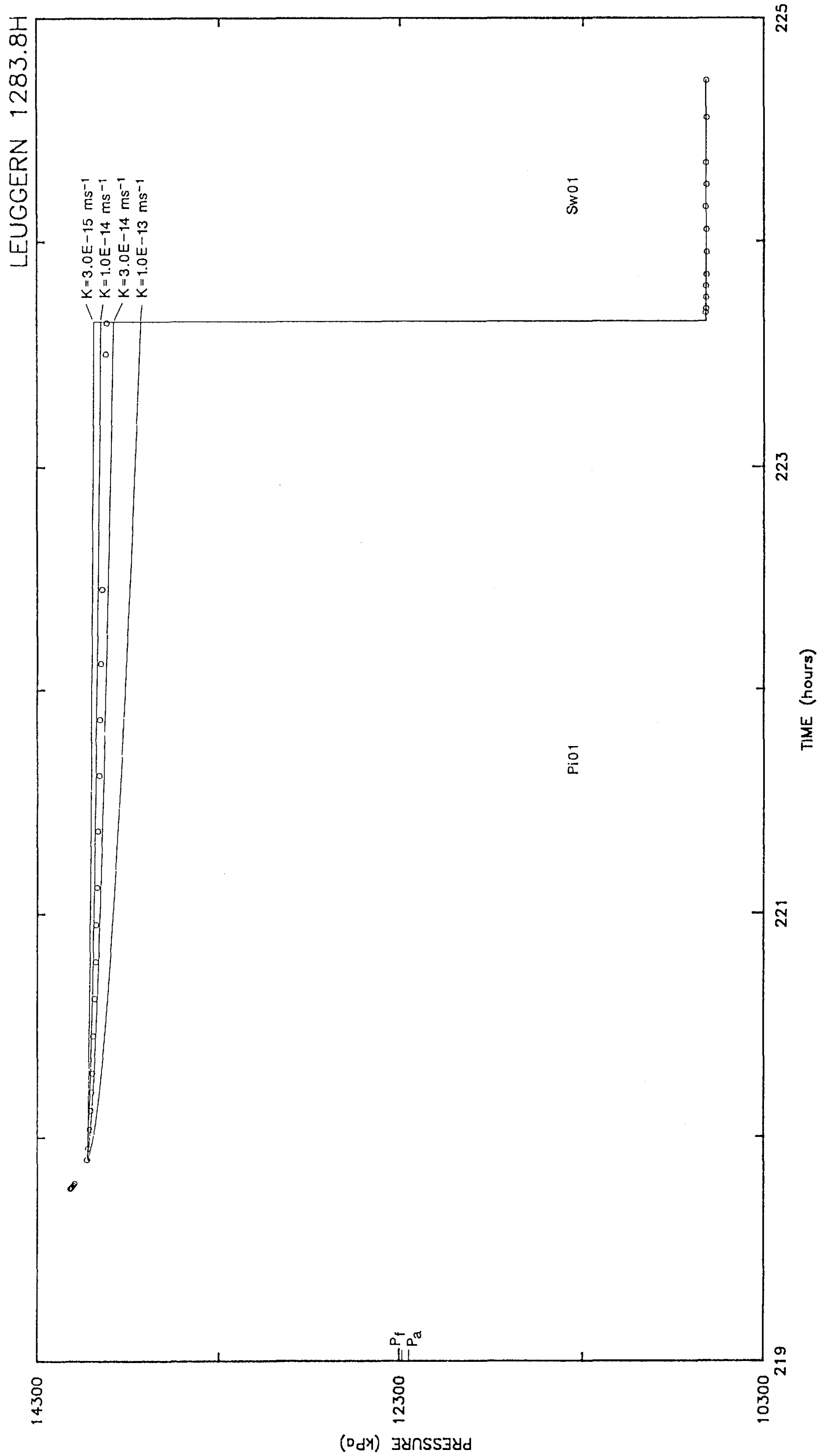


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 1304.2S (1293.35 m to 1315.05 m)

Single packer testing was performed in this interval on 24 to 25 December, 1984 to determine the representative hydraulic conductivity and formation pressure. The simulated pre-test pressure history includes a 19 hour drilling period (half the overpressure for half the drilling period), a 1 day open borehole period at annulus pressure of 12433 kPa, and a short (approximately 1 hour) packer compliance period.

The sequence of tests was as follows: a 13 hour pulse injection (Pi01), a 2 hour pulse withdrawal (Pw01), a 1.8 hour drill-stem test (DST), a 2 hour slug withdrawal (Sw02), and a swab with the shut-in open (SWAB). The DST sequence consisted of an 18 minute flow period (Sw01) followed by a 90 minute shut-in period (Pw02). A 0.4°C temperature increase was measured during testing, primarily during Pi01. Given the low hydraulic conductivity, thermal effects were included for the simulation of test Pi01.

The simulated pressure response was matched to the measured pressure response using a best-fit hydraulic conductivity of 3.0E-11 ms^{-1}, a specific storage of 2.0E-06 m^{-1}, and an assumed formation pressure at P2 depth of 12540 kPa. The effect of varying hydraulic conductivity can be seen in Figure 1 with a value of 3.0E-11 ms^{-1} providing an acceptable fit for all test sequences except for Pw02 which is the DST shut-in period. A specific storage value of 2.0E-06 m^{-1} produced a better fit of the steep, early time recovery in the pulse tests and was therefore selected over the base case value of 2.2E-07 m^{-1}.

The formation pressure was determined by a sensitivity study on test Pi01. The values of formation pressure providing the best fit to the measured pressures match the tail of the Pi01 response but do not match well with the observed response from about 0.5 to 3.0 hours after the initial pulse injection. For this reason the formation pressure used in the simulations should be considered assumed rather than calibrated.

Simulation of thermal effects appeared to have only a slight effect on simulated pressure response for Pi01.

Given the relatively poor simulated fits and the inconsistency with other intervals, the interpreted formation parameters for this interval must be considered very uncertain.

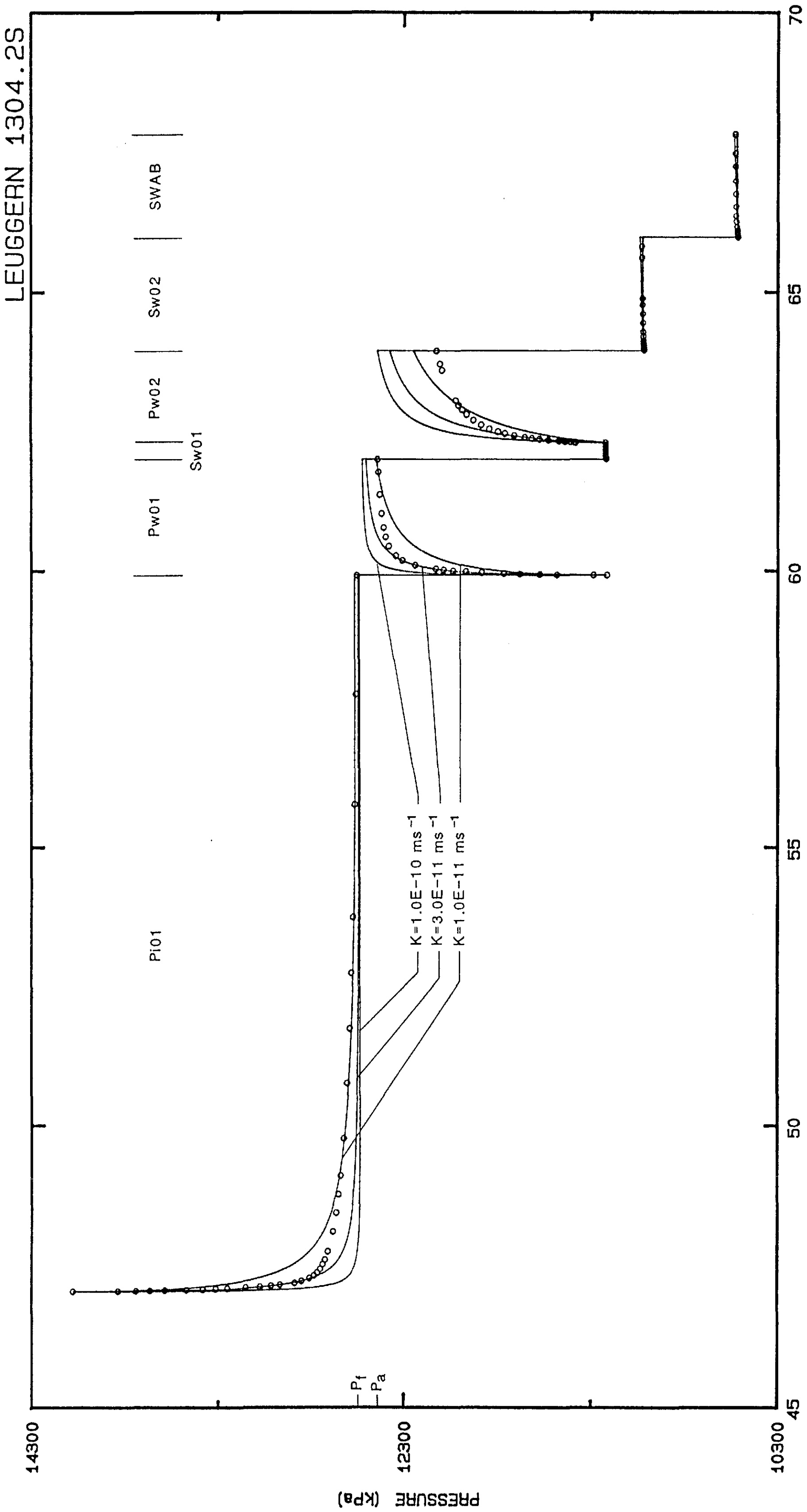


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 1326.5H (1314.03 m to 1339.00 m)

Testing in this interval was performed on 13 to 14 March, 1985, as a part of H-log sequence #5, to determine a formation hydraulic conductivity. For simulation purposes the short initial drilling period was ignored and the mid-point of drilling was determined from the second drilling period. The simulated pre-test borehole pressure history for this interval consists of a 32.2 hour drilling period with a 400 kPa overpressure, a 61.9 day open borehole period at annulus pressure of 12622 kPa, and a 68 minute packer compliance period.

Two tests were performed on this interval: a 12.8 hour pulse injection (Pi01) and a 1.5 hour slug withdrawal (Sw01). The assumed formation pressure (at P2 depth) of 12650 kPa is based on values determined in surrounding single packer tests. A 0.2°C temperature change was measured by all three transducers during Pi01, therefore, thermal effects were included in the simulation.

Figure 1 shows the simulated pressure response for a range of hydraulic conductivities and a specific storage of 4.0E-08 m^{-1}. The best fit to the measured data is obtained with a hydraulic conductivity of about 7.0E-12 ms^{-1}. In this interval, simulations using the best-fit specific storage of 4.0E-08 m^{-1} produced a recovery curve closer to the characteristic shape of the measured Pi01 recovery curve than that produced by simulations using the base case specific storage of 2.2E-07 m^{-1}.

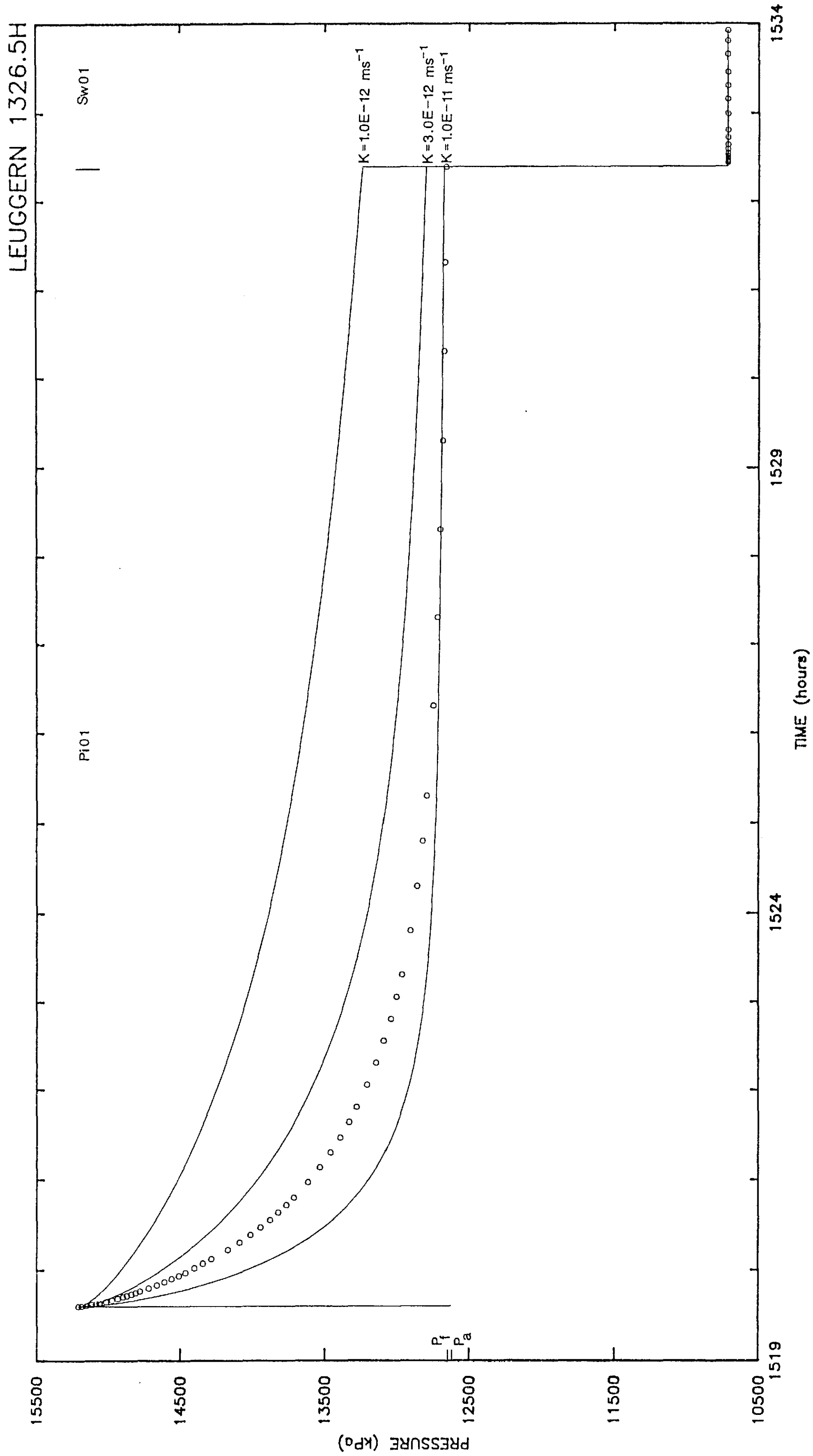


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 1349.2H (1336.68 m to 1361.65 m)

This test sequence was performed on 13 March, 1985, as a part of H-log sequence #5, with the purpose of determining a hydraulic conductivity for the interval. The pre-test pressure history used in GTFM simulations consists of a 24.5 hour drilling period at 425 kPa above annulus pressure, the 60.8 day open borehole period, and a 64 minute packer compliance period.

