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AUGUST 1989

INTERA Technologies, Inc., Austin, Texas

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ZUSAMMENFASSUNG

Der vorliegende Bericht enthält die Resultate der hydrogeologischen Auswertung aller auswertbaren, in der Bohrung Weiach ausgeführten Einfachpacker- und Doppelpackerversuche und der H-Log Tests (Hydrogeological Reconnaissance Tests). Zehn der 37 technisch erfolgreichen Versuche wurden mit einer Einfachpacker-Ausführung ausgeführt. Im Oberen Muschelkalk wurde im temporären Casing ein External Casing Packer (ECP) gesetzt und ein Pumpversuch durchgeführt. 26 Abschnitte wurden mit einer Doppelpacker-Konfiguration getestet. 3 davon wurden nacheinander mit konstantem Packerabstand durchgeführt; sie stellen somit eine systematische Testserie (H-Log) dar. In 28 Abschnitten wurde ein HTT-Gerät (Hydraulic Test Tool) verwendet. In 7 Abschnitten wurde ein DST-Gerät verwendet und die Versuche als Drill-Stem-Test ausgeführt. In einem der Versuche wurde ein DST-Gerät benutzt, um den Testabschnitt für die Durchführung eines Pumpversuches zu isolieren. Alle Tests wurden mit einem oder mehreren der folgenden Testtypen durchgeführt: Slug-Tests, Pulse-Tests, Drill-Stem-Tests (DST) und Pumpverversuche.

Die im vorliegenden Bericht besprochenen Versuche decken den Bohrlochabschnitt zwischen 188 m und dem Bohrlochende bei 2482.2 m ab (Tiefenangaben als scheinbare Tiefe, d.h. als Bohrtiefe). Die Versuche erfolgten im Malm, Dogger, Lias, Keuper, Muschelkalk, Buntsandstein, Perm, Karbon und im Kristallin. Die Versuchs- und Interpretationsmethoden werden dargestellt. Die Daten wurden mit dem Graph Theoretic Field Model (GTFM) von INTERA ausgewertet, das die Berücksichtigung der Bohrlochgeschichte und der thermisch induzierten Druckeffekte bei der Simulation der Versuche erlaubt. Weiter wurden zur Auswertung der Versuche graphische Interpretationstechniken nach HORNER angewandt.

Der Formationswasserdruck (und die ihm entsprechende Süsswasser-Druckspiegelhöhe) wurde für zwei Testabschnitte, die eine verhältnismässig hohe Durchlässigkeit aufweisen, bestimmt. Die er-

mittelten äquivalenten Süsswasser-Druckspiegelhöhen in der Sedimentstrecke des Bohrlochs in Bohrtiefen von 984.2 und 1117.5 m betragen 412.6 bzw. 452.6 m ü.M. Die Ackersohle befindet sich 368.66 m ü.M. Die Bohrlochgeschichte, thermische Effekte oder unzulängliche Versuchsdaten verunmöglichten es, für die übrigen Versuchsabschnitte den Formationswasserdruck (und die entsprechende Druckspiegelhöhe) zu ermitteln.

Die hydraulische Durchlässigkeit wurde für 36 von 37 im Bericht beschriebenen Intervalle abgeschätzt, und für 30 Intervalle mit einem empfohlenen Wert näher bezeichnet. Diese 30 Intervalle decken den gesamten kristallinen Bereich der Bohrung Weiach ab, und kennzeichnen jede der obengenannten sedimentären Formationen. Die ermittelten hydraulischen Durchlässigkeitsbeiwerte liegen in einem Bereich von $1.0 \cdot 10^{-6}$ bis $3.0 \cdot 10^{-13}$ m/s. Hohe hydraulische Durchlässigkeitsbeiwerte (grösser als $1.0 \cdot 10^{-8}$ m/s) wurden für vier Zonen bestimmt: 188-267 m (Malm), 822-896 m (Muschelkalk), 981-990 m (Muschelkalk-Buntsandstein) und 1109-1247 m (Perm).

Für jede Versuchszone, für die ein Durchlässigkeitsbeiwert empfohlen wurde, wurde eine Schätzung der Unsicherheit für diesen Wert angegeben. Sie beruht auf einer Sensitivitätsstudie über den Einfluss des spezifischen Speicherkoeffizienten auf die Durchlässigkeitsbeiwerte. Dazu wurden die Simulationsrechnungen ergänzt durch Berechnungen unter Verwendung von zwei spezifischen Speicherkoeffizienten die je eine Grössenordnung höher bzw. niedriger liegen als der angenommene Basiswert. Der Durchlässigkeitsbeiwert wurde für alle Simulationsrechnungen ermittelt, die erhaltenen Werte werden zusammen mit dem besten Schätzwert wiedergegeben, um die mögliche Variationsbreite des Durchlässigkeitsbeiwertes für jede Zone anzugeben. Die Simulationen der gemessenen Drücke lieferte für alle Versuchsabschnitte einen Schätzwert des spezifischen Speicherkoeffizienten. Dieser variiert in einem Bereich von $6.2 \cdot 10^{-5}$ bis $2.1 \cdot 10^{-7}$ m^{-1}.

Die im Bohrloch während den Versuchen gemessenen Temperaturen lagen im Sedimentabschnitt zwischen ungefähr 27°C und 88°C, in der Kristallinstrecke zwischen 96°C und 114°C. Ein genaueres Temperaturprofil der in der Bohrung Weiach durchquerten Formationen wurde bis in eine Bohrlochtiefe von etwa 2400 m aus den Logs der Messfahrten mit dem High Resolution Thermometer (HRT) und dem Auxiliary Mud Resistivity (AMS) und dem Vergleich dieser Temperaturmessungen mit den in den hydraulischen Tests bestimmten Temperaturen erhalten. Die in den HRT- und AMS-Logs zu Beginn des Jahres 1985 gemessenen Temperaturen dürften die ungestörten Formationstemperaturen darstellen. Der aus diesen Messungen ermittelte thermische Gradient beträgt 4.7°C/100 m.

Die Auswertung der hydraulischen Versuche der Bohrung Weiach wurde erschwert durch verschiedene Probleme, darunter als wichtigste die hohen Bohrlochtemperaturen in der Tiefe, schlechter Packersitz und eine oft ungenügend bekannte Bohrlochgeschichte. Die mit den hohen Temperaturen zusammenhängenden Probleme äusserten sich meist als Versagen der Packer oder der Transducer. In den Fällen, wo diese Effekte die Unsicherheit der Auswertung signifikant erhöhten, wurde versucht, den Unsicherheitsfaktor abzuschätzen.

RESUME

Ce rapport présente les résultats des interprétations des tests hydrogéologiques effectués dans le forage de Weiach. La séquence des pressions observées et simulées est illustrée pour chacun des tests par une figure en appendice. La formation testée a été isolée par un système à obturateur simple pour 10 des intervalles analysés, et un système à obturateur double pour 26 autres intervalles, dont 3 constituent une série continue (H-Log). Quant au Muschelkalk supérieur, isolé par un casing temporaire avec obturateur annulaire externe, il a été testé par essai de pompage. Le système de test était équipé de l'outil HTT de Lynes (Hydraulic Test Tool), sauf pour 7 tests où il s'agissait d'un outil DST (Drill-Stem-Test) conventionnel, avec procédure de test correspondante. En outre, l'outil DST a été utilisé pour isoler une formation et y effectuer un essai de pompage.

Tous les tests sont basés sur l'une ou plusieurs des 4 procédures suivantes: slug-test (injection ou soutirage à débit variable à partir d'une impulsion unique), pulse-test (rééquilibrage de la pression dans la formation isolée par les obturateurs, à partir d'une impulsion unique), drill-stem-test (slug-test suivi de pulse-test sans impulsion additionnelle), et essai de pompage conventionnel.

Les tests sont répartis entre 188 m de profondeur et la base du forage, à 2482.2 m de profondeur apparente, ou 2477.5 m de profondeur vraie. Ils couvrent l'ensemble du cristallin, de la base du forage à 2018 m de profondeur vraie. Des tests ont aussi été effectués dans le Carbonifère, le Permien, le Buntsandstein, le Muschelkalk, le Keuper, le Lias, le Dogger et le Malm.

Le présent rapport donne une description succinte des techniques de test, et traite de leur interprétation de manière plus approfondie. L'accent est mis notamment sur l'évaluation des effets thermiques. Les données ont été analysées par solution analytique au moyen de techniques graphiques (Horner), et par solution

analogique 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.

Pour 2 intervalles de test, on a pu déterminer la pression non-perturbée des formations et calculer le potentiel correspondant à une colonne d'eau douce. Il s'agit de tests effectués en zone de conductivité hydraulique relativement élevée. Le potentiel pour une colonne d'eau douce a été calculé à 412.6 et 452.6 m.s.m pour les sédiments situés respectivement à 984.2 et 1117.5 m de profondeur apparente. La pression des formations et le potentiel n'ont pas pu être déterminés dans les autres portions du forage, en raison d'effets thermiques, de pressions induites en cours de forage, ou de données insuffisantes.

La conductivité hydraulique a été estimée pour 36 des intervalles étudiés, et précisée par une valeur retenue pour 30 intervalles, couvrant l'ensemble du cristallin, et caractérisant toutes les formations sédimentaires sus-mentionnées. Les valeurs se situent entre 3.0E-13 ms^{-1} et 1.0E-06 ms^{-1}. Quatre zones sont caractérisées par une conductivité hydraulique supérieure à 1.0E-08 ms^{-1}. Elles sont comprises entre les profondeurs vraies suivantes : 188-267 m (Malm), 822-896 m (Muschelkalk), 891-990 m (Muschelkalk et Buntsandstein) et 1109-1247 m (Permien).

Pour chaque test où une valeur de la conductivité hydraulique a été retenue, on a déterminé la sensibilité de cette dernière au choix de la valeur du coefficient d'emmagasinement spécifique, en faisant varier la valeur du coefficient d'emmagasinement spécifique d'environ un ordre de grandeur en-dessus ou en-dessous d'une valeur de base, soit entre 6.2E-05 et 2.1E-07 m^{-1}. On obtient ainsi une fourchette d'incertitude raisonnable pour la conductivité hydraulique et le coefficient d'emmagasinement, par rapport à la valeur retenue.

Les températures mesurées dans le forage à l'aide du dispositif de test se situent entre 27°C et 88°C dans la partie sédimentaire et entre 96°C et 114°C dans le cristallin. Un profil thermique plus précis a été établi jusqu'à 2400 m de profondeur, par comparaison des températures mesurées lors des tests avec une diagraphie thermique à haute résolution (HRT) et une diagraphie de résistivité auxiliaire du fluide de forage (AMS). Les températures fournies par ces diagraphies, effectuées au début 1985, semblent correspondre aux températures non perturbées des formations. Le gradient thermique calculé à partir de ces données vaut 4.7°C/100 m.

Différents problèmes ont compliqué le travail d'interpétation des données du forage de Weiach, notamment les températures très élevées dans la partie inférieure du forage, une mauvaise assise pour les obturateurs dans certaines zones, spécialement dans le cristallin, et une incertitude assez grande sur l'histoire des pressions dans le forage avant les tests. Les températures élevées ont nettement raccourci la durée de vie des obturateurs et des cellules de mesure. Lorsque ces effets se sont montrés significatifs, on a tenté d'estimer l'incertitude correspondante sur les résultats.

SUMMARY

This report presents the results of hydrogeologic interpretations of all analyzable single packer, double packer, and H-log tests conducted in the Weiach borehole. Ten of the 37 technically successful tests were conducted using a single packer configuration. One test of the Upper Muschelkalk was configured using temporary casing with an external casing packer to conduct a drawdown-recovery test in the isolated zone. Twenty-six intervals were tested using a double packer configuration. Nineteen of these intervals were tested using a hydraulic test tool (HTT). Seven of these intervals were tested using a drill-stem test (DST) tool and drill-stem test methods and one test was completed with a DST tool used to isolate the test interval for a pumping sequence. Three H-log tests were completed near the bottom of the borehole with the HTT and double packer configuration. All the tests were completed with one or more of the following test methodologies at each test interval: slug tests, pulse tests, drill-stem tests (DST) and pumping tests. The tests discussed in this report cover the section of the borehole from apparent depth (along the borehole length) of 188.0 m to the bottom of the borehole at 2482.2 m. The testing occurred within the Malm, Dogger, Lias, Keuper, Muschelkalk, Buntsandstein, Perm, Karbon, and Crystalline Groups. 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, and Horner-graphical techniques.

Formation pressures (and corresponding equivalent freshwater heads) were determined for two test intervals where the formation had a relatively high hydraulic conductivity. The calculated equivalent freshwater heads were 412.6 and

452.6 m ASL at depths in the sedimentary portion of the borehole of 984.2 m and 1117.5 m, respectively. The surface datum elevation is 368.66 m ASL. Borehole pressure history, thermal effects, or poor data records prevented determination of formation pressures (and corresponding equivalent freshwater heads) in the remaining sections of the borehole.

Hydraulic conductivities were estimated for 36 of 37 tested intervals, and specified with recommended values for 30 intervals, covering the crystalline rock portion of the Weiach borehole and describing every sedimentary formation mentioned above. Interpreted hydraulic conductivities ranged from 1.0E-06 to 3.0E-13 ms^{-1}. Zones of high hydraulic conductivity (greater than 1.0E-08 ms^{-1}) were obtained for 4 zones corresponding to the following apparent depths: 188 m - 267 m (Malm), 822 m - 896 m (Muschelkalk), 981 m - 990 m (Buntsandstein), and 1109 m - 1247 m (Perm). An estimate of the uncertainty in the reported hydraulic conductivity of each zone is given based on a sensitivity study in specific storage. Simulations were completed at a base case specific storage and also at a specific storage one order of magnitude above and below this value. Hydraulic conductivity of the formation was determined from each simulation and reported together with the best-fit value to provide a reasonable range of hydraulic conductivity for the zone.

Simulations of the measured pressures resulted in estimates of specific storage for each interval. Specific storage ranged in value from 6.2E-05 to 2.1E-07 m^{-1}.

The measured temperature in the borehole during hydraulic tests ranged from about 27°C to 88°C in the sedimentary section and 96°C to 114°C in the crystalline section. A more accurate temperature profile for the formations at Weiach, to a depth of about 2400 m, was determined by examining High Resolution Thermometer (HRT) logs and Auxillary Mud

Resistivity (AMS) logs and comparing these temperatures with hydraulic test temperatures. Temperatures measured using HRT and AMS logging in early 1985 appear to represent undisturbed formation temperatures. The thermal gradient in the borehole from this data appears to be 4.7°C/100 m.

Hydraulic test interpretations of the Weiach borehole were complicated by special problems, the most significant of which were high borehole temperatures at depth, poor packer seating, and uncertain borehole pressure history. The thermal related problems manifested mostly as packer failure and transducer failure. In the cases where these effects added significant uncertainty to the interpretation, an estimate of the uncertainty was attempted.

TABLE OF CONTENTS

TABLE OF CONTENTS
(cont'd)

PAGE

TABLE OF CONTENTS
(cont'd)

LIST OF FIGURES

LIST OF FIGURES
(cont'd)

LIST OF FIGURES
(cont'd)

LIST OF TABLES

LIST OF APPENDICES

1. INTRODUCTION

Nagra is currently supervising an investigation of the geologic and hydrogeologic characteristics of crystalline rock in Northern Switzerland. These investigations are intended to provide a high quality database required to assess sites as potential repositories for radioactive waste.

As part of these investigations, Nagra has completed deep boreholes at six sites (Boettstein, Weiach, Riniken, Schafisheim, Kaisten and Leuggern). Twelve deep boreholes have been planned. The location of these boreholes is shown in Figure 1.1. This report provides interpretation details and a summary of hydrogeologic parameters for all of the analyzable single packer, double packer and H-log hydraulic tests in the Weiach borehole which have been completed to date. The interpreted parameters are: average hydraulic conductivity, specific storage, formation pressure, and equivalent freshwater head. Static formation pressures have been expressed as equivalent freshwater head and the equipment-related uncertainty in this head has been calculated. Uncertainty in the average hydraulic conductivity of each interval as related to the choice of specific storage has been estimated by sensitivity study in specific storage.

Packer testing in the Weiach borehole was completed both during drilling and testing phases from March 1983 through June 1984. As the drilling progressed, several single packer tests were run at the bottom of the borehole at 859.1 m, 926.2 m, 984.2 m, 1880.8 m, and 2063.3 m depth. On completion of the borehole, the crystalline section between 2020 m and the bottom of the borehole at 2482 m was tested using a single packer test configuration. Progressively larger intervals were tested corresponding to upper packer settings of 2468.5 m, 2350.5 m, 2306.8 m, 2282.0 m, and

2272.7 m as the single packer was moved up the borehole. Lynes completed DST tests with a DST tool after the borehole was completed to 823.8 m depth. The remaining tests were completed using a double packer test tool configuration following the completion of each stage of the drilling at 1834.2 m, 2067.0 m, 2292.4 m, and 2482.2 m depth. In May and June 1984, the casing was perforated at 1112.0 to 1115.0 m, 1119.0 to 1121.0 m, and 1403.5 to 1413.7 m depth and the final double packer tests were performed straddling the casing perforations. On completion of the packer testing, a dedicated multiple packer system was installed to isolate intervals of interest for the long-term monitoring phase.

The annular space was shut-in at Weiach from mid-November 1983 through early-February 1984 for observation of the pressure recovery in the uncased section of the crystalline (2065 m to 2456 m) and to attempt to dissipate any pressure disturbance around the borehole that may have existed. During this shut-in period, a packer was located near the bottom of the borehole at 2456 m. Casing was installed to about 2065 m into the top of the crystalline rock.

The majority of the hydraulic tests were conducted with the Lynes hydrologic test tool (HTT) using a transducer arrangement to monitor the pressure in the annulus, test interval, and the zone below the bottom packer. The Lynes drill-stem test (DST) tool was used for six sequential tests in the Jurassic and Triassic sediments from 188 m to 740 m, one test in the Upper Muschelkalk at 859.1 m, and one test at 985.3 m in the Buntsandstein. The 985.3 m test was a pumping test with the pump installed in the upper tubing string. Pressure change in the borehole during pumping was monitored with transducers attached to the pump drop pipe. A second pumping test was completed at 859.1 m in the borehole through temporary casing with an external casing packer isolating the Muschelkalk aquifer. Two tests using a double packer configuration of the HTT were completed in shot-perforated casing before installation of the long-term monitoring tools.

The hydraulic testing using the HTT in the Weiach borehole was managed by Nagra and conducted on-site by Gartner-Lee AG (GLAG) in conjunction with Lynes personnel. The six DST tests in the upper borehole above 823 m were conducted by Lynes personnel. A preliminary analysis of the hydraulic testing in Weiach was completed by GARTNER LEE (1983/84, 1985a, 1985b).

Complete test descriptions and interpretations for the Weiach borehole are given in BUTLER et al. (1989). This report presents in detail, in the form of appendices, the analysis approach and the interpreted hydrogeologic parameters for each interval.

2. WEIACH BOREHOLE DESCRIPTION

Weiach was the second borehole to be completed after Boettstein in the Nagra deep borehole program. The borehole is located at coordinates 676'750/268'620 in northern Switzerland. This lies near the northern boundary of the Molasse Basin at 900 m south of the Rhine river and approximately 8 km northwest of the town of Bulach. Surface datum elevation is 368.66 m ASL.

Drilling of the borehole began in January 1983 and was completed in November 1983 to a depth of 2482.2 m. The rig floor elevation was set at 372.95 m ASL (i.e., 4.29 m above ground surface datum) which results in a top of annulus at about 3.0 m above ground, and an annulus outlet valve at about 1.4 m above ground. Sections of the hole were cored and others were drilled using tri-cone techniques. Drilling mud was used to complete the borehole through most of the sedimentary rock groups and traced deionized water was used in much of the crystalline section. As the depth of the borehole increased, the diameter was increased by reaming. Casing was set in the widened sections of the borehole to a depth of 2065 m. The borehole was most deviated from vertical between 500 m and 800 m, and between 1350 m and the bottom of the hole at 2482.2 m, according to HDT and SHDT surveys. The inclination from 500 m to 800 m was about 2 degrees from vertical and from 1350 m to 2450 m was about 5 degrees from vertical. Over the lower 150 m of the hole, the borehole deviation from vertical increased by about 5 degrees. The deviation of the borehole resulted in a total apparent depth error (apparent minus true vertical depth) of about 5.3 m (NAGRA, 1988).

The deviation of the borehole produces depths measured along the borehole that differ from true vertical. Depths measured along the borehole are referred to as apparent depths. 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 pressure and equivalent freshwater heads. The true vertical depths used in this report have been calculated based on the results of geophysical dipmeter surveys (HDT and SHDT) run from the top to the bottom of the borehole. Deviation results are reported in WEBER et al. (1986) as apparent and true vertical depths and inclination at 50 m intervals along the borehole. The true vertical depth, for an apparent depth not measured in the survey, is derived from a linear approximation of true vertical depths corresponding to the two nearest (one above and one below) measured apparent depths from the deviation data.

The geology of the Weiach borehole (Figure 2.1) is composed primarily of sedimentary formations. Weiach intersected a trough in the crystalline basement filled with Permo-Carboniferous sediments. Quaternary sand and gravel deposits are found from surface to a depth of 37.0 m. These deposits are underlain by Tertiary sands and sandstone to a depth of 186.03 m. Jurassic deposits consisting of limestone, marl and claystone are found from 186.03 m to 704.3 m below surface. The Triassic age sediments are similar to those in the Boettstein borehole and include the Keuper Group (704.3 m to 819.1 m), Muschelkalk Group (819.1 m to 981.8 m) and the Buntsandstein Group (981.8 m to 991.5 m). Underlying the Triassic rocks are Permian (991.5 m to 1447.9 m) and Carboniferous (1447.9 m to 2020.4 m) sandstones and siltstones. Crystalline rocks, in the Weiach borehole, begin at 2020.4 m and consist of granitic gneiss, biotite gneiss and aplite. As at Boettstein, the crystalline rocks contain fractures and kakirite zones.