H-log 1349.2H was comprised of a 2.2 hour pulse injection test (Pi01) followed by a 2.3 hour slug withdrawal test (Sw01). A temperature decrease of 0.2°C was measured during Pi01 at thermistor T2 and therefore thermal effects were included in the GTFM simulations. The assumed formation pressure at P2 depth of 12860 kPa was interpolated from values determined from analyses of surrounding single packer tests.

A suite of GTFM simulations was run with hydraulic conductivity varying from 3.0E-13 to 3.0E-12 ms^{-1}. The best fit to the measured Pi01 pressure data was obtained with a hydraulic conductivity between 1.0E-12 and 3.0E-12 ms^{-1} and a specific storage of 2.2E-07 m^{-1}, as shown in Figure 1. A sensitivity analysis of the effect of specific storage on the simulated pressure response showed that the best-fit hydraulic conductivity changed by only a factor of 2 when the specific storage was varied by one order of magnitude.

A set of simulations was performed for this interval with thermal effects not included in order to develop an estimate of the sensitivity of the pressure response to temperature changes. In this interval, neglecting the 0.2°C temperature drop during Pi01 increased the interpreted K value by less than a factor of 2. The relative insensitivity of K to thermal effects in this interval means that even if the temperature measurements are not representative of the interval, the interpreted K value will not be greatly affected.

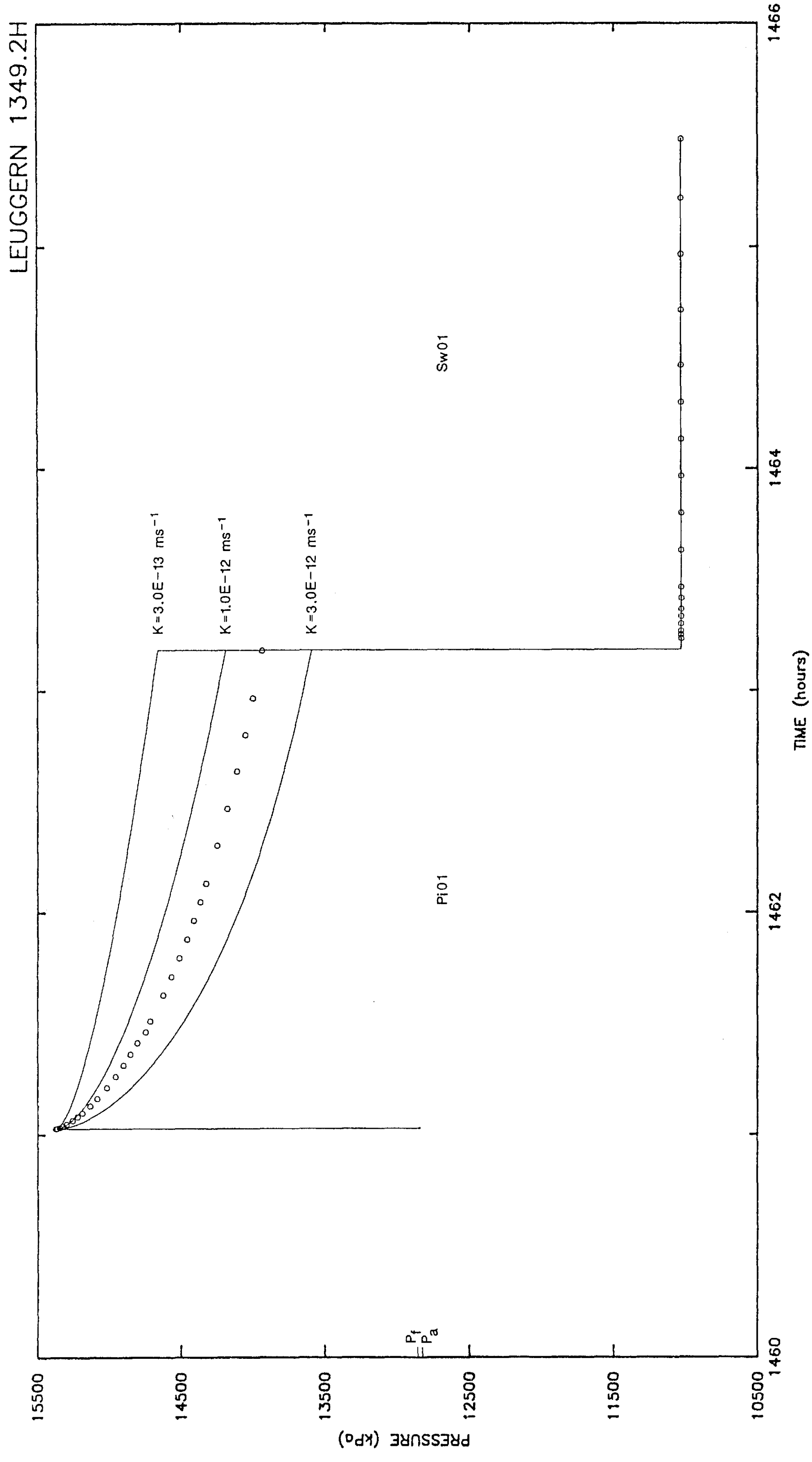


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 1369.3H (1356.85 m to 1381.82 m)

This interval was tested on 12 to 13 March, 1985, as a part of H-log sequence #5, in order to obtain a representative formation hydraulic conductivity. The simulated pre-test pressure history for this interval includes a 20.8 hour drilling period at 450 kPa above annulus pressure, a 57.5 day open borehole period at an annulus pressure of 13011 kPa, and a 66 minute packer compliance period.

The testing period consisted of 2 sequences: a 12.3 hour pulse injection test (Pi01) and a 2.3 hour slug withdrawal test (Sw01). The formation pressure (at true P2 depth) was estimated based on values determined from single packer tests of surrounding intervals. A 0.2°C change was recorded by all three temperature transducers and so thermal effects were included in the simulation.

The results of a suite of simulations using a specific storage of 2.2E-07 m^{-1} are shown in Figure 1. The best-fit hydraulic conductivity, based on the best fit to the observed Pi01 pressure response, is 3.0E-12 ms^{-1}. Simulations showed that by varying the specific storage by one order of magnitude, the best-fit hydraulic conductivity changed by a factor of 2 to 3.

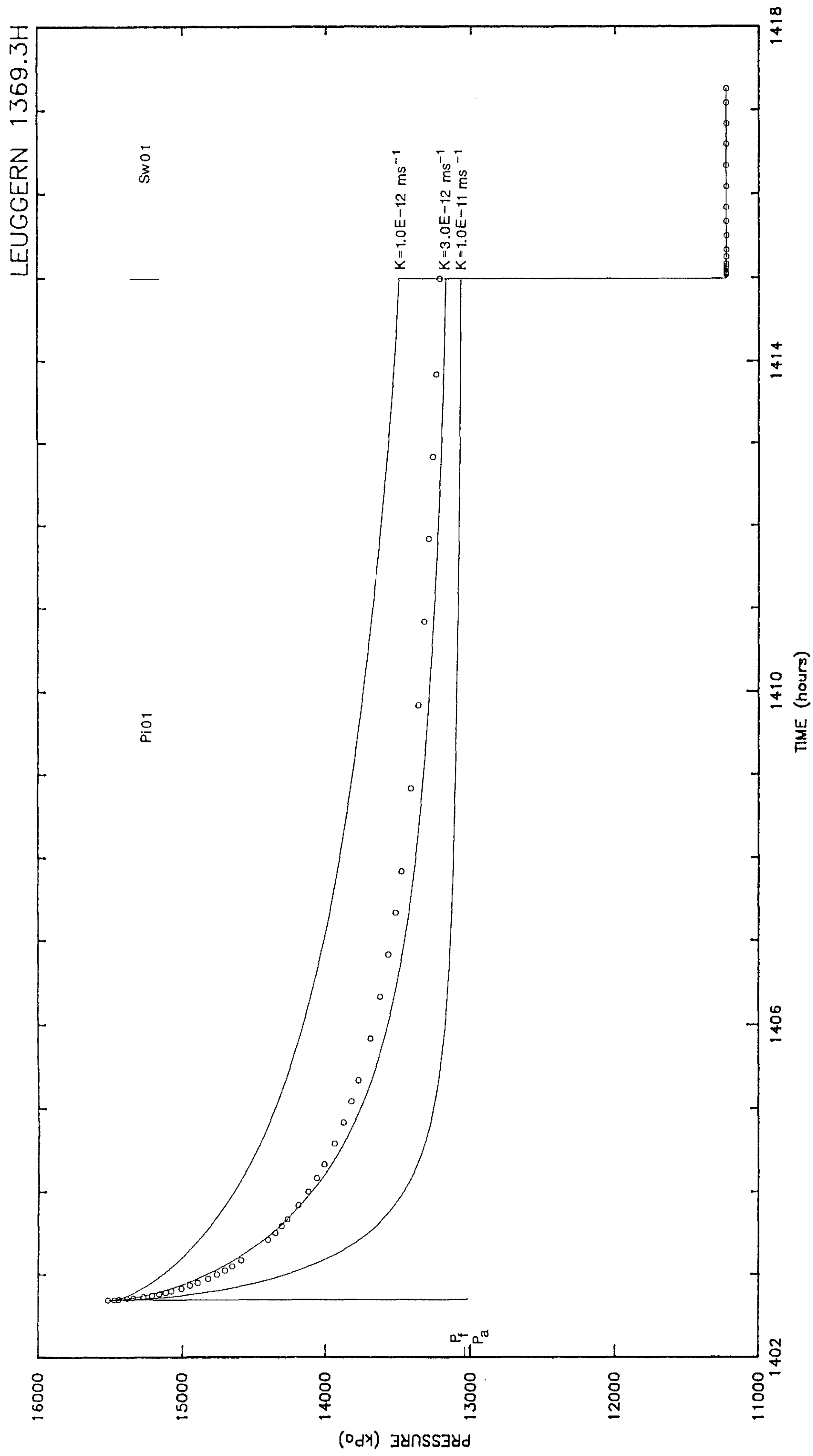


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 1392.1H (1379.65 m to 1404.62 m)

This test sequence was performed on 12 March, 1985, as a part of H-log sequence #5, in an attempt to obtain a representative hydraulic conductivity for the interval. The complete simulated pre-test pressure history for this interval includes a 15.9 hour drilling period with a 400 kPa overpressure, a 56.3 day open borehole period at an annulus pressure of 13217 kPa, and a 65 minute packer compliance period.

Test sequence 1392.1H was comprised of 2 separate hydraulic tests: a 3.4 hour pulse injection test (Pi01) followed by a 1.5 hour slug withdrawal test (Sw01). The formation pressure (at true P2 depth) was estimated based on values determined from single packer tests of surrounding intervals. Thermal effects were included in the simulation because a 0.2°C decrease was recorded by all three temperature transducers during Pi01.

The results of simulations using hydraulic conductivities ranging from 3.0E-14 to 3.0E-13 ms^{-1} and a specific storage of 2.2E-07 m^{-1} are shown in Figure 1. The best-fit hydraulic conductivity, based on a match to the measured Pi01 pressure response, is 1.0E-13 ms^{-1}.

A sensitivity analysis showed that by varying the specific storage by two orders of magnitude, the best-fit hydraulic conductivity changed by about one-half an order of magnitude.

A set of simulations was run without thermal effects and the results were compared to Figure 1 in an attempt to estimate the sensitivity of the simulated pressure response to temperature changes. It was found that without thermal effects the best-fit hydraulic conductivity for this interval is increased by a factor of 3.

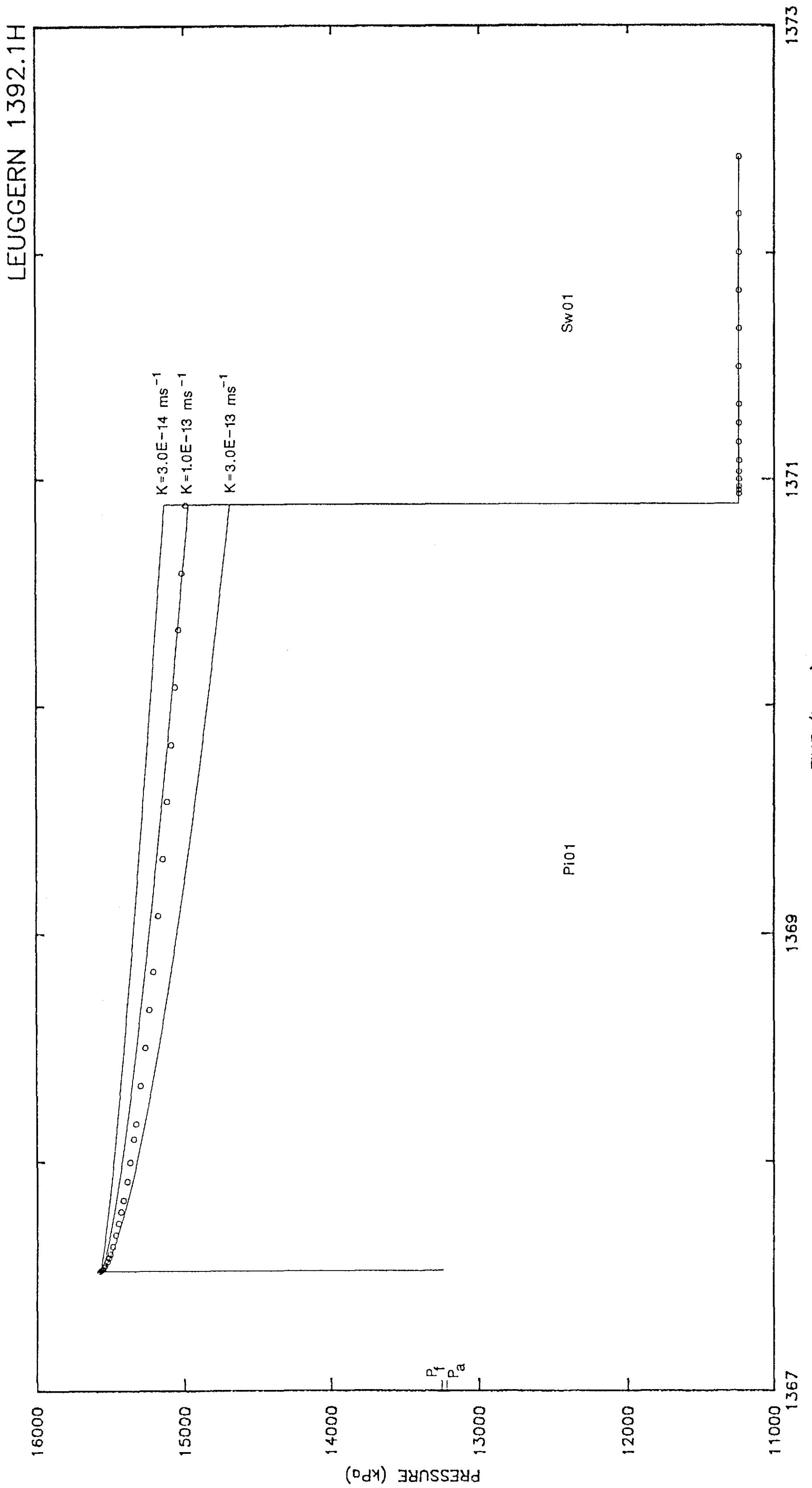


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 1412.5H (1400.03 m to 1425.00 m)

Test 1412.5H was performed on 11 to 12 March, 1985, as part of H-log sequence #5, in order to obtain a representative estimate of hydraulic conductivity of the crystalline rock in the interval. The simulated pretest pressure history includes a 55 day open borehole period at annulus pressure followed by a short packer compliance period.