A surface casing of 20 in. diameter was installed across the Quaternary deposits to a depth of 44.5 m (Figure 2.1). Inside this casing, a 339.73 mm (13-3/8 in.) diameter casing was set at the Muschelkalk to a depth of 813.6 m. A final 244.48 mm (9-5/8 in.) diameter casing was cemented into the top of the crystalline at a depth of 2065.0 m. The 244.48 mm casing was perforated at the following depths in order to access the various sedimentary units:

- Muschelkalk - 824.5 m to 829.5 m
- Buntsandstein - 984.0 m to 985.0 m and
  - 986.5 m to 991.3 m
- Upper Rotliegendes - 1112.0 m to 1115.0 m and
  1119.0 m to 1121.0 m
- Lower Rotliegendes - 1403.5 m to 1413.7 m

The remainder of the borehole in the crystalline rock is open.

The distribution of fractures in the borehole is primarily in the crystalline section below 2020 m to about 2280 m. Several crystalline zones tested showed more than 100 fractures per meter in the core. Kakirite zones, often an indicator of local permeability, were relatively thin (less than 2 m) in the crystalline formation.

Drilling fluid losses to the formation are reported for the following zones in the Weiach borehole:

Fluid Loss (m^3)	Depth (m)	Formation
7	195.7 to 199.8	Malm
20	827.5 to 832.8	Muschelkalk
12	896.1	Muschelkalk
67	896.3 to 923.3	Muschelkalk
1.2	1026.3 to 1030.3	Perm
~12	1834.2 and	Permo-Karbon
	880 to 895 (while enlarging the borehole to 895 m)	Buntsandstein

3. FIELD TESTING METHODS

3.1 Equipment Description

Hydraulic testing equipment used in the Weiach borehole was provided by Lynes GmbH and was operated by Lynes and Gartner Lee AG (GLAG). The first testing in the borehole consisted of a sequence of six drill-stem tests (DST) completed after drilling to 823 m into the Trigonodus dolomite. Each of these tests were completed using Lynes DST equipment fitted with pressure and temperature transducers and 194 mm diameter packers. Other downhole equipment included the Lynes 3.5 inch and 5 inch hydrologic test tools (HTT). Most of the interval testing with the hydrologic test tool was completed with either 137 mm packers on the 3.5 inch tool or 279 mm packers on the 5 inch tool. One pumping test with the DST tool used to isolate the interval was completed with the sensor carrier attached to the drop pipe above a submersible pump lowered into the tubing string. For the remaining tests, the DST tool and HTT were equipped with downhole sensors. Several tests were run using the HTT with a data collection system which monitored temperature and pressure for the test interval only. The Lynes HTT is described in detail in LEECH et al. (1984) and only a brief description will be provided here. An overview of the Lynes DST tool operation is also provided. A more detailed discussion is available in the Lynes product literature.

The hydraulic testing equipment for the HTT consists of the following major components:

- Hydraulically inflatable packers (single or double configuration) 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 in the annular space (P3). Temperature transducers (T1, T2, T3) measure the operational temperature of the respective pressure transducers. 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. The P1 and T1 sensors are located 0.25 m below the P2 and T2 sensors and the P3 and T3 sensors are located 0.25 m above the 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. As the stands of tubing string are lowered into the borehole, fluid is added to the tubing to reduce buoyancy. At this point, the test tool is configured for a hydraulic connection between the tubing string and the packers. The fluid in 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. In this configuration, fluid is allowed to flow between the test interval and tubing string. To perform a pulse test, the shut-in valve is opened to allow under- or overpressurization of the test interval and then closed to trap the pressure in the shut-in zone and to isolate the borehole test interval. 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, however, testing methods that incorporate a compliance 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 pumping tests in test intervals with high hydraulic conductivity.

Of particular importance in the Weiach borehole were the effects of temperature on equipment performance. Temperatures exceeded 100°C near the bottom of the borehole where the HTT was used extensively. The Lynes packer elements are not designed for prolonged exposure to high temperatures; packer specifications for the Lynes equipment indicate 100°C as the upper operating limit. About 80°C was the proven optimum design limit for short tests (several hours) with conventional rubber elements on the HTT. To better handle the bottom hole temperatures, Lynes incorporated stainless steel elements on the HTT for the bottom hole tests with a covering of high temperature rubber-compound. This rubber cures in the test zone and can be reset several times at depth allowing testing of several zones in the borehole without retrieving the tool.

The reported accuracy of the pressure transducers for the HTT at full scale of 41370 kPa is ± 0.05 percent with a resolution of 0.005 percent. This corresponds to an accuracy of about ± 21 kPa or ± 2 meters of water at full scale. The temperature transducers have a reported accuracy of about ± 1°C with a resolution of 0.1°C.

The Lynes drill-stem test tool uses a straddle packer arrangement to isolate the test interval, similar to the HTT in double packer configuration. Operation of the shut-in valve to isolate the tested zone or allow flow to and from the test zone is by up-and-down movement of the drill pipe, rather than movement of a mandrel through a J-slot mechanism. The components of the Lynes DST tool are summarized below:

- Hydraulically inflatable packers using an in-line packer inflation pump and inflation fluid from annulus;
- Hydraulic shut-in valve operated using the attached drill pipe to connect and disconnect the test interval from the drill pipe interior;
- Inside and outside pressure-temperature recorders; inside recorder carrier measures the test interval conditions from above the top packer below the shut-in valve; outside recorder carrier is isolated in the test interval between packers and is exposed to the fluid stored between the tool and the borehole wall;

- Equalizing bypass to equilibrate annulus pressure and pressure below the lower packer;
- Wireline conductor cable to transmit pressure and temperature signals to surface from CWL probes, as required;
- Surface data collection equipment for wireline-based (CWL) and self-recording-type (DMR) transducers.

The simplified operation of the Lynes Inflatable Drill-Stem Testing tool is as follows. The DST tool sequence is lowered to the test interval attached to the drill-stem. The drill pipe slips are set and the surface recording equipment is connected. Rotating the drill pipe to the right operates the downhole DST pump, inflating both packers simultaneously. To prepare for testing, the hydraulic shut-in valve is closed by picking up on the drill pipe. In this position the drill pipe fluid level can be swabbed down without influencing the pressure in the test interval. The shut-in valve is then opened by setting weight on the tool and exposing the test interval to the underpressure. The open valve allows fluid flow from the test interval into the drill pipe. The interval is then shut-in to complete the drill-stem test by picking up on the drill pipe. Providing the packers are well seated, the drill pipe weight can be shifted to open and close the tool without affecting the packers' seal. On completion of the DST sequence, the pressure differential between the annulus and test zone is dissipated by rotating the drill string a quarter turn at the tool which allows communication of the test zone with the annulus above the top packer. After equalization, the packers are deflated by picking up on the drill pipe.

As with the HTT, the packer elements are susceptible to rupture and leakage. Inflating the packers in oversized holes to beyond the inflation specifications and moving the tool in irregular boreholes can wear the packers resulting in test failures, however, the performance of the tool is generally trouble free.

The DST tool employed in the Weiach borehole recorded pressures and temperatures using a CWL 300 (wireline) transducer system and a DMR 314/200 self-recording system. The Conductor Wireline (CWL) System has a reported accuracy of ± 0.05 percent at full scale of 34500 kPa within the operating range 0°C to 105°C with a resolution of 0.005 percent. This corresponds to an accuracy of ± 17.25 kPa at full scale and a resolution of 1.73 kPa. The temperature transducers measure the operating temperature of the pressure transducers to an accuracy of ± 0.1°C and a resolution of 0.1°C within the operating range of 0°C to 125°C. The DMR 314/200 quartz crystal transducers are stand alone probes which record temperature and pressure at pre-set intervals. On completion of the DST test, the probe is retrieved and connected to a surface recording unit to access the data. The unit has an operating pressure range of 0 through 34500 kPa with an accuracy of ± 0.005 percent through full scale operation and a resolution of 0.01 percent of full scale. This translates to an accuracy at full scale of ± 17.25 kPa and a resolution of 3.45 kPa. The operating temperature range of the DMR tool is 0°C through 105°C. Temperatures at the probe are recorded to an accuracy of ± 1°C and resolution of 0.14°C.

Testing in Weiach at 859.1 m was completed through temporary 244.48 mm (9-5/8 in.) casing with an external casing packer isolating the Muschelkalk aquifer. During drawdown and drawdown recovery, water levels were measured in the open borehole.

3.2 Tool Configuration and Testing Methods

Testing in the Weiach borehole was completed using a variety of testing tool configurations including a Lynes DST tool, single packer-configured HTT, double packer HTT, and fixed-straddle (H-log) HTT. One test was completed in the open borehole with temporary casing installed to isolate the test zone.

The test equipment configuration is usually determined by the purpose and time allocated for each interval. Single packer tests are typically used during the drilling phase to isolate the bottom section of the borehole, thus only one packer is required. These tests are typically run in zones of higher hydraulic conductivity where high fluid loses during drilling are observed or where there is an indication of a change in formation pressure. Their primary use is to shut-in an interval immediately after drilling to determine accurate formation pressures, but the shut-in interval of a single packer test may also be used for geochemical sampling as well as hydraulic testing. Single packer tests conducted during drilling are typically short in duration in order not to delay the continuation of drilling. In the Weiach borehole, 10 of the 37 technically successful tests were conducted with a single packer configuration. Among them, nine were using the HTT and one the DST tool. One test of the Upper Muschelkalk was configured using temporary casing with an external casing packer to conduct a drawdown recovery test in the isolated zone.

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 an interval. Within the Weiach borehole, 26 double packer configured intervals were tested. Seven of these tests used DST equipment and one of them was a pumping test, the others being conventional DST's. Three H-log tests were completed near the bottom of the borehole. H-logs use a special configuration of the HTT with the packers set at a fixed spacing. Testing is completed by isolating uniform test zones as the test tool is moved up the borehole.

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

The four test tool configurations used at Weiach (single packer, double packer, DST tool and open borehole) typically used one or more of the following hydraulic test methodologies at each test interval:

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

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 Weiach 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. The pressure above and below the test interval was also monitored by the pressure transducers in the sensor carrier. For slug injection tests, the tubing string was pressurized with a standing column of water and then, by opening the shut-in valve, the fluid in the tubing string 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 pressure 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 buildup period).

In the Weiach borehole, pumping tests were conducted in intervals of relatively high hydraulic conductivity using either double packers or, if the interval was at the bottom of the borehole, a single packer to isolate the test section. If the entire drilled section of the borehole is to be tested, pumping can be conducted in the open borehole. Temporary casing may also be set to isolate a specific test zone. The test interval is pumped using a submersible pump placed within the tubing string or open borehole below the static fluid level. The pressure response of the formation is monitored for the duration of the pumping. After the pumping period, the pressure recovery can also be monitored.

Each of these tests described above can be completed using either the HTT in single or double packer configuration or the DST tool. The purpose of the testing described above is to measure a pressure or water-level response which is analyzed to obtain representative formation parameters such as formation pressure, average hydraulic conductivity and, where possible, specific storage.

4. TEST INTERPRETATION APPROACH

The purpose of this section is to provide a description of the methods used to interpret the hydraulic tests in the Weiach borehole. The interested reader is directed to GRISAK et al. (1985) for a detailed discussion of the theory of hydraulic test analysis.