Testing in the interval consisted of a 12.5 hour pulse injection (Pi01) followed by a 2.4 hour slug withdrawal (Sw01). Test Sw01 was not simulated due to the negligible pressure recovery. Thermal effects were not included in the simulation as temperatures remained essentially constant throughout the testing period. An assumed reference pressure of 13300 kPa was selected based on sensitivity studies on Pi01 simulations.

Results of the Pi01 simulations are shown in Figure 1. The selected hydraulic parameters for the test interval are a hydraulic conductivity of 5.0E-13 ms^{-1} and a base case specific storage of 2.2E-07 m^{-1}.

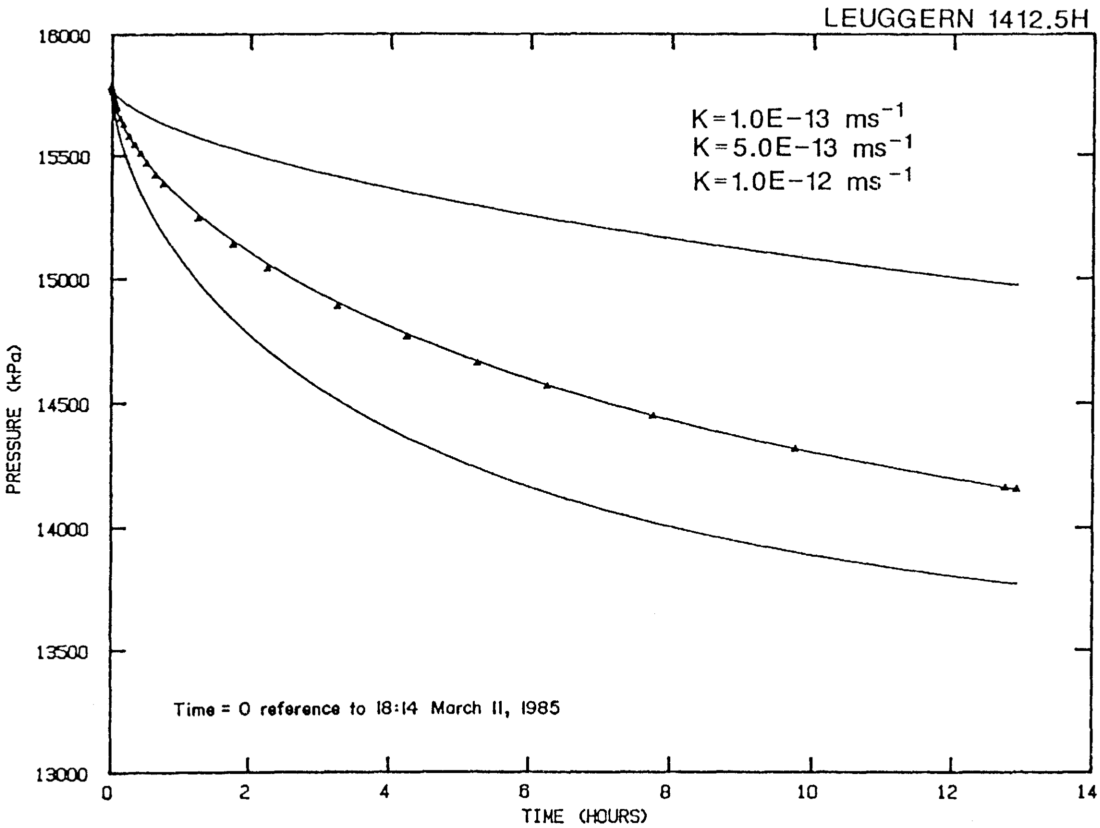


Figure 1: Measured (△) and Simulated Pressure Response for Test Pi01

Test 1433.4D (1427.38 m to 1439.40 m)

Double-packer test 1433.4D was performed on 2 May, 1985 to obtain a representative estimate of hydraulic conductivity of the crystalline rock in this interval. The simulated pretest history includes an 106 day open borehole period at annulus pressure followed by a 1.3 hour packer compliance period.

Testing in the interval consisted of a 1.5 hour DST test (DST01) followed by a 18.3 hour slug withdrawal test (Sw02). The DST test consisted of a 35 minute flow period (Sw01) and a 55 minute build-up (Pw01). The long history period makes the analyses insensitive to formation pressure. Therefore, the reference pressure used in the analyses was set equal to the annulus pressure. Thermal effects were not simulated as no significant temperature variations were encountered over the duration of Pw01.

Results of the simulations are shown in Figures 1 through 3 (Sw01, Pw01 and Sw02, respectively). The selected hydraulic parameters for the test interval are a hydraulic conductivity of 1.0E-10 ms^{-1} at a base case specific storage of 2.2E-07 m^{-1}.

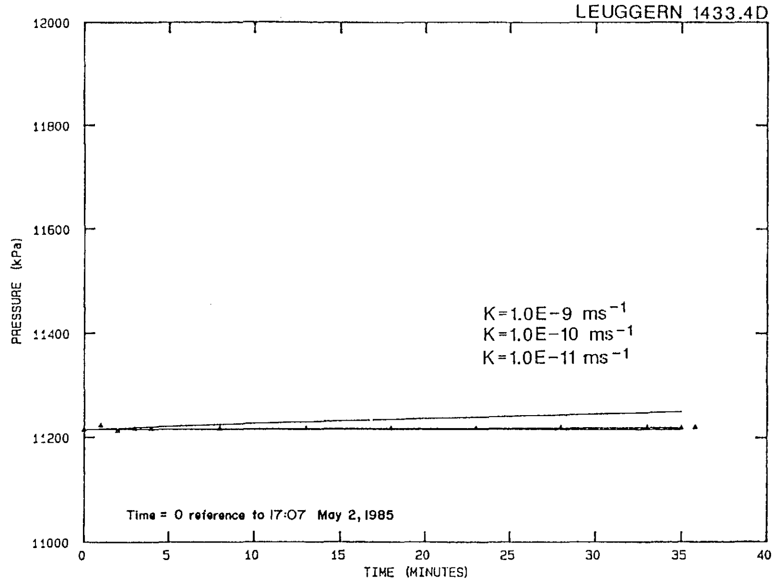


Figure 1: Measured (△) and Simulated Pressure Response for Flow Period (Sw01) of Test DST 01

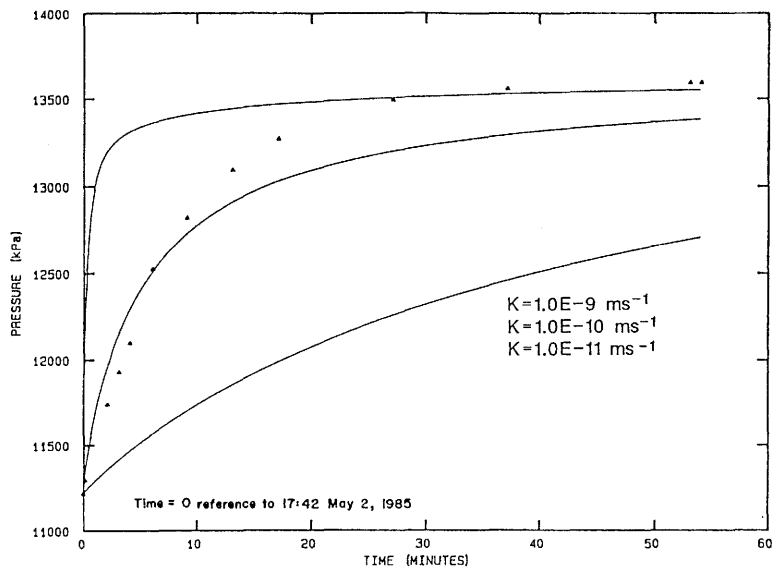


Figure 2: Measured (△) and Simulated Pressure Response for Buildup Period (Pw01) of Test DST 01

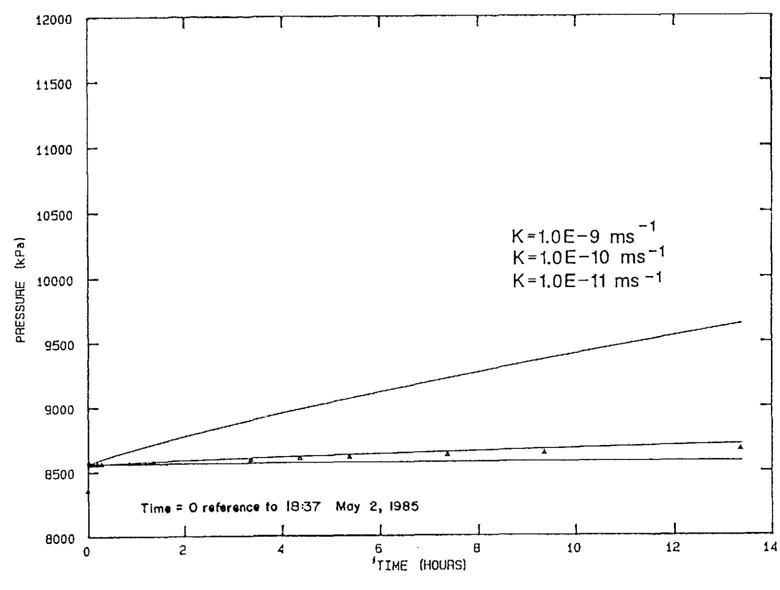


Figure 3: Measured (△) and Simulated Pressure Response for Test Sw02

Test 1437.0H (1424.53 m to 1449.50 m)

Test 1437.0H was performed on 11 March, 1985, as part of H-log sequence #5, in order to obtain a representative estimate of hydraulic conductivity of the crystalline rock in this interval. The simulated pretest pressure history includes a 52 day open borehole period at annulus pressure followed by a 1.3 hour packer compliance period.

Testing in the interval consisted of a 1.4 hour pulse injection (Pi01) followed by a 3.2 hour slug withdrawal (Sw01). Thermal effects were not included in the simulation as temperatures remained essentially constant throughout the testing period. The assumed reference pressure of 13620 kPa was set approximately equal to annulus pressure based on the anticipated influence of the long borehole history period in test recovery.

Results of the simulations are shown in Figures 1 and 2 (Pi01 and Sw01, respectively). The selected hydraulic parameters for the test interval are a hydraulic conductivity of 1.0E-11 ms^{-1} and the base case specific storage of 2.2E-07 m^{-1}.

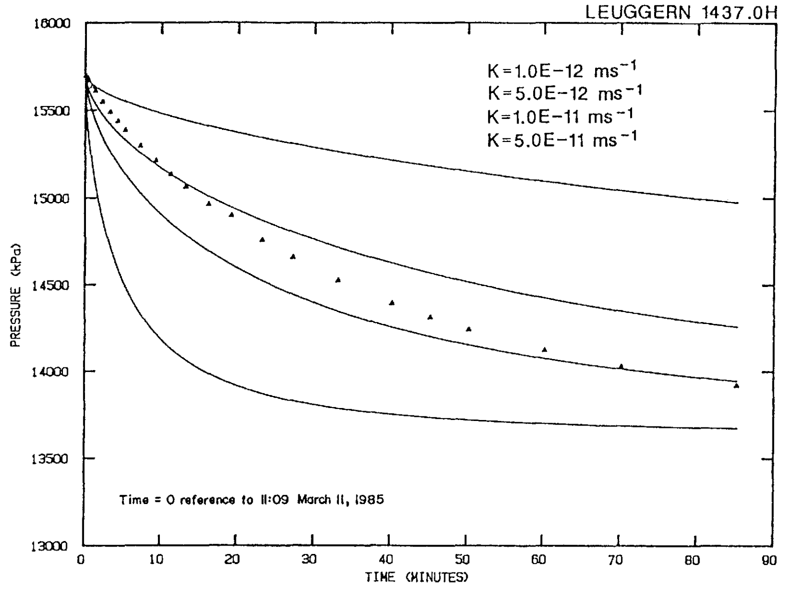


Figure 1: Measured (△) and Simulated Pressure Response for Test Pi01

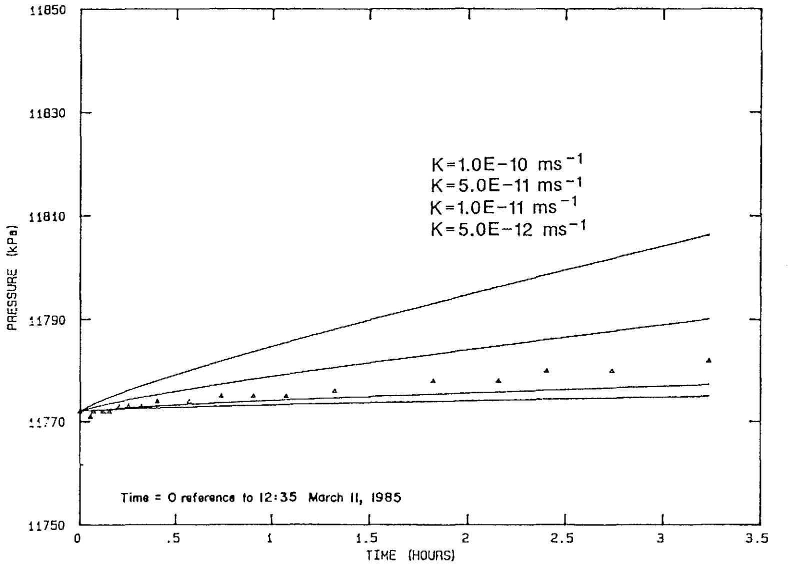


Figure 2: Measured (△) and Simulated Pressure Response for Test Sw01

Test 1456.8H (1444.35 m to 1469.32 m)

Test 1456.8H was performed on 9 to 11 March, 1985, as part of H-log sequence #5, in order to obtain a representative estimate hydraulic conductivity of the crystalline rock in the interval. The simulated pretest pressure history includes a 48 day open borehole period at annulus pressure followed by a 70 minute packer compliance period.

Testing in the interval consisted of a 38 hour pulse injection (Pi01) followed by a 2.25 hour slug withdrawal (Sw01). The assumed reference pressure of 13795 kPa was set equal to annulus pressure. Sw01 was not simulated due to short duration and negligible pressure recovery.

Temperature variations of approximately 0.5°C were encountered during testing, therefore, thermal effects were included in the simulations.

Results of the Pi01 simulations are shown in Figure 1. The selected hydraulic parameters for the test interval are a hydraulic conductivity of 3.0E-12 ms^{-1} and the base case specific storage of 2.2E-07 m^{-1}.