4.1 Definition of Formation and Fluid Properties

The hydraulic test interpretation methods for the Weiach 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 and 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, formation pressure and specific storage are dependent on accurately simulating, with mathematical models, the measured pressure response of the formation. The basic input parameters, as discussed above, are relied upon to provide a reasonable range of specific storage which reflects the formation.

This section provides a definition of the properties describing the hydraulic system under study and a discussion of quantities 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 describe 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 interpretation of the borehole tests. 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:

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

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 Weiach 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 sedimentary rock and crystalline rock. Each major lithology was assigned a reasonable value or range of values for Young's modulus and Poisson's ratio from which rock compressibility could be determined using Equation 4.1-2. Factors that could contribute to the range of values for a lithology include the stress levels used for stress-strain testing, and whether the samples tested were pure or contained some mixture of other rock types. For limestone and dolomitic limestone, formation compressibility ranged from 6.0E-10 to 6.3E-09 Pa^{-1}. Evidence of brecciation, vugs, significant dissolution features, or extensive fracturing was treated by increasing the compressibility of that unit by as much as an order of magnitude. Sandstone was described by a range of formation compressibility from 2.0E-11 to 8.5E-09 Pa^{-1}. The large range of compressibility is attributed to structure within the formation and also to the mixture of other types of sediments with the sandstone such as clays and calcareous mudstone. Anhydrite is described by a compressibility of 3.0E-10 Pa^{-1} which is about half an order of magnitude lower than would result from experimental values. This difference is attributed to the mix of the anhydrite with less compressible dolomite. For the crystalline formation, which includes gneiss, aplite, aplite-granite and mixtures of these lithologies, the formation compressibility ranged from 2.0E-12 to 2.2E-10 Pa^{-1}. Formation compressibility calculated from the Young's modulus and Poisson's ratio of TOULOUKIAN et al. (1981) is 4.1E-11 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 may not entirely represent the natural system where the rock formations may contain more or fewer fractures than the tested cores. The presence of a fracture set in a test interval will increase the rock compressibility with the amount of change depending on the fracture density. In highly fractured rock, the formation compressibility is likely to increase over that for unfractured rock by an order of magnitude or more. Given that the crystalline rock of the Weiach borehole contains fracturing to varying degrees, then it seems that a reasonable range of compressibility may extend as high as 2.2E-10 Pa^{-1}.

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 or between crystals in a chemical precipitate such as a carbonate rock. 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 sedimentary rocks intersected by the Weiach borehole have been described in this report with a range of porosities from 10 percent to 20 percent. This range of porosity used in the interpretation of the hydraulic tests represents the primary or matrix porosity of the rock. The fractures (e.g., secondary porosity) in the rock could be expected to contribute as much as one percent to the total porosity of a unit volume of rock. The porosity assigned to the rock in each test zone represents a value obtained from a review of the literature and is considered representative.

For the crystalline rocks, such as the gneiss and granites, the effective porosity or interconnected porosity can usually be related to the permeability of the formation. Where the crystalline rocks are relatively impermeable with a hydraulic conductivity of 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.

A porosity of 0.5 percent was used in the analysis of the hydraulic tests in the crystalline section of the borehole. This value is considered to be a reasonable estimate of the effective porosity for the matrix, and when discrete fractures or a fracture set is evident, for the fracture porosity.

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:

$$C_w = \frac{d\rho/\rho}{dP} \qquad (4.1\text{-}4)$$

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 Weiach 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 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. System compliance enhances the compressibility within the test interval.

Most of the system compressibility for the Lynes equipment used in the testing of the Weiach 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 Weiach borehole. Although the Lynes system is considered to be more rigid than these systems under normal testing conditions, the high temperatures encountered in the Weiach borehole may affect the system compliance. In our opinion, the system compressibility is probably not more than a factor of 2 or 3 greater than water under normal testing conditions. Under the extreme temperatures encountered at the bottom of the borehole, the system compressibility may approach the factor of 2 to 6 increase, as discussed above.

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 the condition 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 cannot be used in the interpretation of hydraulic testing in the Weiach 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 represents in-situ conditions. To estimate an appropriate fluid density, a pure-water density is assumed and adjusted for in-situ temperature, pressure, and salinity. The formation temperature is selected based on measured temperatures of the borehole fluid as reported in the interval reports. The in-situ pressure is derived from the measured pressure at the end of the shut-in period of the hydraulic testing sequence.

The variation of density of pure-water with changes in temperature and pressure is given in tabular form on Table 4.1 and graphically on Figure 4.2. Figure 4.2 illustrates the nonlinear dependence of density on temperature and pressure. The ranges of temperature and pressure given include the formation temperatures and pressures observed near the Weiach borehole. The density values were derived from the compressibilty data and specific volume/pressure derivatives reported in DORSEY (1968). Compared to other sources of relative density data reported at one atmosphere (WEAST, 1982), the derived densities do not exactly agree for the temperatures listed. However, since the purpose of the density data is to generate correction terms, of primary interest is the difference between the density at a specific temperature and pressure and the density at a reference temperature (usually 20°C) and pressure (1 atmosphere). For one atmosphere and temperatures greater than 20°C, the average relative error of the correction term is less than 2 percent, indicating that the predicted density is accurate to within 0.002 percent.

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 borehole fluid within the shut-in interval. 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 in the test zone as the borehole fluid equilibrates to formation temperature will result in a fluid volume change which will result in a corresponding pressure change. The magnitude of the 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°C to 100°C, the thermal expansion coefficient varies from -3.9E-05 to $7.5E\text{-}04 °C^{-1}$.

In the analysis of the Weiach 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 - 0.3°C) temperature change during the build up period of a hydraulic test. 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 fluid pressure representative of the static pressure around the borehole and into the formation must be estimated as an initial condition for the analysis method. The Horner method of analysis (MATTHEWS and RUSSELL, 1967; EARLOUGHER, 1977; LEE, 1982) was used to determine this pressure for each of the Weiach test intervals documented with suitable data.

The effect that borehole fluid pressure (i.e., annulus pressure) exerts on a test interval prior to testing can be important for test interpretation purposes. Annulus pressure is 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 at the center of the interval is estimated from the P3 transducer during the installation of the test tool, and prior to the start of testing. 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 temporarily), 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 = fluid pressure, $ML^{-1}t^{-2}$;
ρ = fluid density, ML^{-3}.

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

Equivalent freshwater head is useful in the comparison of formation pressures from intervals at the same depth with similar salinity. Equivalent freshwater head is reported at the center of an interval and is therefore based on the formation pressure at the center of the interval. In the context of the hydraulic tests analyzed for the Weiach borehole, the formation pressure is derived from transducer measured pressures. Formation pressure is found by:

$$P_{fc} = P_{ft} + \rho g d_{ct} \qquad (4.1\text{-}8)$$

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};

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

The fluid density term in Equation 4.1-8 is interpreted as the average density between the point of measurement and the interval center. For transducer-monitored tests, the distance between these points is normally short enough to justify a density estimate at the interval center only. The estimate is based on the temperature and pressure at the interval center and the total dissolved solids. To estimate total dissolved solids, it may be necessary to account for the drilling fluid used, swabs taken both before and during testing, and the composition of the in-situ formation fluid.

For the hydraulic testing program being conducted by Nagra, the datum for reporting equivalent freshwater head is sea level. Using the formation pressures at interval center, the application of Equation 4.1-7 specializes to:

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

where H = equivalent freshwater head (m ASL), L;
ρ_f = reference density of fresh water, ML^{-3};
d_c = true vertical depth to the center of the interval, L;
Z = borehole surface elevation (m ASL), L.

The values reported for equivalent freshwater head are based on best estimates of the variables appearing in Equations 4.1-8 to 4.1-9. There can be uncertainties surrounding the best-estimate values due to data interpretation, operator error, undetected equipment failure, and accuracy and resolution specifications of the monitoring devices used. An assessment of the uncertainty of the freshwater head values due primarily to instrument accuracy specifications is presented as part of the results in this report. The uncertain variables and the statistical techniques used are discussed in Section 4.4.

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}.

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 fracturation.

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 an isolated test interval to an applied stress. The K_{erm} is an average for the test interval and it is recognized that higher or lower hydraulic conductivity zones may be contained within the interval in the form of fractured or brecciated areas or separate permeable lithograhic 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:

$$S_s = g\rho\ (C_R + \Theta\ C_W) \qquad (4.1\text{-}12)$$

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). 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 hydrogeologic 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 4.1-12, 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 range of porosity from 10 to 20 percent was assumed for the sedimentary rock and 0.5 percent for the crystalline rock. Compressibility was calculated from literature values of Young's modulus and Poisson's ratio that were considered to be representative of the rock types encountered at Weiach. The specific storage of a test interval can therefore be changed over the range of the porosity and formation compressibility. The approach used to determine the sensitivity of the interpreted hydraulic conductivity of the interval to this uncertainty in specific storage is discussed in Section 4.3.4.

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. The concept assumes that 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 interpretation of the hydraulic tests at the Weiach borehole, 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 dependable and representative for the test interpretations.

4.2 Hydraulic Test Interpretation Methods

4.2.1 Graphical Analysis Method (Horner Analysis of Drill-Stem Tests)

Graphical analysis or "Horner plot" methods are frequently used for evaluation of drill-stem tests (DST) and are well documented in the petroleum engineering literature (e.g., MATTHEWS and RUSSELL, 1967; EARLOUGHER, 1977; LEE, 1982). These methods allow determination of formation pressure and hydraulic conductivity of the tested formation. As will be discussed further in Section 4.3.2, the Horner method of analysis has been used to interpret formation pressure in two tests from the Weiach borehole where the pressure response has not been adversely affected by history or changing temperature within the test interval.

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 Weiach 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. The net effect of the "pressure disturbance" developed during 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 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 annulus pressure is generally taken as the pressure associated with the height of the water column in the borehole from the transducer depth prior to inflating the test tool packers at the test zone.

The annulus pressure may be uncertain if the casing outflow elevation or the borehole fluid density changes 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. Formation inflow into the borehole results in mixing of the formation and borehole fluids causing a change in fluid density and annulus pressure. With the annulus pressure changing with time, the pressure measured prior to the start of testing may not be entirely representative of the annulus pressure during the history period 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.

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 Pstat 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 T, 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, then 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 temperature profile into the formation 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 Borehole/Formation Skin Effects

As a result of borehole drilling, the hydraulic conductivity of the formation at and immediately surrounding the borehole wall may be altered. This borehole/formation skin may have a significant effect on the measured pressure response during hydraulic testing, resulting in incorrect estimates of both formation pressure and hydraulic conductivity. This altered skin zone may have either a higher or lower hydraulic conductivity than the surrounding formation. A higher hydraulic conductivity skin zone may occur in cases where the borehole wall and adjacent formation are degraded to some extent. This degradation may occur within both intergranular porous media and fractures. In contrast, drilling fluids such as mud may invade the formation and build up a filter cake at the borehole wall, thus causing a lower hydraulic conductivity skin zone. In some cases, plugging of the pore spaces and fractures may result from reactions between the drilling fluid and minerals in the formation.

The magnitude of skin effects are difficult to quantify but are related to the radius of influence of the hydraulic pressure response during testing, the thickness of the skin zone and the hydraulic conductivity contrast between the skin zone and the formation.