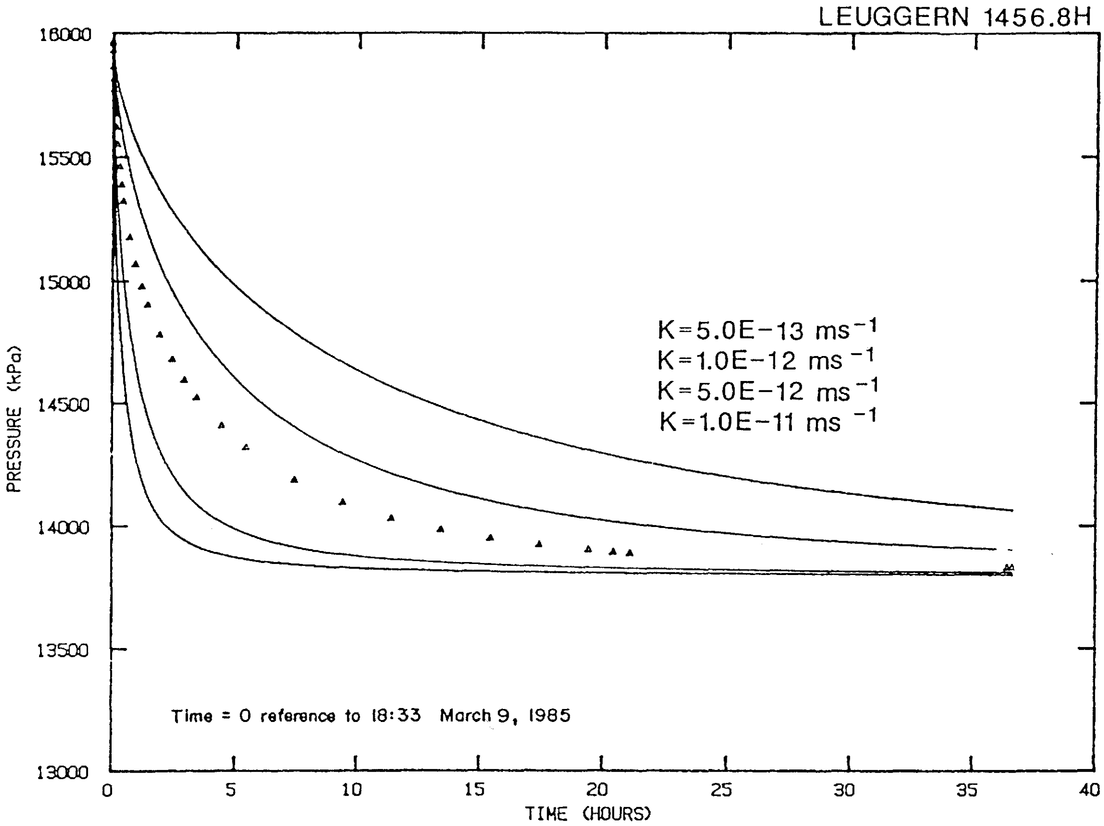


Figure 1: Measured (△) and Simulated Pressure Response for Test Pi01

Test 1462.0D (1457.16 m to 1466.89 m)

Double-packer test 1462.0D was performed on 29 January, 1985 to obtain a representative estimate of hydraulic conductivity of the crystalline rock in this interval. The simulated pretest history consisted of an 8.3 day open borehole period at annulus pressure followed by a 1.5 hour packer compliance period.

Testing in the interval consisted of a single pulse injection test (Pi01) of about 5.4 hours duration. Thermal effects were not simulated as no significant temperature variations were encountered over the duration of the test.

Results of the simulations are shown in Figure 1. The assumed reference pressure of 14600 kPa was selected based on sensitivity studies. The selected hydraulic parameters for the test interval are a hydraulic conductivity of 1.0E-11 ms^{-1} at a base case specific storage of 2.2E-07 m^{-1}.

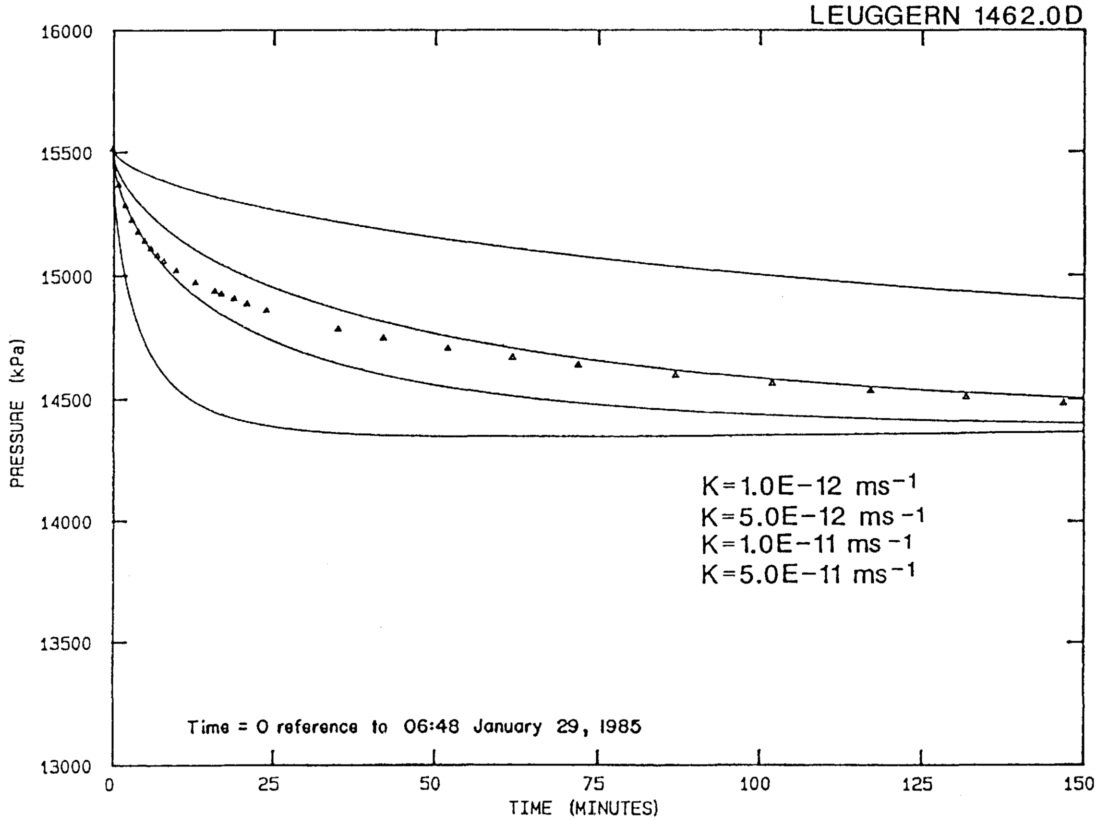


Figure 1: Measured (△) and Simulated Pressure Response for Test Pi01

Test 1480.0H (1467.52 m to 1492.49 m)

Test 1480.0H was performed on 9 March, 1985, as part of H-log sequence #5, in order to obtain a representative estimate of hydraulic conductivity for the crystalline rock in the interval. The simulated pretest pressure history includes a 46 day open borehole period at annulus pressure followed by a 85 minute packer compliance period.

Testing in the interval consisted of a 2.6 hour pulse injection (Pi01) followed by a 1.5 hour slug withdrawal (Sw01). The assumed reference pressure of 14000 kPa was set approximately equal to annulus pressure due to the long borehole history period. Sw01 was not simulated due to the negligible pressure recovery. Thermal effects were not included in the simulation as temperature remained essentially constant throughout the testing period.

Results of the Pi01 simulations are shown in Figure 1. The selected hydraulic parameters for the test interval are a hydraulic conductivity of 1.0E-13 ms^{-1} and the base case specific storage of 2.2E-07 m^{-1}.

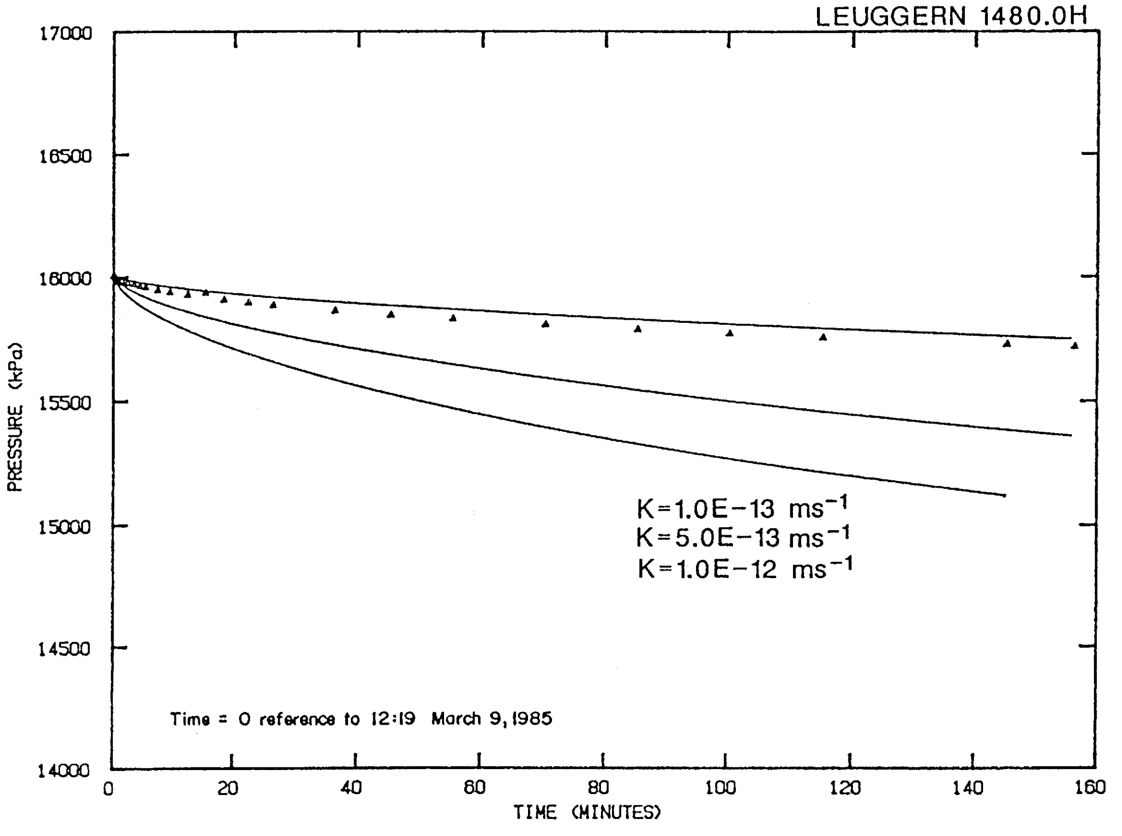


Figure 1: Measured (△) and Simulated Pressure Response for Test Pi01

Test 1504.7H (1492.24 m to 1517.21 m)

This interval was tested on 8 to 9 March, 1985, as a part of H-log sequence #5, in an attempt to obtain a representative hydraulic conductivity. The simulated pre-test pressure history for this interval includes a 26.8 hour drilling period with a 620 kPa overpressure, a 42.1 day open borehole period at an annulus pressure of 14226 kPa, and a 50 minute packer compliance period.

Test sequence 1504.7H was comprised of two separate hydraulic tests. A 12.9 hour pulse injection test (Pi01) was followed by a 1.8 hour slug withdrawal test (Sw01). The formation pressure at P2 depth was interpolated from values determined in surrounding single packer tests.

Temperature changes were measured during Pi01 by both the T1 and T3 transducers. The T2 temperature transducer showed a similar irregular response observed in earlier H-log tests. Despite this apparently non-representative T2 response, all three transducers were consistent in showing a 0.5°C decrease between measurements taken at the beginning and end of Pi01. Thermal effects were, therefore, included in the simulation.

Simulations were run using hydraulic conductivities ranging from 1.0E-12 to 1.CE-11 ms^{-1}. The results, using a specific storage of 2.2E-07 m^{-1}, are shown in Figure 1. The interpreted hydraulic conductivity, based on the best match of the simulated Pi01 pressure response to the observed response, is between 1.0E-12 and 3.0E-12 ms^{-1}. A sensitivity analysis showed that by varying the specific storage by one order of magnitude, the best-fit hydraulic conductivity changed by a factor of 2.

Although the temperature change measured between the start and end of test Pi01 is considered to be representative of the test interval, a set of simulations was run without thermal effects and the results were compared to Figure 1 in an attempt to estimate the sensitivity of the simulated pressure response to temperature changes. It was found that without thermal effects the best-fit hydraulic conductivity for this interval was about 3.0E-12 ms^{-1}, an increase of less than a factor of 2 over the best-fit value which was determined with thermal effects included in the simulations.

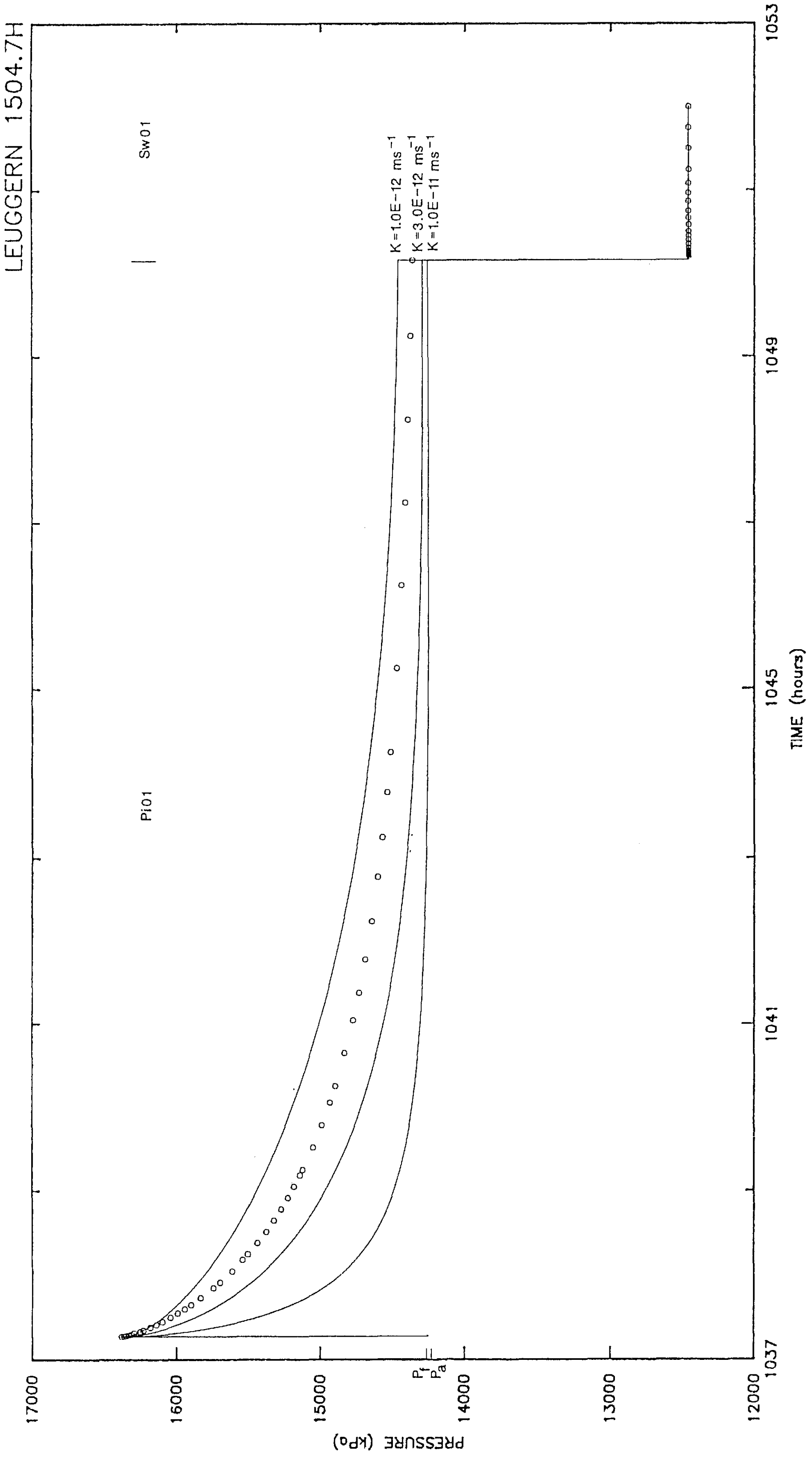


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 1529.4H (1516.96 m to 1541.93 m)

This test was performed on 8 March, 1985, as a part of H-log sequence #5, in order to determine a representative of hydraulic conductivity for this interval. To simplify the simulated pre-test pressure history the mid-point of drilling was chosen to coincide with the end of the second drilling period. The simulated pre-test borehole pressure history includes a 42.0 hour period between the mid-point and the start of the third drilling period, a 25.5 hour drilling period (third sequence) with a 600 kPa overpressure, a 36.1 day open borehole period at an annulus pressure of 14444 kPa, and a 60 minute packer compliance period.