At Weiach, much of the borehole through the sediments was drilled using high viscosity muds which, at least potentially, can cause a cake on the borehole wall and alter the permeability. Where this potential existed the assumption was often made that a low permeability filter cake existed on the borehole wall between the time of drilling the test interval and reaming the interval prior to hydraulic testing. In this condition it was assumed that the formation was not influenced by the pressures in the borehole until the reaming took place and therefore the pressure history should start at the mid-point of reaming the borehole. Where this assumption was made in interpreting a hydraulic test, a discussion is provided in the test appendix.

In addition to the more obvious drilling induced skin features, it should be noted that other natural skins or boundaries may exist in the vicinity of the borehole such as heterogeneities within the rock or hydraulic boundaries located adjacent to the borehole. These features may also affect the pressure response and are equally as difficult to assess.

The presence and characteristics (i.e., thickness and hydraulic conductivity) of a skin zone surrounding a borehole are very difficult to establish. While their existence and effects must not be overlooked during interpretation of hydraulic tests, one must be careful not to include unsubstantiated skin effects in a simulation for the sole purpose of obtaining an improved fit to the measured pressure response. For these reasons, the use of skin effects in the Weiach borehole was limited to developing the conceptual model of the borehole history for several of the test zones. Skin effects were not included in the hydrogeologic model of the test zone in any case.

4.2.2.5 Non-Homogeneous Medium

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

Heterogeneities in the formation being tested may include fault or shear zones, lithologic changes or changes in the fracture frequency and distribution. 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.

4.2.2.6 Evaluating Formation 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 from about 5 percent to as much as 30 percent in the sedimentary rocks and from 0.1 percent to several percent in the crystalline rocks. It is reasonable to expect that the formation compressibility could vary by several orders of magnitude and still fall within a reasonable range for the types of rock at Weiach considering the uncertainty in the degree of fracturing and type of structure in the rock. One approach to determine the effect is to simulate the measured pressure-time data using a range of specific storage that brackets the expected variability in porosity and formation compressibility. The result is a range of hydraulic conductivities corresponding to a range of specific storage. The hydraulic conductivity corresponding to a value of storage that most reasonably describes the formation 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 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 in a test. 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 Weiach borehole. In general, the interpretation approach consists of the following steps: estimating the borehole pressure history for the test zone during the drilling phase and between drilling and the start of testing; determining the borehole temperature condition; deriving the physical properties of the formation, formation fluid and test interval; and then, by selecting a range of values for hydraulic conductivity and formation pressure, generating, using GTFM, a series of simulated pressure curves for each hydraulic test. The hydrogeologic properties are adjusted until a best-fit simulation is obtained. The hydrogeologic properties used in the simulations are intended 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. Included in the discussion is the determination of the borehole pressure history and the temperature change within the test interval, the selection of appropriate input parameters and estimation of the hydrogeologic properties. The interval selected as an example is test 926.2S which was conducted in the Weiach borehole at an apparent depth of 901.40 m to 950.90 m on 16 and 17 April, 1983. This test sequence is appropriate because it represents a complex interpretation involving borehole history effects, a temperature change during testing, hydraulic conductivity determination and a specific storage sensitivity study. The formation pressure for this test was assumed by extrapolating from a nearby interval, as will be discussed below. Since the static formation pressures for the Weiach borehole were generated using the Horner analysis method, the reader is referred to Section 4.2.1 for references discussing this method.

The specifications and characteristics of the formation, 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 vertical depth) and field hydraulic test reports (i.e., equipment configuration, depth interval, borehole temperature and testing sequences). The testing sequence for 926.2S is illustrated in Figure 4.5 and consists of a static pressure shut-in period (PSTA), followed by a slug withdrawal test (Sw01), and finally a pulse withdrawal test (Pw01).

4.3.1 Initial Conditions

4.3.1.1 Borehole Pressure History

In order to develop an accurate pre-test pressure history in the borehole adjacent to the test interval for the test interpretations in the Weiach borehole, an attempt was made to quantify the drilling related pressure history on the test interval using the methods discussed below. The events affecting the pressure history were the fluid level in the borehole and the pressure exerted above annulus pressure caused by fluid flow in the borehole during drilling, reaming and circulation. The fluid level in the borehole was determined from information in the Nagra documents, correspondence with Nagra, and pressure readings taken in the annulus. The drilling overpressure on the interval is the pressure required to overcome the frictional losses to move the drilling fluid up the annulus of the borehole. The drilling overpressure was determined for the P2 transducer depth by estimating resistance to flow of drilling fluid moving up the borehole. This estimation is based on principles of fluid dynamics as discussed in GATLIN (1960).

The hydrostatic pressure in the borehole is a function of the length of the fluid column and the fluid density as,

$$P = \rho g h \qquad (4.3\text{-}1)$$

where ρ = density of the borehole fluid, ML^{-3};

g = gravitational acceleration, Lt^{-2};

h = height of the fluid column, L.

The fluid level in the borehole can be changed whenever fluid or the drill string or tubing is added or removed from the borehole. The pressure change is dependent on the head of fluid added to or removed from the borehole. The pressure change is therefore given by:

$$\Delta P_h = \rho g \Delta h \tag{4.3-2}$$

where Δh = $\Delta V/A$;
ΔV = volume change in the borehole, L^3;
A = cross-sectional area of the borehole, L^2.

In the condition where the head is adjusted in the borehole by adding or removing tubing, test tools etc., the volume change (ΔV) is given by:

$$\Delta V = \frac{\pi}{4} (d_o{}^2 - d_i{}^2)L \tag{4.3-3}$$

where d_o = outside diameter of tubular good, L;
d_i = inside diameter of tubular good, L;
L = length of tubing string or other hardware, L.

The fluid inside the tubular goods must be added to the volume change if it is removed also.

The frictional pressure loss is based on the drilling fluid parameters, the mud pump's flow rate, the dimensions of the drill string, and the borehole dimensions and configuration. The equation used to determine the frictional pressure loss is dependent on whether the fluid in the borehole is Newtonian (e.g., water) or plastic (e.g., drilling mud) and whether the flow in the annulus is laminar or turbulent. A separate equation for laminar plastic flow is required to calculate the minimum pressure needed to overcome the yield point (pressure required to initiate flow) of the plastic fluid. The equation to determine the pressure required to overcome the frictional losses for laminar flow of a Newtonian fluid is:

$$\Delta P = \frac{\mu h \bar{v}}{d^2} \tag{4.3-4}$$

and the equation for laminar flow of plastic fluids is:

$$\Delta P = \frac{h}{d} \left(Y_b + \frac{\mu_p \bar{v}}{d}\right) \tag{4.3-5}$$

where ΔP = pressure required to overcome frictional losses, $ML^{-1}t^{-2}$;

μ = fluid viscosity, $ML^{-1}t^{-1}$;

h = length of interval of fluid flow, L;

$\bar{v}$ = average fluid velocity, Lt^{-1};

d = hydraulic equivalent diameter of the annulus, L;

Y_b = yield point of drilling mud, $ML^{-1}t^{-2}$;

μ_p = plastic viscosity of drilling mud, $ML^{-1}t^{-1}$.

The equation for turbulent flow is:

$$\Delta P = \frac{f \rho h \bar{v}^2}{d} \tag{4.3-6}$$

where f = Fanning friction factor.

The hydraulic equivalent diameter of the annulus (d) and the average fluid velocity in the annulus ($\bar{v}$) are defined by:

$$d = d_o - d_i \tag{4.3-7}$$

$$\bar{v} = \frac{Q}{A_a} \tag{4.3-8}$$

where Q = mud pump flow rate, L^3t^{-1};

A_a = cross-sectional area of annulus, L^2.

The flow is determined to be laminar or turbulent by calculating its Reynold's number. The flow in the annulus is considered laminar for a Reynold's number less than 2000 and turbulent for a Reynold's number greater than or equal to 2000. The Reynold's number for Newtonian fluid is found by:

$$Re = \frac{\rho d \bar{v}}{\mu} \tag{4.3-9}$$

The Reynold's number for a plastic fluid is defined by:

$$Re = \frac{3.2 \rho d \bar{v}}{\mu_p} \tag{4.3-10}$$

The Reynold's number is required to determine the Fanning friction factor to be used in the frictional pressure loss equation for turbulent flow. The friction factors used to determine the drilling overpressure were taken from a graph of friction factor vs Reynold's number in GATLIN (1960).

The drilling history pressure was calculated for the different borehole configurations which were present while drilling the Weiach borehole and summed to get a total friction pressure loss for the fluid flow in the annulus. In general, the borehole configurations requiring separate calculations were: drilling pipe inside casing; drilling pipe in open borehole, and; drill collars and core barrel in open borehole. In addition, the calculation of frictional pressure loss was broken down to account for segments of the open borehole with differing diameters. Drilling overpressures had to be calculated as the drill string moved down the borehole, changing the borehole configuration, and whenever the mud pump rate or drilling fluid properties were changed. The drilling overpressures determined for the Weiach borehole were negligible (<50 kPa) in the 444.5 mm (17-1/2 in.), 311.2 mm (12-1/4 in.), and 215.9 mm (8-1/2 in.) borehole. The overpressures while drilling the 158.8 mm

(6-1/4 in.) and 152.4 mm (6 in.) borehole ranged from 100 kPa to over 1000 kPa.

The pressure on the test interval was increased or reduced each time the drill string was tripped in or pulled from the borehole during the drilling period. The pressure change on the interval from tripping in or removing the drill string was generally more significant than the pressure increase from drilling but these events were much shorter in duration. The pressure increases from drilling were averaged with the pressure changes from tripping the drill string to obtain a representative pressure for the drilling period. To reproduce the average situation on the interval, the start of the pre-test history was set as the mid-point of interval drilling. Several periods during the pre-test may be averaged for the pre-test history period depending on the pre-history length and complexity.

The duration and magnitude of the pressure history which results from this type of analysis is input to GTFM in order to define the pressure disturbance surrounding the borehole (i.e., the pressure transient) prior to the start of testing.

For test 926.2S, the testing interval was drilled over 6 days from 10 April, 1983 to 16 April, 1983. The drilling fluid was a bentonite mud of specific gravity 1.24. The pressure history on the interval from the mid-point of drilling until the start of testing consisted of drilling and circulation pressures for 45 hours and an open borehole period at annulus pressure for 15 hours. The average pressure during drilling was estimated to be 10847 kPa. The averaging of pressures was done to accommodate the pressure fluctuation during the periods of drilling and movement of the drilling tools in and out of the borehole. During drilling, the pressure at the test interval was estimated to be 10890 kPa and with all drilling tools out of the borehole, 10558 kPa. The drilling tools were removed from the hole five times during the completion of the lower half of the test interval. Since the time the test interval was exposed to the lower pressures associated with tripping in and out of hole was short relative to the period of drilling, the average pressure chosen to model the drilling period pressures is close to the full drilling pressure. The interval pre-test pressure history is shown in Figure 4.6.

4.3.1.2 Temperature Changes During Testing

The 926.2S testing sequence experienced a significant temperature change of 4.5°C across the testing sequence from the start of the static shut-in period to the end of pulse withdrawal testing. The temperature trend during testing is shown in Figure 4.7 as an averaged temperature response for the test interval from the T1, T2, and T3 sensors in the borehole. Briefly, the temperature change likely results from the drilling of the test interval with fluid at a temperature of about 25°C when the expected temperature near the center of the test interval is about 51°C, as determined from the temperature-depth approximation of Figure 7.5. As the cooler fluid was circulated in the borehole, the formation adjacent to the borehole cooled down. When the circulation stopped in preparation for the start of testing, the fluid temperature in the borehole increased as the formation dissipated the temperature disturbance. Since the system volume was small, the temperature change appears to occur during the interval shut-in period and since the hydraulic conductivity of the interval was estimated to be low from test Sw01, the effect of the fluid expansion within the test interval resulting from the fluid temperature increase was significant. In order to incorporate the thermal effect into the test interpretation, a curve was fit to the general trend of the averaged temperature data, as shown in Figure 4.7. The fluid in the test interval is described with a thermal expansion coefficient taken from Figure 4.4 to describe the volume change of the fluid on heating. The model of fluid thermal expansion in the shut-in zone is used to compensate the transient pressure response. This prevents an overestimate of the formation permeability by misinterpreting the rapid response of, for example, test Pw01 as due to high hydraulic conductivity.

Several problems related to interpreting the measured temperature data have been encountered and should be mentioned here. Since a thermal effect can have a significant influence on the interpreted hydraulic conductivity for a test interval, it is important to be able to distinguish anomalous temperatures from the temperature representative of the test interval. Much of the uncertainty in relating the measured temperatures to the test interval temperature lies in the fact that the temperature transducers are located in the sensor carrier, approximately 4.7 m above the top of the test interval. The temperature sensors are positioned to measure the operating temperature of the pressure sensors and therefore will respond to the local fluid temperatures around the sensor carrier and will not necessarily reflect the test interval temperature. Several cases have been observed in Weiach where the measured temperature response reflects the movement of fluid past the sensor carrier during pressurization for a pulse injection test. In this instance, the fluid temperature is usually observed to change very rapidly during the early period of testing with little or no temperature increase or decrease during the remainder of the pulse test. This behavior is usually dismissed as not reflecting the test zone. Usually, interval temperatures will show an increasing or decreasing trend across the testing period and this trend has to be evaluated from each of the three transducers in the sensor carrier.

One approach that can be taken to evaluate the representativeness of a thermal trend in the test interval is to compare the simulated pressure response with thermal effects against the measured pressure response. If the shape of the simulated pressure curve differs significantly from the measured pressure curve and the difference does not appear to be related to hydrogeologic parameters, then the temperature record may not be representative.

4.3.1.3 Parameter Selection

The list of parameters chosen for the analysis of test 926.2S are given in Table 4.3. The most representative formation compressibility was estimated to be 3.0E-10 Pa^{-1}. This value is based on a literature review, which included TOULOUKIAN et al. (1981), of values of Young's modulus and Poisson's ratio for a mixture of anhydrite and dolomite. The formation compressibility (and corresponding specific storage) reported in the table was used in calculating the most reasonable fit to the measured pressure data.

The effective formation porosity was estimated to be 10 percent based on a literature review, which included TOULOUKIAN et al. (1981), of reported values.

The fluid compressibility has been estimated by assuming a pure-water compressibility and correcting for temperature and pressure at the test interval (see Figure 4.1). In this case, the average fluid temperature in the interval during testing of about 40°C and average pressure of about 8644 kPa (86.4 bar) (i.e., approximate formation pressure) results in a fluid compressibility of 4.34E-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 994 kgm^{-3} and 4.1E-04$°C^{-1}$, respectively.

The specific storage can be calculated using the formation compressibility, porosity, fluid compressibility and fluid density to yield a value of 3.3E-06 m^{-1}.

The test interval length is the distance from the bottom of the single packer to the bottom of the borehole. The borehole diameter at the time of testing was taken as the drilled borehole diameter.

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 analyzed in the sequence in which they were conducted. This is necessary as the pressure disturbance around the borehole is modified by each preceding test.

The testing sequence at 926.2S consists of a static shut-in period followed by a slug withdrawal test and then a pulse withdrawal test, as shown in Figure 4.5. The static shut-in test is designed to permit the test interval to recover to a static formation pressure following a period of disturbance such as a borehole history period. An initial shut-in squeeze of about 88 kPa occurred when closing the shut-in tool for the static recovery test. The simulated recovery is started at the maximum pressure obtained following the packer squeeze, which in this instance is 9003 kPa. The temperature of the fluid in the test interval was allowed to change during the pressure recovery. During the static recovery test, a 100 m swab was pulled from the tubing string with the shut-in valve closed, in preparation for test Sw01. Test Sw01 was simulated by specifying the starting pressure as that measured at P2 when the shut-in valve was opened following the static shut-in period. For this simulation, the test interval is in hydraulic connection with the tubing string fluid. The starting pressure is 8003 kPa. On completion of the slug withdrawal test, the shut-in valve of the HTT was closed to start the pulse withdrawal test. The simulation of the pulse withdrawal test was initiated by specifying the starting pressure at shut-in. A shut-in squeeze of about 36 kPa preceded test Pw01 and this squeeze was incorporated into the simulated test response by incrementing the starting pressure by this amount. The starting pressure for this test was therefore 8040 kPa. The test interval pressure was allowed to vary over the duration of the pulse withdrawal test and the thermal effect was superimposed on the pressure response.

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 and equipment compliance. In this test sequence, compliance of the packers as the shut-in valve was closed induced a measurable squeeze within the test interval. 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.

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 to model a test. The initial estimate of formation pressure has been determined using five different approaches in Weiach. For tests completed in lower permeability zones where recovery to static was not obtained and where the history period was significant, the fluid pressure in the formation was assumed equal to either the mud-filled annulus pressure or the recovery pressure from one of the hydraulic tests. This approach assumes that the pressure transient around the borehole at the start of testing, which results from the history pressure period, will dominate during the pressure recovery, an assumption which generally is valid when the pressure transient extends into the formation beyond the outer influence of the hydraulic test. Tests 550.0D, 859.1SI, 985.3D, 1240.1D, and 1456.9D were interpreted in this manner. Strictly speaking, since these pressures represent a local condition around the borehole during testing and not a static formation pressure, then they should be referred to as reference pressures. Another approach to determining formation pressure is useful when the formation is of relatively high permeability and the history period is short and without influence on the testing sequence. Under these conditions, the formation pressure can be taken as the pressure which provides the most accurate simulation of the pressure recovery curve. This method is referred to as pressure calibration. This approach provides the most accurate estimate of an undisturbed formation pressure using GTFM. This approach was attempted in several of the tests (e.g., 728.0D, 1369.4D, 1603.1D, 1965.1D, 2063.3D, and 2458.2H), however, the simulated pressure recovery curves, in each of these cases, were found to be influenced by a residual pressure transient even though it was thought to have dissipated. Since the choice of pressures used in developing the pressure transient resulting from the pressure history is very uncertain, a pressure derived by calibration under the influence of a pressure transient would be uncertain and could not be used as a static formation pressure. If the testing conditions are such that a DST pressure recovery is not influenced by pressure history then a Horner-type graphical analysis of the pressure data can be used to determine static formation pressure. Horner analyses were used on seven test intervals with tests 984.2S and 1117.5D providing confident static formation pressures. Other tests were influenced by a pressure transient around the borehole during the recovery of the particular test sequence that was used for the Horner analysis.

It is possible to evaluate the influence of a pressure transient around a borehole on a test response by plotting the pressure with distance profile into the formation at the end of the test. Since the outer limit of testing is known approximately (see GRISAK et al., 1985; pp. 152-160), then by examining the pressure profile, it can be determined whether a pressure disturbance exists in the tested region. This technique has been used for the Weiach interpretations to confirm a static formation pressure and has resulted in the rejection of many of the attempted calibrated formation pressures.

When an interval is located adjacent to or between intervals at which the static formation pressure has been accurately determined, then the formation pressure for this zone has been extrapolated or interpolated from the known values. The static pressures derived from the long-term monitoring observation tests were used in this manner to determine the initial estimate of formation pressure for test 987.9D.

These static pressures were extrapolated from the center of their test zone to the P2 depth of the short term test.

The average hydraulic conductivity of the test intervals was determined using two different approaches. These are the Horner analytical/graphical approach and the GTFM numerical method. The Horner method does not require an initial estimate of hydraulic conductivity, and K can be solved for directly. For the GTFM method it is often necessary to choose three or four values of hydraulic conductivity which are separated by an order of magnitude in order to provide a wide enough range for the simulated responses to bound the measured pressure response. The measured rate of the hydraulic test 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 rule is combined with an understanding of recovery rates for slug and pulse tests at various formation hydraulic conductivities to determine an initial estimate. Also, the Horner method may be used to provide an initial estimate of hydraulic conductivity for a test zone in which GTFM is to be used for the interpretation.

When required, the initial estimate of the formation specific storage is taken as the base case value calculated from the fluid compressibility, average porosity, and average formation compressibility. During the initial simulation of the pressure-time data 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 using GTFM, 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 bound the data. In this case the hydraulic conductivity is a variable parameter and all other parameters (i.e., formation pressure, specific storage, etc.) are constant. The simulated pressure curves can be compared to the measured field data to determine which curve provides a match and if the final pressures of the simulated curves are similar to the final pressures of the field data. Based on this initial estimate of hydraulic conductivity, three simulations are then run, each representing a hydraulic conductivity half an order of magnitude different from the previous simulation to closely bound the measured pressures. 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.

Assuming that the borehole history, thermal effect, and formation pressure are accurate, the analyst can vary the hydraulic conductivity and specific storage assigned to the test zone in order to improve the fit of the simulated pressures. 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

For each of the interpreted test sequences, the sensitivity of the hydraulic conductivity to the natural variability in specific storage of the formation was evaluated. The iterative approach to determining a representative 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 probable heterogeneity of the formation adjacent to the borehole and the range of compressibility calculated from stress and strain data in the literature for a particular rock type similar to that of the test zone, it is reasonable to assume that specific storage could vary by as much as one order of magnitude above and below the base case value. 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}. The effect of varying specific storage for hydraulic conductivity less than 1.0E-10 ms^{-1} can be significant with uncertainty in hydraulic conductivity up to one order of magnitude depending on the choice of the specific storage for the interval.

4.4 Propagation of Instrumentation Uncertainties in the Determination of Equivalent Freshwater Head

The two primary formation properties obtained from the borehole tests described above are formation pressure and hydraulic conductivity. Equivalent freshwater head can be computed by substituting formation pressure and appropriate measured or estimated values into Equations 4.1-8 and 4.1-9. For the most part these measured or estimated values have a quantifiable degree of uncertainty which can be used to generate corresponding uncertainty surrounding reported head values. Determination of hydraulic conductivity involves more complex data fitting with use of tools such as GTFM. The uncertainties involved in this data-fitting interpretation process are not as readily quantified and are beyond the scope of the current effort. Thus, this section only addresses the uncertainty in freshwater head calculations.

Typically, equivalent freshwater head is determined from Equation 4.1.9 by substituting best-estimate values for the input variables appearing on the right hand side of the equation. These best-estimates are based either directly or indirectly on measured quantities. The objective of the uncertainty analysis presented in this report is to quantify the uncertainty surrounding the reported head values arising from the measurement errors that could be present in the best estimates.