The testing sequence consisted of two hydraulic tests: a 3.1 hour pulse injection test (Pi01) and a 1.6 hour slug withdrawal test (Sw01). The formation pressure at P2 depth was interpolated from values determined in surrounding single packer tests. All three temperature transducers measured a 0.4°C decrease over the 3.1 hour duration of Pi01. The T2 temperature transducer showed an unexplained increase after about 1.5 hours of testing. Despite this apparently non-representative T2 response thermal effects were included in the simulation. The interpolated temperature curve was based on measured data from T2 in the first 1.5 hours of the test and from T1 and T3 in the last half of the test.

Simulations were completed with hydraulic conductivities ranging from 3.0E-13 to 3.0E-12 ms^{-1}, using a specific storage of 2.2E-07 m^{-1}. The results are shown in Figure 1. The interpreted hydraulic conductivity, based on the best match of the simulated Pi01 pressure response to the measured late-time Pi01 response, is between 3.0E-13 and 1.0E-12 ms^{-1}. A sensitivity analysis showed that varying the specific storage by one order of magnitude changed the best-fit hydraulic conductivity by a factor of 2.

Due to the anomalous T2 temperatures measured during the last half of Pi01 and the relatively poor fit obtained using thermal effects, a set of simulations was run without thermal effects. The isothermal results were compared to the previous non-isothermal results in an attempt to estimate the sensitivity of the simulated pressure response to temperature changes. It was found that the isothermal simulations showed a characteristic shape much closer to that of the measured data and indicated a hydraulic conductivity for this interval of 1.0E-12 ms^{-1}, an increase of less than a factor of 2 over the best-fit value with thermal effects included.

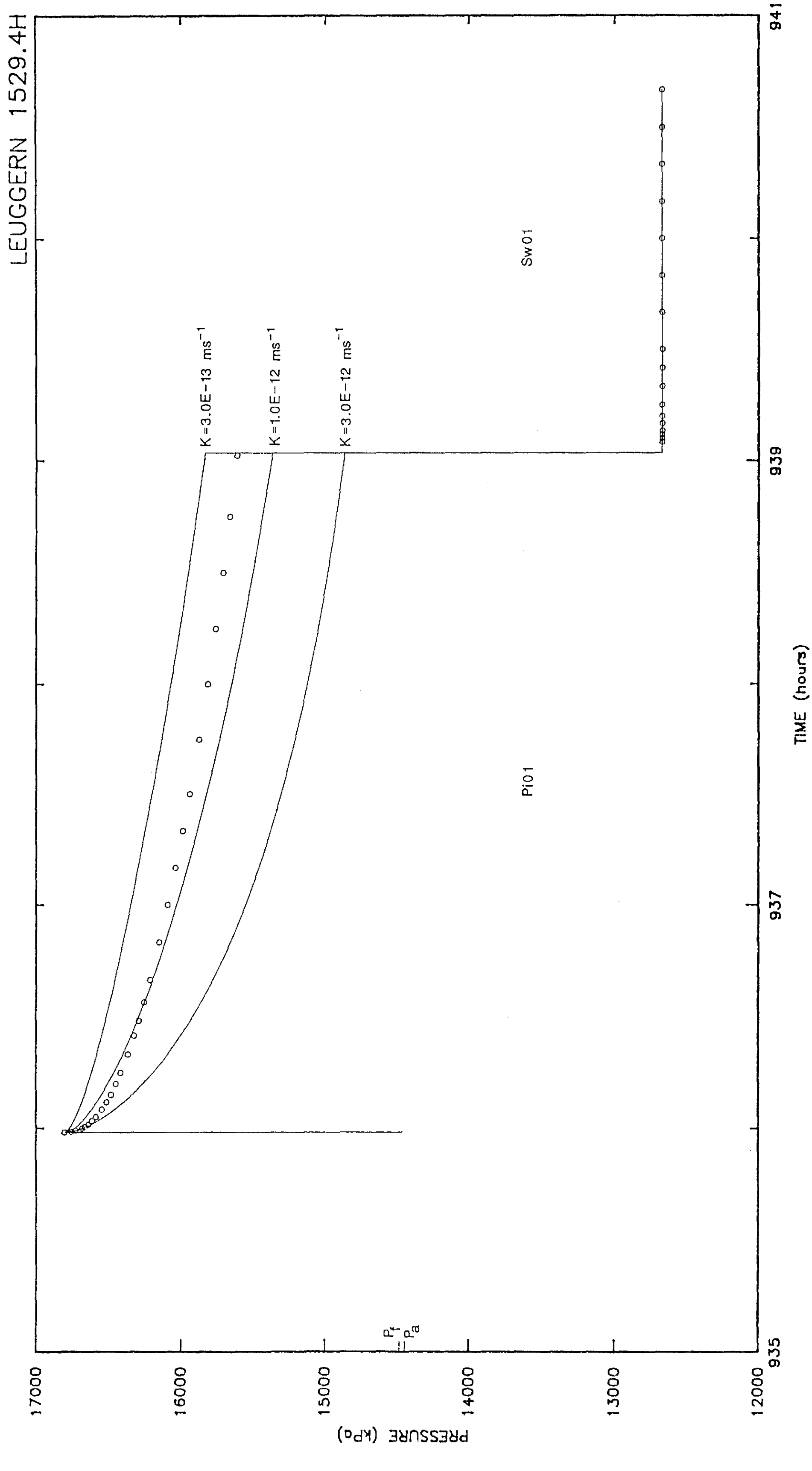


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 1553.8H (1541.34 m to 1566.31 m)

Test 1553.8H was performed on 7 to 8 March, 1985, as part of H-log sequence #5, in order to obtain a representative estimate of hydraulic conductivity of the crystalline rock in this interval. The simulated pretest pressure history includes a short drilling overpressure period followed by a two day open borehole period followed by a second drilling overpressure period of about 32 hours duration followed by a 32.5 day open borehole period at annulus pressure followed by a short packer compliance period.

Testing in the interval consisted of a 13 hour pulse injection (Pi01) followed by a two hour slug withdrawal (Sw01) test. The assumed reference pressure of 13795 kPa was set equal to annulus pressure. Sw01 was not simulated due to the short duration and negligible pressure recovery. Temperature variations of approximately 0.4°C were encountered during testing, therefore, thermal effects were included in the simulations.

Results of the Pi01 simulations are shown in Figure 1. The selected hydraulic parameters for the test interval are a hydraulic conductivity of 3.0E-13 ms^{-1} and a specific storage of 2.0E-06 m^{-1}.

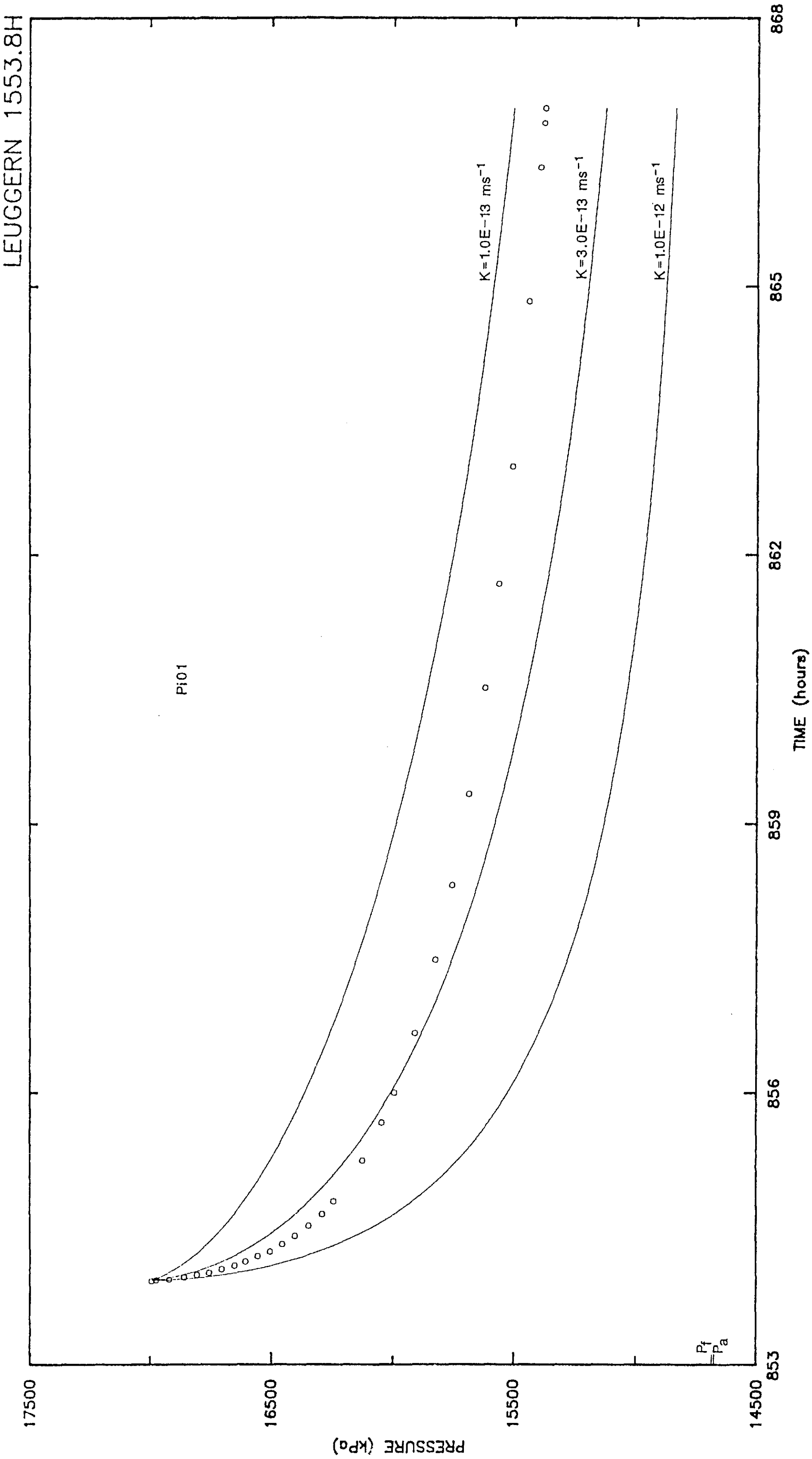


Figure 1: Measured (o) and Simulated Pressure Response for Test Pi01

Test 1578.6H (1566.16 m to 1591.13 m)

Test 1578.6H was performed on 7 March, 1985, as part of H-log sequence #5, in order to obtain a representative estimate of hydraulic conductivity of the crystalline rock in this interval. The simulated pretest pressure history includes drilling overpressure period of 31 hours duration followed by a 29.3 day open borehole period at annulus pressure followed by a short packer compliance period.

Testing in the interval consisted of a 1.75 hour pulse injection (Pi01) followed by a three hour slug withdrawal (Sw01) test. The estimated formation pressure of 14909 kPa was derived from the pressure gradient across the borehole based on calibrated formation pressures. Sw01 was not simulated due to short duration and negligible pressure recovery. Temperature remained essentially constant throughout the Pi01 test, therefore, thermal effects were not included in the simulations.

Results of the Pi01 simulations are shown in Figure 1. The selected hydraulic parameters for the test interval are a hydraulic conductivity of 5.0E-12 ms^{-1} at a base case specific storage of 2.2E-07 m^{-1}.

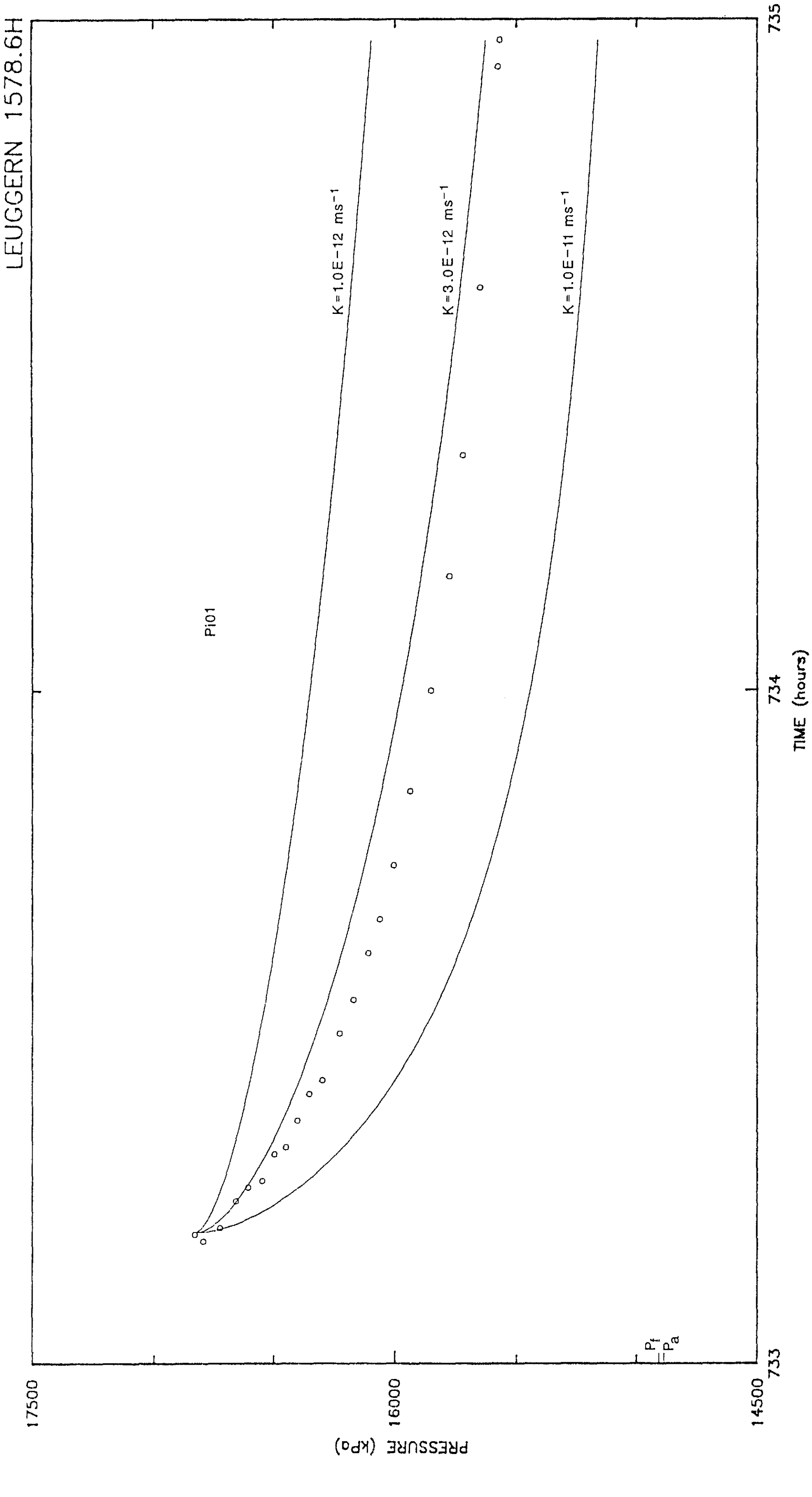


Figure 1: Measured (o) and Simulated Pressure Response for Test Pi01

Test 1603.5H (1590.98 m to 1615.95 m)

Test 1603.5H was performed on 6 to 7 March, 1985, as part of H-log sequence #5, in order to obtain a representative estimate of hydraulic conductivity of the crystalline rock in this interval. The pretest borehole history was complicated by an aborted test performed on the interval prior to the actual test. The simulated pretest pressure history consisted of the following: a 1 day drilling overpressure period, a 25.2 day open borehole period at annulus pressure, a short period of underpressure reflecting the aborted test, a 28 hour period at annulus pressure, and a short packer compliance period.