Accuracy and resolution specifications for measuring instruments are used whenever possible to determine uncertainty ranges for the input variables. Input variables are then assigned probability distributions that cover their uncertainty range. Section 4.4.1 describes the assumptions made for each input variable.

The approach taken to propagate input variable uncertainties to uncertainty in freshwater head involves statistical sampling and multiple evaluations of Equations 4.1-8 and 4.1-9. The statistical properties of the resulting distribution of head values can be examined and those input variables contributing most to the uncertainty in head can be identified. The procedures used are discussed in Section 4.4.2 and the results are presented in Section 7.

4.4.1 Independent Variables

This section quantifies the uncertainties that can be attributed to measurement errors for the variables of Equations 4.1-8 and 4.1-9. The order of the discussion in terms of variable symbols is: d_{ct}, P_{atm}, ρ_f, Z, d_c, g, P_{ft}, and ρ. Pressure at formation center, P_{fc}, is not on the list since Equation 4.1-8 can be substituted into Equation 4.1-9 thereby eliminating P_{fc}. In practice, however, Equation 4.1--8 is evaluated separately and pressure at formation center is reported as the second output variable (after equivalent freshwater head). Further, as will be seen, gravity is treated as a function of surface elevation, depth, and average rock density from surface to depth. Thus, gravity is also reported as an output variable and rock density, ρ_r, is treated as an input variable.

The first variable examined is d_{ct}, the true vertical distance between the transducer and the center of the interval. Variable d_{ct} is found by subtracting the apparent vertical depth to the transducer from the apparent vertical depth to the interval center. Since this is a relatively short distance, any cumulative deviation from vertical at one depth should be approximately the same as at the other. Thus, by subtraction, deviation errors will tend to cancel. Further, since tubing stretch can be accurately predicted (BAKER, 1985) and is accounted for in reported apparent depths, that potential source of uncertainty need not be addressed. Therefore, d_{ct} is considered a known, fixed value for the uncertainty analysis.

The second variable is P_{atm}, the barometric pressure. For the transducer monitored tests, formation pressure is normally calibrated during shut-in conditions. Under those conditions, changes in atmospheric pressure have little affect on downhole pressure measurements. For this reason, the average fixed value reported for each test is not varied in the uncertainty analysis.

The third variable is ρ_f, a reference density for fresh water. Since the only purpose of ρ_f is to establish a convention for reporting head values, any reasonable value can be used. EARLOUGHER (1977) reports 999.014 kgm^{-3} at

15.56°C. Other distilled water densities that could be used are 998.23 kgm^{-3} (at "standard conditions", one atmosphere pressure and 20°C), 999.87 kgm^{-3} (at standard temperature and pressure, one atmosphere and 0°C), or 1000 kgm^{-3} (at one atmosphere and 3.98°C) (WEAST, 1982). This report adopts 1000 kgm^{-3} primarily to be consistent with other reports describing interval hydraulic testing and long-term monitoring in the Riniken, Boettstein, Weiach, and Leuggern boreholes.

The fourth variable is Z, the height above sea level of the top of the borehole. Surface elevations are assumed to be accurate to ± 10 cm (± 0.10 m). Thus, for the Weiach borehole, the true surface elevation is in the range 368.56 m to 368.76 m. In the absence of any detailed data on the behavior of the measurement error, these extremes are considered to be the 0.1 and 99.9 percentiles of a normal distribution. The percentiles are labeled on Figure 4.8 along with the mean, Z, and one standard deviation.

The fifth variable is d_c, the true vertical depth from the borehole surface to the interval center. True vertical depth is derived from apparent vertical depth using a gyro or similar survey as described in Section 2. Uncertainties in true depth can arise from at least three sources:

- uncertainties in the apparent depth,
- the measurement gradation with depth in the borehole and resulting interpolation of deviation angles to predict true depth, and
- instrumentation accuracy.

The apparent depth is based on cumulative tubing length adjusted for tubing stretch. As stated above for variable d_{ct}, the uncertainty analysis assumes that insignificant errors are introduced in the prediction of tubing stretch.

Thus, uncertainty in apparent depth is based on measurement error for individual tubes and inconsistent joining of the tubes. As indicated by the Weiach field reports, tubing lengths are measured to the nearest centimeter, suggesting a ± 0.5 cm rounding error for each tube. Error in total tubing length can also be introduced at the joints. Although tubing is joined at a specified torque, the connections are not necessarily subject to the same threading overlap. Reducing the measurement error by a factor of two (to account for the probable error cancellation caused by summing rounded numbers), and assuming a ± 0.1 cm per tube threading error, gives a total error in apparent depth of ± 0.35 cm per tubing length. The error range, 0.7 cm/tube (0.00077 $m \cdot m^{-1}$ for an average 30-ft tube), is folded into the general error expression presented below.

The summary report for apparent versus true vertical depth for the Weiach borehole (WEBER et al., 1986) is graded with 50 m intervals of apparent depth. Deviations between data points can contribute to uncertainty in the interpolations used to derive true vertical depth. For example, if the borehole is assumed to follow a straight line between two data points, the derived true vertical depth is smaller than the depth derived assuming the hole follows a true vertical direction for some distance then deviates. The extent of uncertainty can be as large as 0.5 cm/data interval or 0.0001 $m \cdot m^{-1}$. Accuracy and resolution of the instrument used to measure angular deviations also propagate through the interpolation scheme. Deviation logging was done using both a HDT (near surface) and a SHDT (deeper regions). Since most of the deviation occurs at deeper regions, the overall instrumentation accuracy is assumed to be that of the SHDT. The reported accuracy is ± 0.2 degrees. Applying this uncertainty band to a total effective straight-line deviation leads to 0.56 m uncertainty at 2450 m depth or 0.00023 $m \cdot m^{-1}$. If all three error ratios are added and applied linearly with depth, the error multiple used for the Weiach borehole is 0.0011 $m \cdot m^{-1}$. At any depth, the range of uncertainty is applied symmetrically about the depth as shown in Figure 4.9, where 0.00055 is one half the multiplier 0.0011. The depth variable is assigned a uniform probability distribution so that values at the extremes of the range are sampled with the same frequency as those near the midpoint of the range.

The sixth variable is g, the acceleration due to gravity. It is generally considered constant at a given latitude. However, it varies with depth and is affected by earth tides and nearby large topographical features. The latitude at the Weiach borehole is 268,620 m north of 45 degrees, which is approximately 47.42 degrees. Using the International Gravity Standardization Net 1971, IGSN 71, (TSUBOI, 1983), the equation for g (cms^{-2}) at any latitude ϕ (degrees) is

$$g_\phi = 978.03185\ (1 + 5.3024E\text{-}03 \sin^2\phi - 5.9E\text{-}06 \sin^2 2\phi) \tag{4.4-1}$$

Thus, at $\phi = 47.42$ degrees, $g_\phi = 980.838$ cms^{-2} at sea level. The equation for g_ϕ is derived from an ellipsoidal fit of worldwide gravity data that is subject to refinement with time. WOOLLARD (1979) states that IGSN 71 is in general accurate to within ± 0.05 mgal (± 0.00005 cms^{-2}), which does not affect the significance of g_ϕ calculated above. Below land surface two corrections to g due to depth are considered. The first is a free-air correction and the second is the simple Bouguer reduction. In gravitational units (1 g.u. = 0.0001 cms^{-2}) these corrections are given by (PARASNIS, 1972)

$$\Delta g = 3.086\ (d_c - Z) - 0.4191\ d_c\ \rho_r \tag{4.4-2}$$

where Δg = total elevation correction, g.u.;

ρ_r = average rock density from surface to d_c, gcm^{--3}.

Earth tides can affect g by at most 3 g.u. and topographical features may reduce g by a few tens of g.u. However, for the depths examined at the Weiach borehole, the correction term in Equation 4.4-2 is in thousands of g.u., implying that the effects of earth tides and topography can be ignored for this application. Therefore, the combined expression used for g (cms^{-2}) is

$$g = g_\phi + \Delta g/10^4 \qquad (4.4\text{-}3)$$

In this analysis Δg is uncertain since Z and d_c are uncertain as described above. Furthermore, the rock density factor, ρ_r, is a length-averaged density subject to uncertainty. Minimum and maximum densities for each rock type (TOULOUKIAN et al., 1981) encountered from surface to depth are thickness-weighted to determine the total average rock density range. Thus, the range varies from test interval to test interval and only a generic representation for ρ_r can be shown (Figure 4.10). The minimum and maximum values found are treated as the 0.1 and 99.9 percentiles of a normal distribution.

The seventh variable is P_{ft}, the fluid pressure measured at the P2 transducer. The accuracy and resolution of the transducer can vary from test to test depending on the transducer model and tool used. For all tests for which uncertainty is examined a HTT was used. Since transducer model numbers and specifications are not fully reported, obtaining the exact transducer specifications for each test is difficult. For this reason a generic set of specifications have been adopted for pressure transducers. Typical of such tools is an operating range of 0 to 6000 psi (0 to 41370 kPa), having full scale accuracy and resolution of ± 3.0 psi (20.7 kPa) and ± 0.3 psi (± 2.07 kPa), respectively. Assuming that the accuracy bounds do not account for resolution error, the accuracy and resolution bounds are additive, so that any measured value may be in error by ± 22.8 kPa. Errors in the pressure readings can also be caused by transducer drift. However, unless there is evidence to the contrary, such as large differences in the before and after test pressure readings, it is assumed that drift is included in the scale accuracy uncertainty. For the tests analyzed at the Weiach borehole, observed transducer drift did not appear abnormal. The distribution on P_{ft} is therefore based only on transducer performance specifications. It is assumed to be a normal distribution with the 0.1 and 99.9 percentiles defined as P_2 - 22.8 kPa and P_2 + 22.8 kPa, respectively, where P_2 is the reported pressure at transducer P2. This is equivalent to a normal distribution with a mean P_2 and a standard deviation of 7.38 kPa as shown on Figure 4.11.

The eighth variable is ρ, the fluid density within the borehole, rather than the in-situ fluid density discussed in Section 4.1.4. For the purposes of Equation 4.1-8, it should be the fluid density between the point of pressure measurement and the interval center. For the two tests analyzed, the point of pressure measurement is the location of the transducer at P2. Estimation of the densities require information regarding temperature, pressure, and salinity of the resident fluid. The following list summarizes the mean densities used and the remainder of this section discusses the justification for each value:

Test Designation	Density kgm^{-3}
984.2S	1003.2
1117.5D	1015.5

Density at a given temperature, pressure, and salinity is determined by adding a correction term to the density measured at known temperature and pressure. The laboratory or on-site measurement is used to account for density due to dissolved solids. The correction term accounts for the affect of in-situ temperature and pressure on density and is developed using the fresh water densities of Table 4.1, as described in Section 4.1.4. If temperature and pressure at all depths are known, then the density correction term can be treated as a function of depth. Since the temperature of the actual fluid in a test interval is not typically measured, this analysis uses average temperature and pressure relationships with depth. Temperature is approximated using a gradient of $0.0468°Cm^{-1}$ and a surface temperature of 7.8°C. This relationship is a least-squares fit of temperature data obtained from a salinity log run on 29 March, 1985 which closely parallels the temperature log run on 24 January, 1985. The maximum differences between observed temperatures and those produced by the data-fit are used to define the ± 4°C uncertainty band for temperatures at the Weiach borehole. Fitting pressure data as a linear function of depth yields a surface pressure of 3.7 atm and a gradient of 0.097 atm m^{-1}. The differences between predicted and observed pressures can be as large as ± 6 atm. Since the prediction error for ± 4°C (about ± 2 kgm^{-3}) is nearly eight times the prediction error for ± 6 atm (about 0.26 kgm^{-3}), pressure effects are ignored in computing uncertainty bounds for density. However, pressure effects are accounted for in computing the mean density, as shown below.