Testing in the interval consisted of a 14.4 hour pulse injection (Pi01) followed by a 1.5 hour slug withdrawal (Sw01). The estimated formation pressure of 14909 kPa was derived from the pressure gradient across the borehole based on calibrated formation pressures. Sw01 was not simulated due to negligible pressure recovery. Temperature varied by approximately 0.7°C over the duration of the Pi01 test, therefore, thermal effects were included in the simulations.

Results of the Pi01 simulations are shown in Figure 1. The selected hydraulic parameters for the test interval are a hydraulic conductivity of 1.0E-13 ms^{-1} at a base case specific storage of 2.2E-07 m^{-1}.

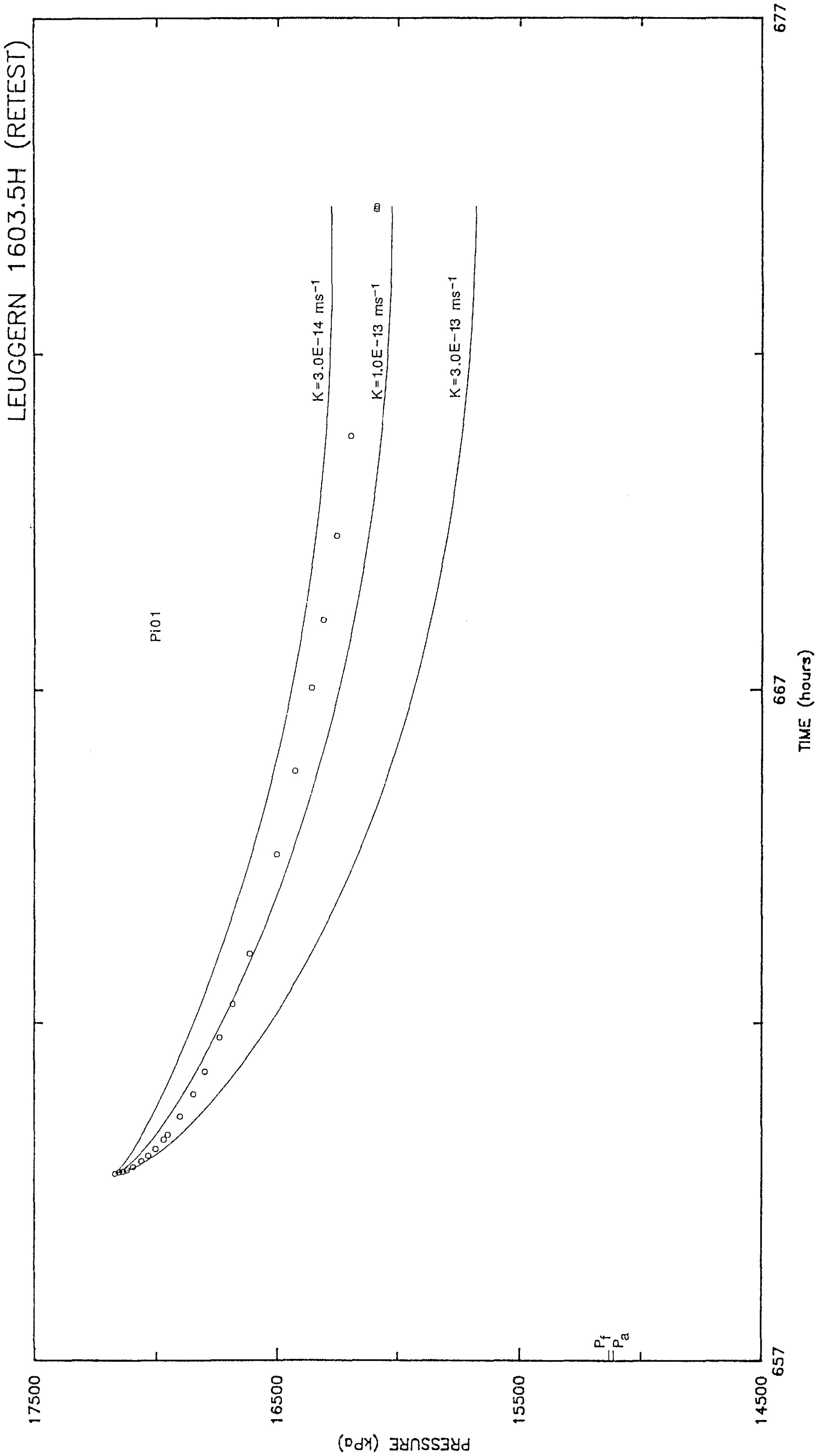


Figure 1: Measured (o) and Simulated Pressure Response for Test Pi01

Test 1628.3H (1615.85 m to 1640.82 m)

Test 1628.3H was performed on 2 to 4 March, 1985, as part of H-log sequence #5, in order to obtain a representative estimate of hydraulic conductivity of the crystalline rock in this interval. The simulated pretest pressure history consisted of the following: a 31 hour drilling overpressure period, a 19.6 day open borehole period at annulus pressure, and a short packer compliance period.

Testing in the interval consisted of a pulse injection and withdrawal, a DST test, and a slug withdrawal test. Test designations and durations are as follows: PiO1 for 36.7 hours, PwO1 for 37 minutes, DST01 for 1.1 hours (flow period SwO1 for 20 minutes, build-up period PwO2 for 48 minutes), and SwO2 for 1.7 hours. A flow rate of 0.07 $Lmin^{-1}$ was observed during the flow period of the DST (SwO1). The assumed formation pressure of 15358 kPa was derived from the pressure gradient across the borehole based on calibrated formation pressures. Temperature varied by approximately 0.2°C over the duration of the testing period. Thermal effects were not included in the simulation as the measured variation was felt to be insignificant due to the apparent relatively high hydraulic conductivity of the formation.

Results of the simulations are shown in Figure 1. The selected best-fit hydraulic parameters for the test interval are a hydraulic conductivity of 1.0E-09 ms^{-1} at a base case specific storage of 2.2E-07 m^{-1} based on fits to the PiO1 and PwO1 tests.

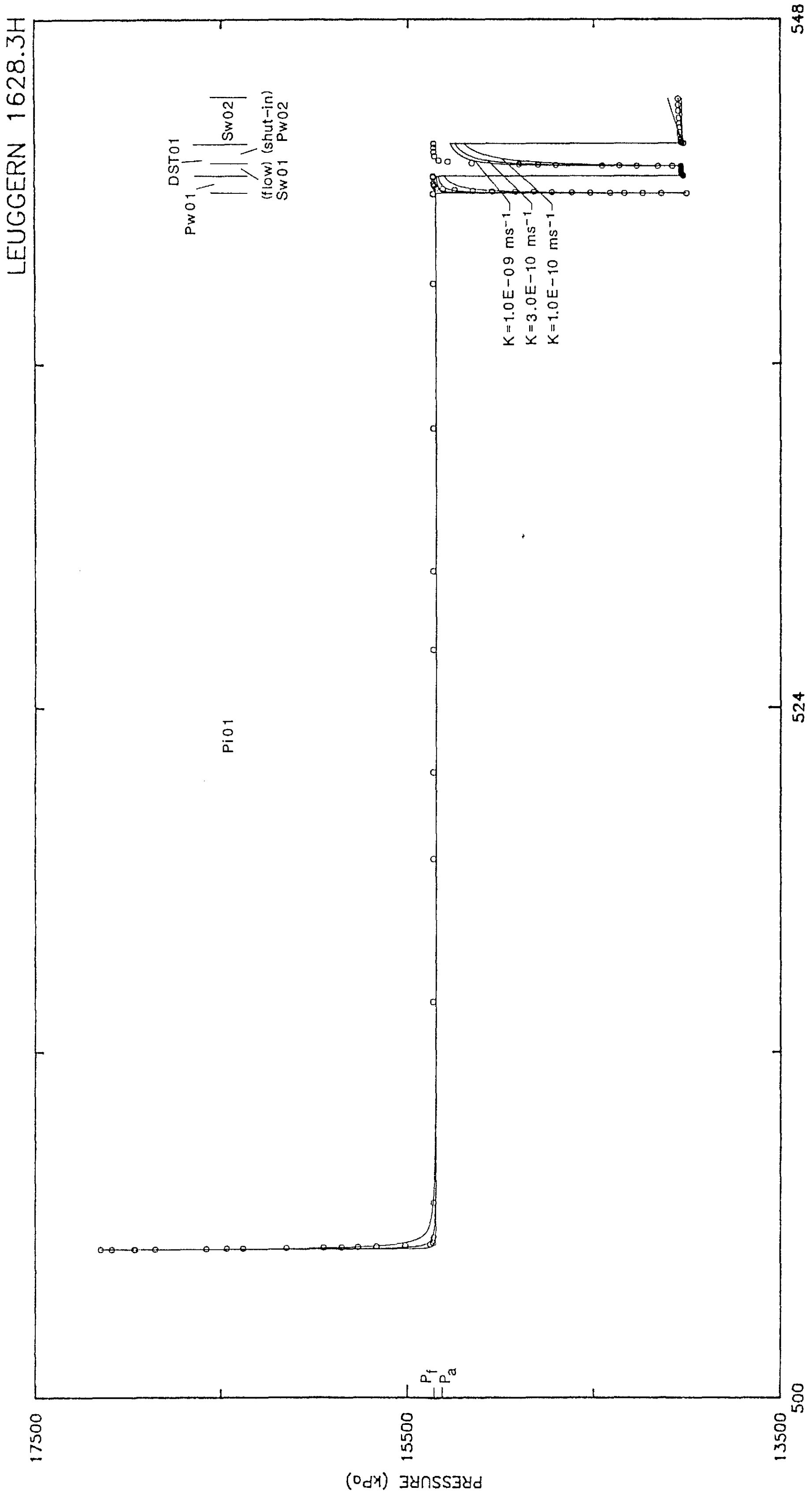


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 1643.4S (1637.40 m to 1649.30 m)

Test 1643.4S was a single packer test performed on 12 to 13 February, 1985 in order to obtain a representative estimate of interval formation pressure and of the hydraulic conductivity of the crystalline rock. The simulated pretest pressure history consisted of the following: a 10.2 hour drilling overpressure period, a 19.1 hour open borehole period at annulus pressure, and a 1.9 hour packer compliance period.

Testing in the interval consisted of a pulse injection and withdrawal, and two consecutive DST tests. Test designations and durations are as follows: Pi01 for 1.3 hours, Pw01 (inclusive of P_{stat}) for 12.6 hours, DST01 for 2.26 hours (flow period Sw01 for 15 minutes, build-up period Pw02 for 121 minutes), and DST02 for 40 minutes (flow period Sw02 for 2 minutes, build-up period Pw03 for 38 minutes). Pi01 and Pw01 both recovered very quickly. Pw01 recovered to a near stable pressure in 20 minutes after initial shut-in. For the duration of Pw01 (over 12 hours) the P2 transducer measured an essentially constant pressure of 15563 kPa. The assumed formation pressure of 15563 kPa was based on the constant pressure measured during Pw01. Although temperature variations of approximately 1.4°C over the duration of the testing period were encountered, thermal effects were not included in the simulation as the measured variation was felt to be insignificant due to the apparent relatively high hydraulic conductivity of the formation.

Results of the simulations for DST01 and DST02 are shown in Figure 1. The selected best-fit hydraulic parameters for the test interval are a hydraulic conductivity of 1.5E-06 ms^{-1} at a base case specific storage of 2.2E-07 m^{-1}. The equivalent freshwater head corresponding to the formation pressure extrapolated to the interval center is approximately 356.5 m ASL.

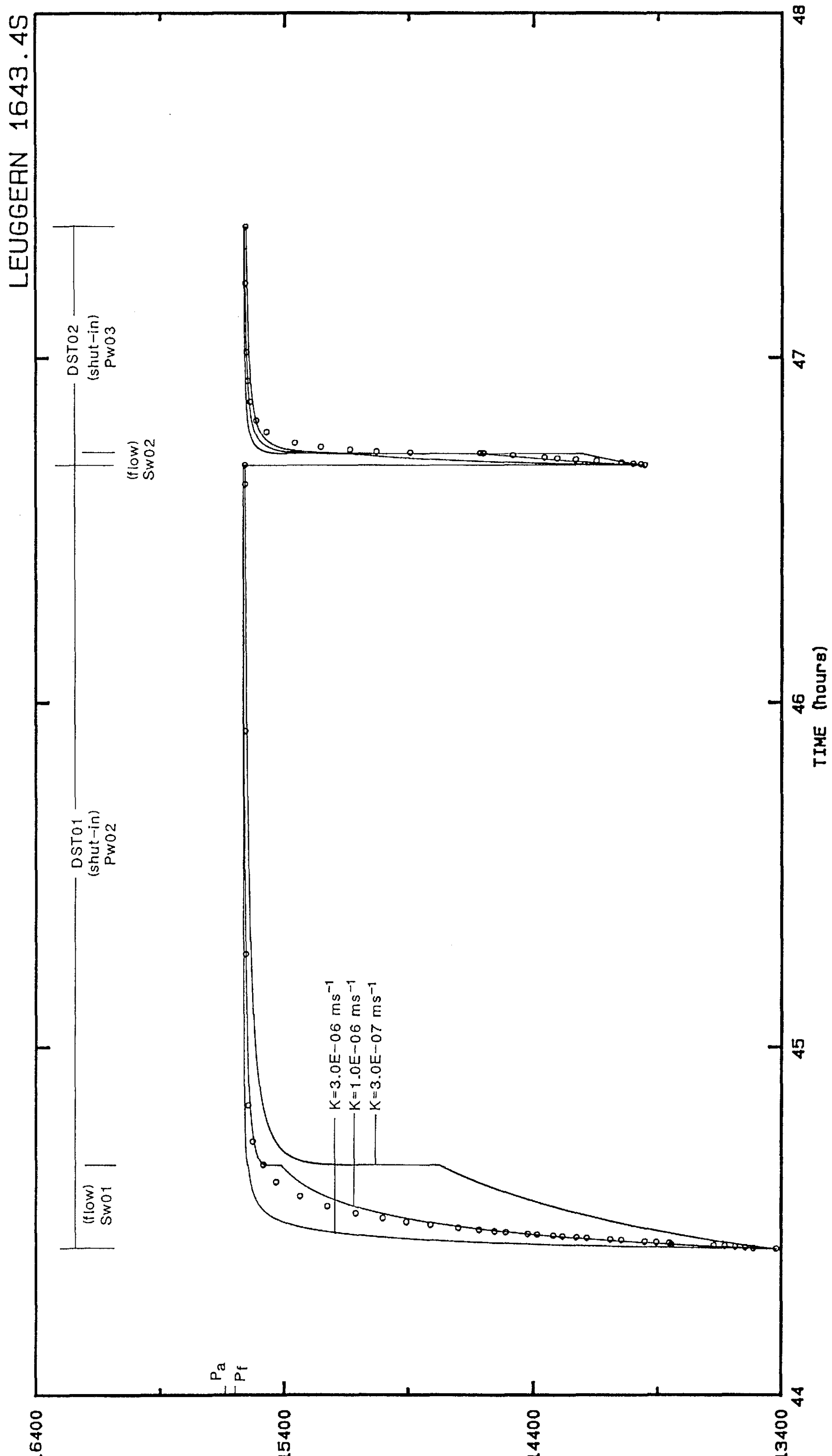


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 1649.8D (1637.33 m to 1662.30 m)

No hydraulic testing was conducted at the 1649.8D interval, but the sampling sequence, which consisted of a period of pumping, was analyzed to determine the hydraulic conductivity of the rock at this depth. An undisturbed formation pressure of 15574 kPa was derived from a hydraulic gradient across the borehole calculated by regression against single packer test formation pressures.

The borehole pressure history included in the simulation of the pumping sequence is complicated by the interference of single packer test 1643.4S (1637.4 to 1649.3 m) and the H-log test 1652.1H (1639.65 to 1664.62 m). Each of these tests were dominated by periods of underpressure. The drilling period was simulated by applying 50 percent of the drilling overpressure to the test interval over one-half of the drilling period. A series of swabbing events that took place prior to the start of pumping were incorporated into the history as a period of underpressure.

A significant complication during this pumping and recovery sequence is the observed communication between the test interval and the lower borehole which could cause a non-ideal test interval response. During the sampling exercise, nine pumping rate changes were reported, most changes on the order of several liters per minute. Prior to recovery, a decrease in pumping rate of about 14 $Lmin^{-1}$ was observed. The simulations of drawdown incorporated only two pumping rates which were considered representative, a value of 86 $Lmin^{-1}$ which represents the initial pumping rate at the start of sampling followed by 70 $Lmin^{-1}$ after about 39 hours. A base case value of specific storage of 2.2E-07 m^{-1} was chosen for the interval, representing a rock compressibility of 2.0E-11 Pa^{-1}. The best fit of the simulated pressure curves to the measured data, by inspection of Figure 1, is for a formation hydraulic conductivity of 7.0E-07 ms^{-1}. The poorer fit of simulated to measured pressures immediately preceding and during period "Pump 02" probably results from a gradual reduction in the pumping rate from about 1.4E-03 m^3s^{-1} to about 1.2E-03 m^3s^{-1} during sampling with this change not incorporated into the pumping period simulations because of the absence of measured rates.

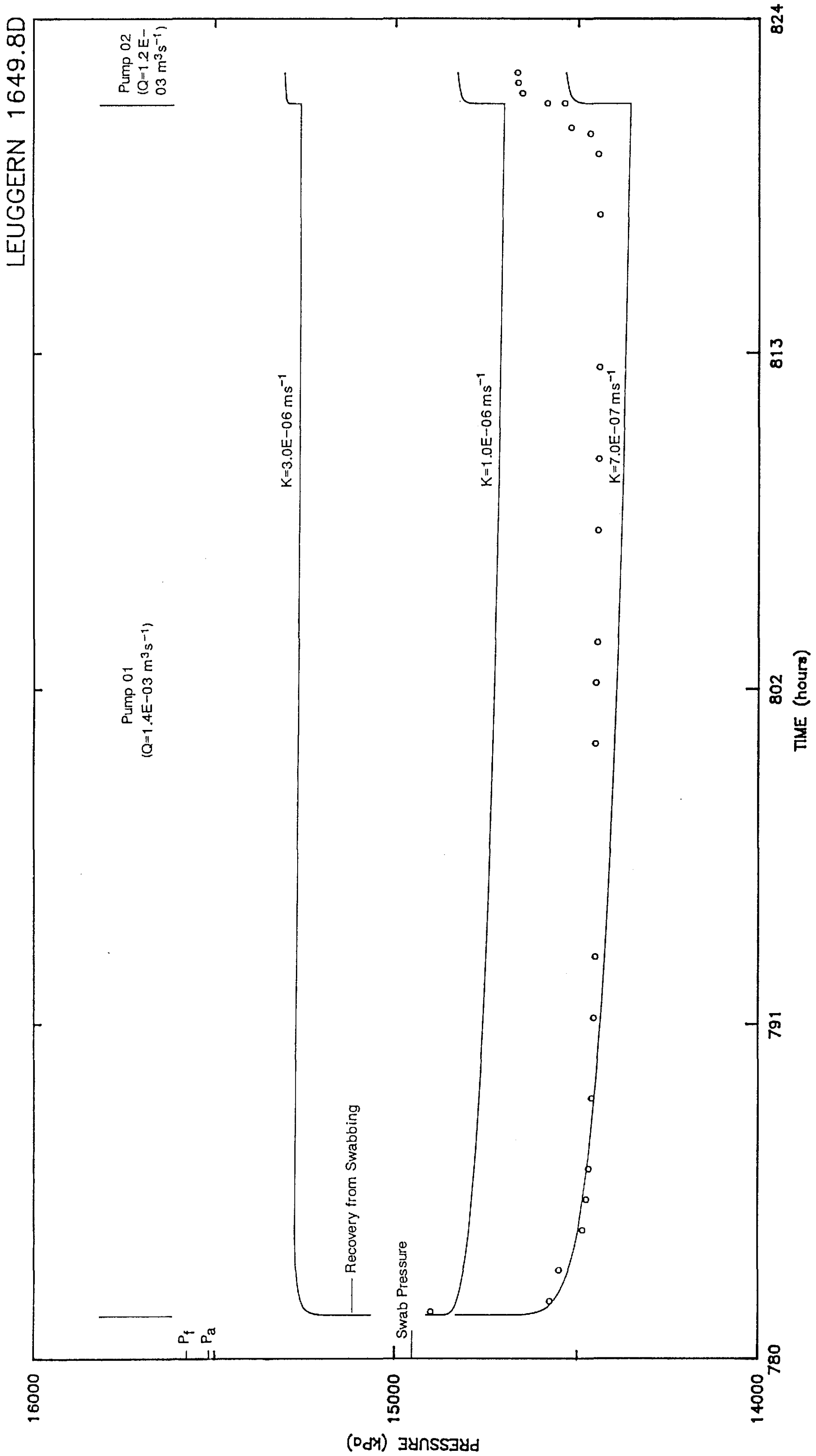


Figure 1: Measured (o) and Simulated Drawdown for the Pumping Events

Test 1651.5H (1638.97 m to 1663.94 m)

Test 1651.5H was performed on 4 March, 1985 in an attempt to retest the formation in the vicinity of test 1652.1H without the effects of P1/P2 communication noted during test 1652.1H. The test was performed immediately subsequent to the 1652.1H test by resetting the tool 0.68 m higher in the borehole. The goal of the test was to obtain a representative estimate hydraulic conductivity of the crystalline rock in the interval. The simulated pretest pressure history was assumed to be identical to that used in the simulations of the 1652.1H test; a 30 hour drilling overpressure period followed by a 15.1 day open borehole period at annulus pressure, and a short packer compliance period. Possible history effects due to the 1652.1H test were ignored due to the apparent high hydraulic conductivity of the formation.

Testing in the interval consisted of a DST test followed by a slug withdrawal test. Test designations and durations are as follows: DST01 for 12.6 hours and Sw02 for 9 minutes. A flow rate of 99 $Lmin^{-1}$ was estimated for the first few minutes of the flow period of the DST (Sw01). There was evidence of P1/P2 communication as measured P1 pressures indicated pressure changes of about 5 percent of those measured by P2. This was slightly less than encountered in the 1652.1H tests where 10 percent of the P2 pressure change was observed at P1. The assumed formation pressure of 15567 kPa was derived from the pressure gradient across the borehole from calibrated formation pressures. As discussed for test 1652.1H, it appears that the assumed value may be a slight (6 kPa) underestimate. Thermal effects were not included in the simulation as the temperature remained stable throughout the duration of the testing.

Results of the simulations are shown in Figure 1. The selected best-fit hydraulic parameters for the test interval are a hydraulic conductivity of 1.0E-06 ms^{-1} at a base case specific storage of 2.2E-07 m^{-1} based on fits to the DST01 and Sw01 tests.

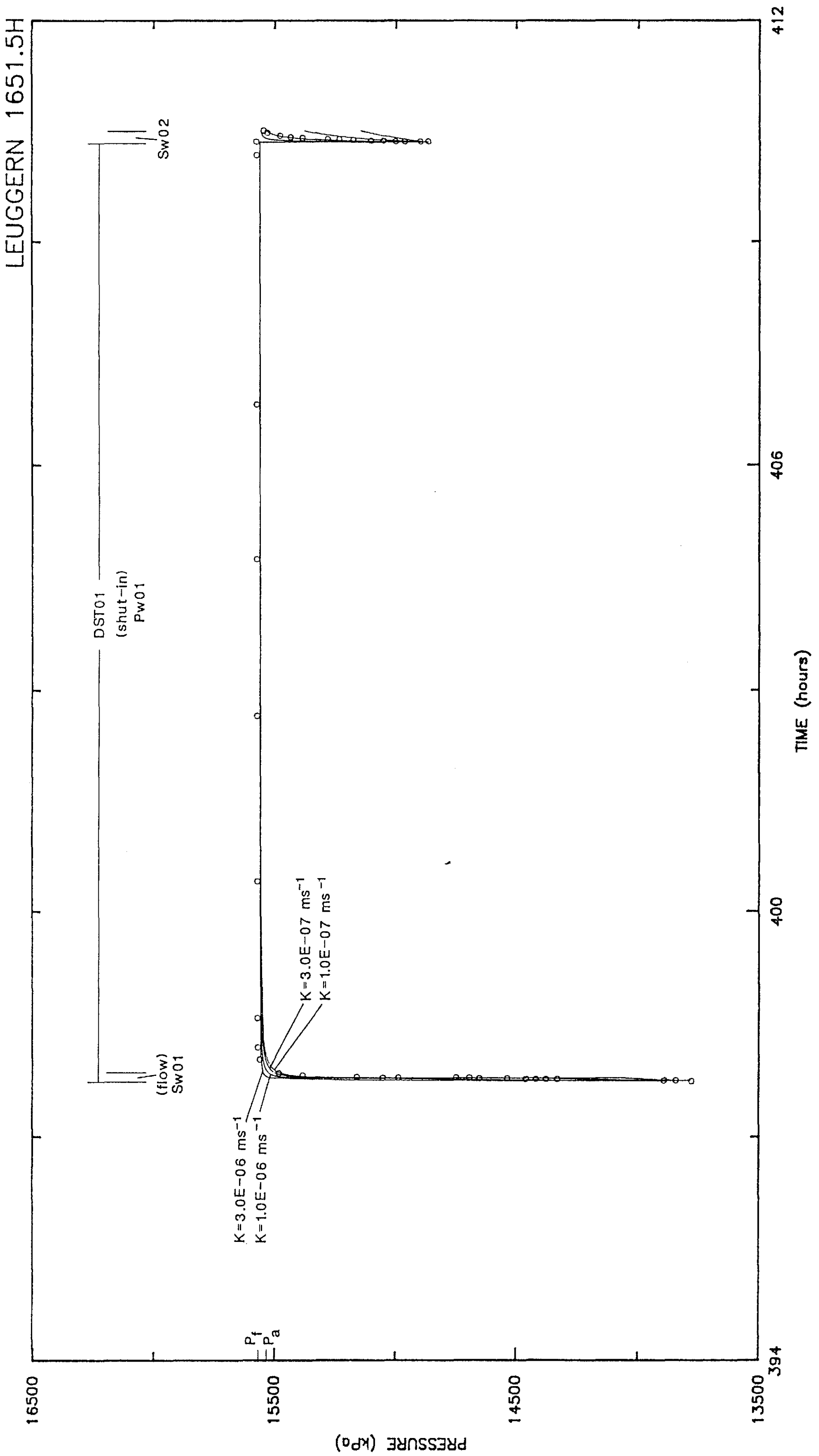


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 1652.1H (1639.65 m to 1664.62 m)

Test 1652.1H was performed on 4 March, 1985, as part of H-log sequence #5, in order to obtain a representative estimate of hydraulic conductivity of the crystalline rock in this interval. The simulated pretest pressure history consisted of the following: a 30 hour drilling overpressure period, a 15.1 day open borehole period at annulus pressure, and a short packer compliance period.

Testing in the interval consisted of a pulse injection and withdrawal, a DST test, and a slug withdrawal test. Test designations and durations are as follows: Pi01 for 19 minutes, Pw01 for 23 minutes, DST01 for 35 minutes, and Sw02 for 1.5 hours. A flow rate of 90.0 $Lmin^{-1}$ was estimated for the first few minutes of the flow period of the DST (Sw01). There were a number of difficulties encountered in the test due to communication between the P1 and P2 zones, indicating that a larger zone was being tested than intended. Communication may have been through the surrounding rock or may have been due to leakage past a suspected damaged lower packer. The assumed formation pressure of 15573 kPa was derived from the pressure gradient across the borehole from the calibrated formation pressures. Given that all tests recovered to an apparent pressure 6 to 8 kPa higher, it appears that the assumed value may be a slight underestimate. Thermal effects were not included in the simulation as the temperature remained stable throughout the duration of the test.

Results of the simulations are shown in Figure 1. Tests Pi01 and Pw01 are not useful for determining a formation K due to their rapid recovery. The selected best-fit hydraulic parameters for the test interval are a hydraulic conductivity of 7.0E-07 ms^{-1} at a base case specific storage of 2.2E-07 m^{-1} based on fits to the DST01 and Sw01 tests. The reliability of these test results is adversely affected by the apparent P1/P2 communication.

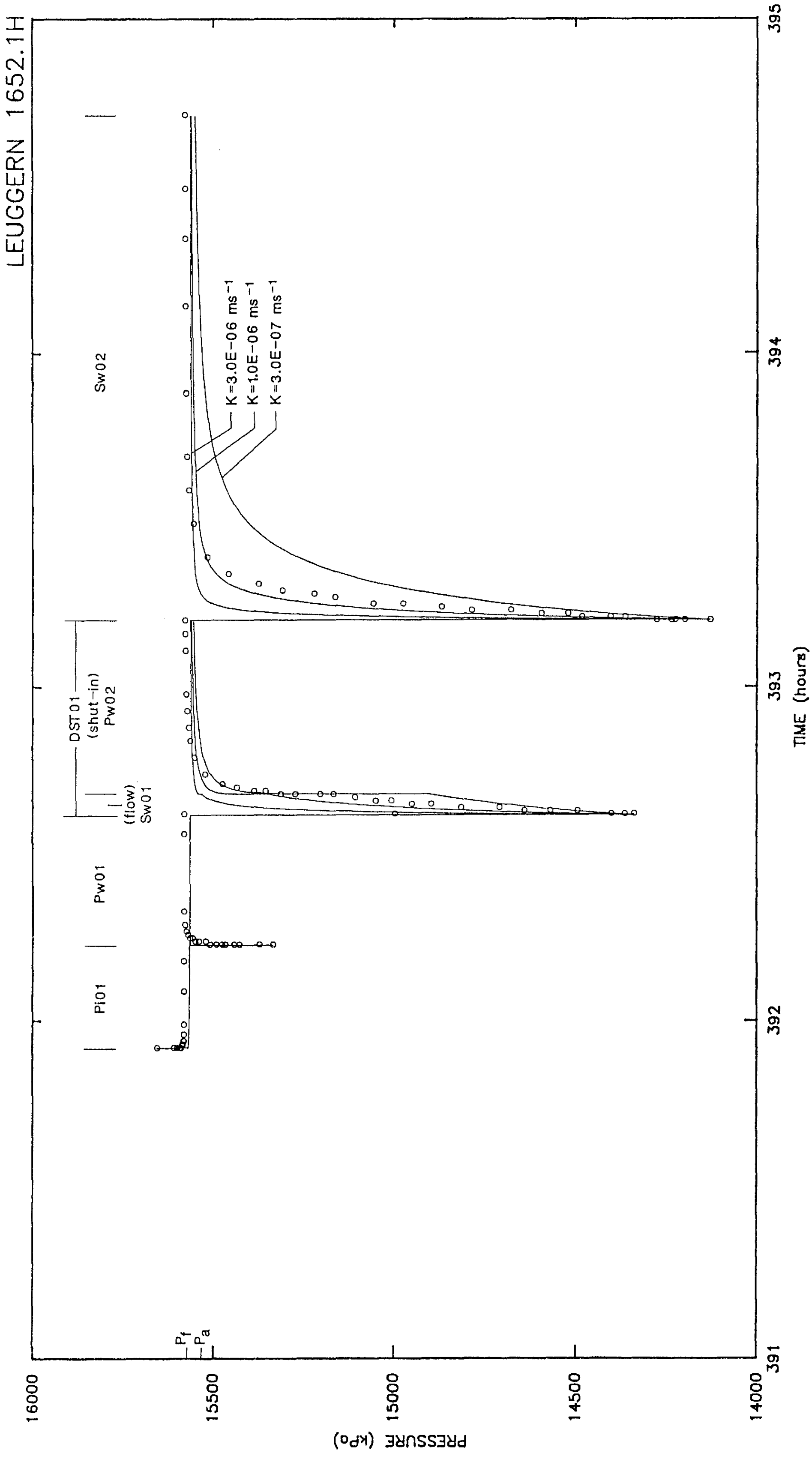


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 1665.5S (1642.17 m to 1688.90 m)

To provide an estimate of the hydraulic conductivity of the bottom 46.73 m length of the Leuggern borehole, the drawdown and recovery sequences of the 1665.5 m sampling exercise were analyzed by GTFM simulation. A review of the pumping history shows a decrease in the discharge rates in three stages, from 94 $Lmin^{-1}$ initially, to 50 $Lmin^{-1}$, and then to about 38 $Lmin^{-1}$ before the start of sampling. The simulation sequence for this interval consisted of three flow (drawdown) periods, each at a constant pumping rate, separated by recovery periods. Recovery was simulated as a slug withdrawal sequence. The pressure history for this interval was not included in the test simulation. It was felt that the two month period between drilling and pumping of this zone was sufficient to dissipate any drilling overpressure effects. Also, because of the high hydraulic conductivity of the zone, as evidenced in the pumping rates, any pressure skin resulting from contact of the interval with open borehole pressure should also dissipate quickly at the start of testing. Although this was not evaluated directly for the conditions of this test, the observations from tests 1651.5H and 1676.4S inferred this conclusion. A sensitivity study of formation pressure was conducted for the purpose of calibrating P_f. A formation pressure of about 15600 kPa resulted in the best match of the measured pressure curves during the recovery periods after pumping.

The duration of pumping events was as follows: 94 $Lmin^{-1}$ for 5 hours, 50 $Lmin^{-1}$ for 28 hours, and 40 $Lmin^{-1}$ for 29 hours. The simulated pressures for a range of hydraulic conductivity are shown in Figure 1. Best-fit hydraulic conductivity values for matching the measured pressures varied from 5.0E-07 ms^{-1} for the highest flow rate, to 6.0E-07 ms^{-1} for the intermediate flow rate, to 8.0E-07 ms^{-1} for the lowest flow rate. In summary, it could be concluded that the hydraulic conductivity of the 1665.5 m interval, covering the lower 46.73 m of the borehole, is greater than or equal to 8.0E-07 ms^{-1}.

The equivalent freshwater hydraulic head estimated for this interval is about 355.8 m ASL.

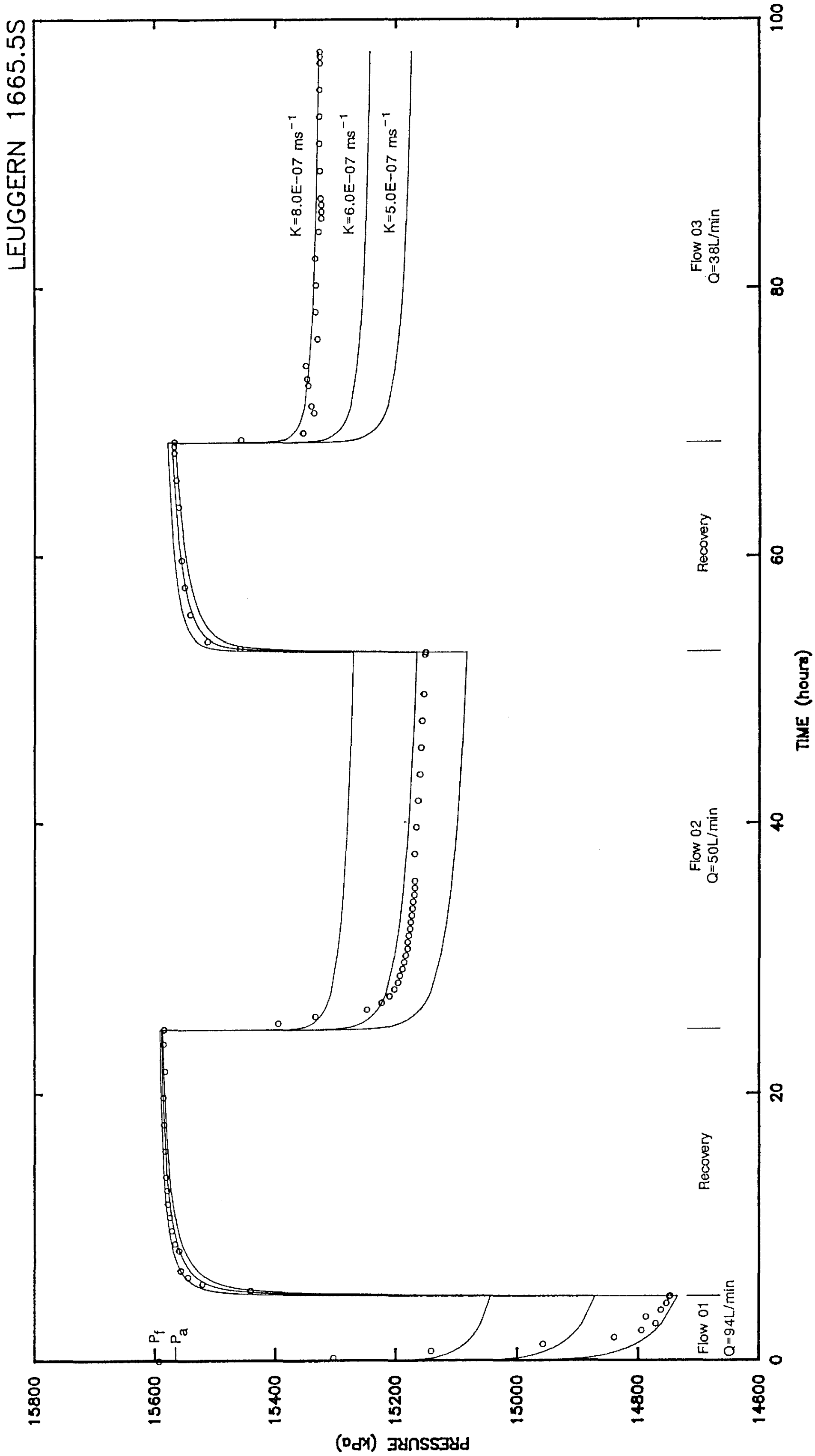


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence

Test 1676.4S (1663.93 m to 1688.90 m)

Test 1676.4S was a single packer test performed on 1 March, 1985 in order to obtain a representative estimate of interval formation pressure and of the hydraulic conductivity of the crystalline rock in this interval. The simulated pretest pressure history consisted of the following: a 20.6 hour drilling overpressure period, a 10.3 day open borehole period at annulus pressure, and a short packer compliance period.

Testing in the interval consisted of a pulse injection and withdrawal, followed by two consecutive DST tests, followed by two consecutive slug withdrawal tests. Test designations and durations are as follows: Pi01 for 50 minutes, Pw01 for 19 minutes, DST01 for 58 minutes (flow period Sw01 for 3 minutes, build-up period Pw02 for 55 minutes), DST02 for 52 minutes (flow period Sw02 for 3 minutes, build-up period Pw03 for 49 minutes), Sw03 for 1.9 hours, and Sw04 for 16 minutes. Pi01 and Pw01 both recovered very quickly to stable pressures of 15760 kPa. The static formation pressure of 15760 kPa, selected for this interval, was based on the stable recovery pressures shown by all tests. The equivalent freshwater head representative of this interval is approximately 351.9 m ASL. Measured fluid temperature in the borehole remained constant, therefore, simulations were performed without thermal effects.

Results of the simulations for Pi01, DST01 and DST02 are shown in Figure 1. Pw01 was not included in the simulation due to its rapid recovery. A sensitivity study on specific storage indicated that a better fit was obtained using a specific storage of 2.2E-08 m^{-1} as opposed to the base case value of 2.2E-07 m^{-1}. The selected best-fit hydraulic parameters for the test interval are a hydraulic conductivity of 1.0E-06 ms^{-1} at a specific storage of 2.2E-08 m^{-1}.

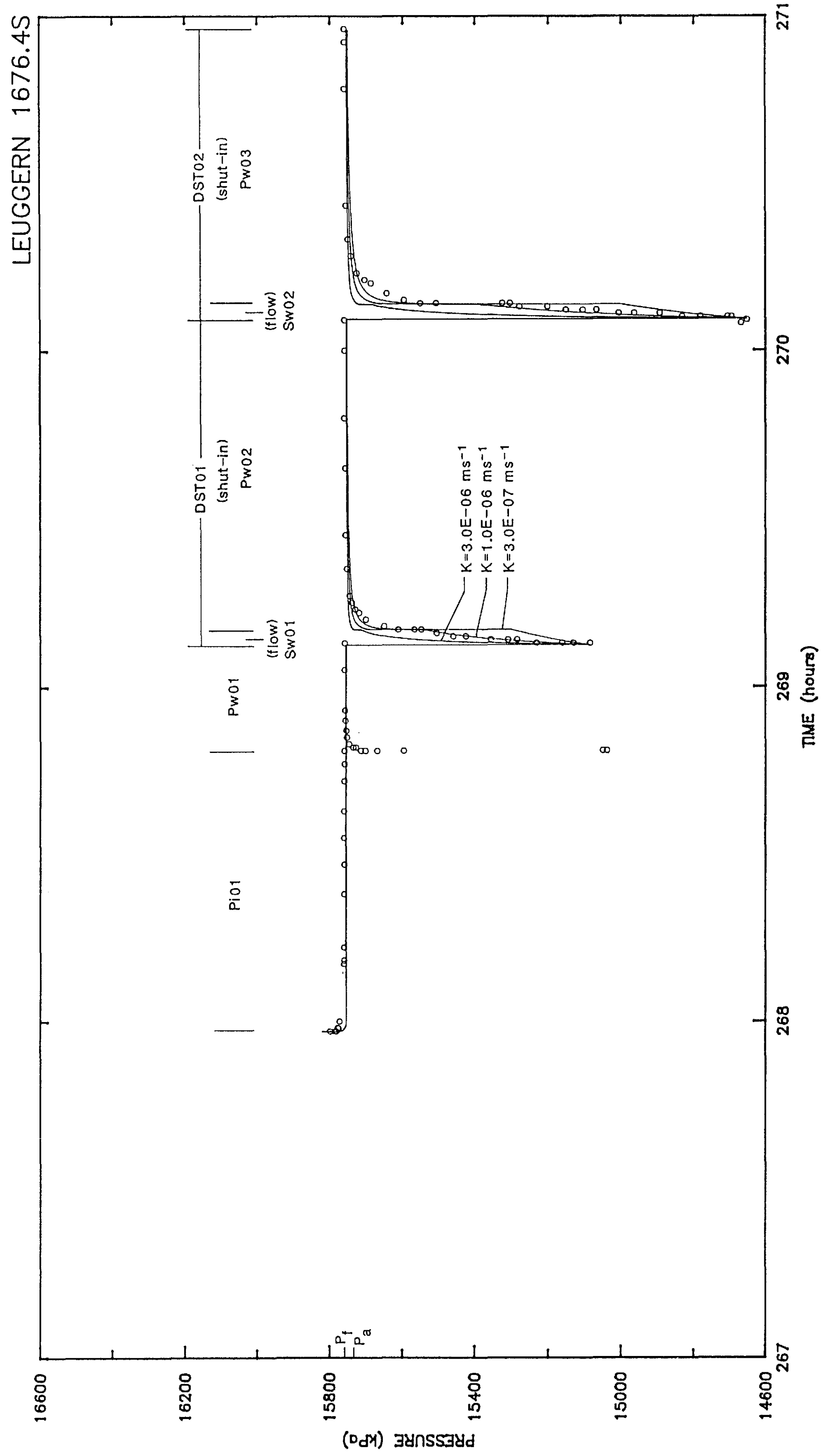


Figure 1: Measured (o) and Simulated Pressure Response for the Testing Sequence