For any depth, d, the temperature at d, T_d (°C), and the pressure at d, P_d (atm), are first estimated using the equations:

$$T_d = 0.0468d + 7.8 \qquad (4.4\text{-}4)$$

$$P_d = 0.097d + 3.7 \qquad (4.4\text{-}5)$$

Table 4.1 is then interpolated linearly to approximate the density of fresh water, ρ_{fd}, at T_d and P_d. Finally, if the density of a fluid sample taken at depth d, ρ_{cd}, has been measured at 20°C and one atmosphere, then the fluid density at d, ρ_d, is determined by:

$$\rho_d = \rho_{cd} - (998.00 - \rho_{fd}) \qquad (4.4\text{-}6)$$

Here, as indicated in Table 4.1, the density of fresh water at 20°C and one atmosphere is taken to be 998 kgm^{-3}. Uncertainty is folded into the density at d by interpolating ρ_{fd} at $T_d \pm 4$°C and P_d from Table 4.1 to determine the correction term extremes.

The procedure described in the preceding paragraph is used to calculate fluid density at a point. For the two transducer monitored tests analyzed here, the point of interest is taken to be the true vertical depth to interval center. Since the distance between the interval center and transducer is relatively short (generally less than 20 m), the density at the transducer is considered equal to that at the interval center. This may not be the case for four intervals at Weiach, where the distance between the interval center and the transducers is greater than 100 m (2272.7S to 2350.5S).

The remaining uncertainty on density is the variation of concentration of total dissolved solids in the fluid during the test. For both tests analyzed, the borehole fluids are assumed to be primarily formation fluids. Formation fluid densities are taken from PEARSON and LOLCAMA (1987). The available information does not indicate the type or precision of the hydrometer used to measure the densities reported in PEARSON and LOLCAMA (1987). To ensure that density uncertainties are addressed, accuracy specifications for a multi-purpose hydrometer (rather than a precision hydrometer) were adopted. Formation densities for fluid samples taken at the Weiach borehole are therefore assumed to be accurate to $\pm$ 1.5 kgm^{-3}.

The top part of the interval for test 984.2S was drilled with mud. Drilling was stopped and deionized water was circulated for 2.6 days. The remaining portion was drilled with deionized water. In the 17-hour period between the end of drilling and the beginning of testing, formation fluid from the high hydraulic conductivity Buntsandstein ($\simeq 10^{-6}$ ms^{-1}) is assumed to replace the deionized fluid in the test interval. A formation fluid density of 1010.6 kgm^{-3} (PEARSON and LOLCAMA, 1987) is reduced by 7.4 kgm^{-3} to account for the combined effects of temperature and pressure on density (see Figure 4.2 and Table 4.1). The interval for test 1117.5D was drilled with mud and the borehole was then left open for about one day. Applying the observed flow rate during the compliance period (1.2 L min^{-1}) to a 24-hour period shows an inflow of 1.7 m^3 from the formation. This is sufficient to displace the test interval volume (0.94 m^3) by almost twice. Thus, it is assumed that the test interval fluid is formation fluid for test 1117.5D. A formation fluid density of 1025.3 kgm^{-3} (PEARSON and LOLCAMA, 1987) is reduced by 9.8 kgm^{-3} to account for the combined effects of temperature and pressure on density (see Figure 4.2 and Table 4.1).

The uncertainty around the densities reported above is assumed to be a function of hydrometer specifications ($\pm$ 1.5 kgm^{-3}) and temperature uncertainty ($\pm$ 4°C). Minimum values are calculated by subtracting 1.5 kgm^{-3} and the correction for the highest temperature from the value reported at 20°C. Maximum values are calculated by adding 1.5 kgm^{-3} and subtracting the smallest possible temperature correction, which arises from the lowest temperature. The minimum, ρ_{min}, and maximum, ρ_{max}, values are used as the endpoints of a uniform distribution as shown in Figure 4.12.

4.4.2 Statistical Approach

The five variables of the previous section that are considered uncertain are surface elevation, true vertical depth to interval center, average rock density to that depth, pressure at the P2 transducer, and fluid density. Each variable has an associated probability distribution. All variables are sampled n times prior to model execution (i.e., evaluation of Equations 4.1-8 and 4.1-9) using Latin Hypercube Sampling (LHS) (IMAN and SHORTENCARIER, 1984). Here, n is the user-specified number of trials and is set to 100 for the analysis. Thus, on every trial a sampled value for each of the five variables is used either directly or indirectly to solve Equations 4.1-8 and 4.1-9.

LHS was introduced into the literature in 1979 (MCKAY et al., 1979). The motivation for the development of LHS was to improve sampling efficiency over the widely used Monte Carlo approach. In general, LHS produces smaller mean-square-errors of estimators than does Monte Carlo for small sample sizes. Thus, the number of trials can be smaller when using LHS. The mechanics of LHS are as follows: Each variable has its probability distribution partitioned into n intervals of equal area. A value is sampled randomly within each interval with respect to the density function in the interval. These two steps help ensure that the entire range of uncertainty is covered even for smaller sample sizes. The n sampled values are then mixed in a prescribed manner and are entered as a column in the sample matrix. Thus for trial k, the 5 entries in the k^{th} row of this array are used as the values for the 5 input variables mentioned above.

All five variables are assumed to be uncorrelated. The sampling scheme attacks this problem by forcing the correlations among the ranks of the variables to be small. In fact this is a special case of a mixing scheme to induce any valid rank correlation structure amongst sampled variables. The technique used in treating the ranks of variables, as opposed to the values of variables, has the following desirable properties (IMAN and CONOVER, 1982):

1. It is distribution free. That is, it may be used with equal facility on all types of input distribution functions.
2. It is simple. No unusual mathematical techniques are required to implement the method.
3. It can be applied to any sampling scheme for which correlated input variables could logically be considered, while preserving the intent of the sampling scheme. That is, the same numbers originally selected as input values are retained; only their pairing is affected to achieve the desired rank correlation. This means that in LHS the integrity of the intervals is maintained. If some lattice structure is used for selection of values, that same structure is retained.
4. The marginal distributions remain intact.

The current thinking for the hydraulic tests at the Weiach borehole is that there is no justification for inducing any nonzero rank correlations amongst input variables. However, the capability is in place if future analyses indicate the need. Further, the concept of rank correlation is used in the analysis of the output, as discussed below.

One measure of the relative importance of input variables (the 5 discussed above) is the size of the correlations between the input variables and the response variable (equivalent freshwater head). The concept of correlations is illustrated in Figure 4.13. There is more of a trend evident between variable 1 and the response variable than between variable 2 and the response variable. Apparently variable 1 has a higher degree of importance in computing the response variable than does variable 2. A commonly used measure of the relationship between two variables is the correlation coefficient. Simple correlation coefficients provide a relative measure (from -1 to +1) of how well the observed variation can be explained by a linear relationship between two variables. For problems having non-linear relationships, simple correlations may not provide an adequate measure of importance.

In this analysis the concept of rank correlations is used. For computation of correlations, each variable has its n values replaced by their ranks; the smallest having rank 1 and the largest having rank n. By using the ranks of the variables, any monotonic relationship between variables is transformed to a linear relationship. Thus, simple correlations on ranks can have broader application and can be more meaningful in some situations.

The concept of linear rank correlations is taken one step further. Simple correlations explain the variation of output to input while ignoring the presence of other input variables. Partial correlations explain the variation of output to a given input variable by systematically eliminating the effects of the other variables. In theory, this involves the computation of the differences of the observed values from those predicted by fitting a variable to be eliminated; and finding the simple correlation between the residuals. In practice, partial correlations are computed using selected entries taken from the inverse of the simple correlation matrix. In this analysis partial correlations on the ranks of variables are used as the primary measure of variable importance.

The size of the uncertainty about the mean freshwater head value is measured by the sample standard deviation. The mean and one and three standard deviations are routinely reported. In addition, a histogram is shown of the head distribution for each test interval. Symmetry of the distribution, or lack of symmetry, should be readily apparent from the figure. An example histogram appears in Figure 4.14. Histograms for head are generated with the horizontal plot limits being the nearest integers that encompass the range.

The results for each test interval show the uncertainty of freshwater head due to instrumentation error, for the conditions of the test. Given that any required data interpretations are correct, that there was no operator error, and that instrumentation has operated within specifications, the equivalent freshwater head value should be contained in the reported uncertainty range. In addition to the examination of each individual test, general statements can often be made that apply to all tests. The general accuracy of freshwater head values throughout the borehole may be significant in predicting regional flow. Important input variables for the borehole may suggest the need for further examination of documentation or of refined testing procedures.

5. FORMATION TEMPERATURE DETERMINATION

The purpose of this section is to examine the temperature data for the Weiach borehole and discuss the approach taken to determine a representative set of formation temperatures for the borehole. The data used in determining the temperatures of the formation with depth in the borehole consisted of borehole fluid temperatures measured using High Resolution Thermometry (HRT) and Auxillary Mud Resistivity (AMS) logging. The borehole fluid temperatures measured during all of the interval hydraulic tests were examined and compared against the temperatures from geophysical logs to determine their representativeness of formation conditions.

5.1 Borehole Temperature Data

Downhole temperatures were available from nearly all of the hydraulic tests. The fluid temperatures measured during the first six tests were taken using a CWL 300 transducer system and a DMR 314/200 self-recording transducer system in the Lynes drill-stem test (DST) tool. A transducer located inside the tubing string, above the top packer of the DST tool, measured the temperatures during testing. The temperature transducer is coupled with the pressure transducer for the purpose of providing an operating temperature for the frequency-correction of the quartz crystal transducer. A single bottom hole temperature measured at the transducer depth of the DST tool was recorded during test 859.1SII. Except for test 859.1SI (pumping test in the Muschelkalk), the remaining temperature data from interval hydraulic testing was collected using the transducers of the Lynes Hydrologic Test Tool (HTT). This data consisted of the temperatures recorded by the three temperature transducers located in the HTT sensor carrier. The group of HTT sensors are housed together below the shut-in valve. Any fluid movement in the HTT past the shut-in valve also flows past the sensor carrier. The purpose of coupling the pressure and temperature transducers is to measure the operational temperature of the pressure transducers. Since the temperature transducers in the DST tool and HTT are located in a section of the tool above the packed off interval, they measure the temperature at the test tool sensor carrier and not the temperature in the interval. The temperatures measured during pumping test 859.1SI were not downhole temperatures, they were instead the temperature of the surface discharge. The minimum and maximum temperatures measured at the transducer depth during testing with the Lynes DST and HTT are summarized in Table 5.1 and the maximum temperatures are plotted in Figure 5.1.

The HRT and AMS logs used in determining the temperature-depth profile for the Weiach borehole were conducted by Schlumberger on the following dates:

Log	Date
HRT-1	02 July, 1983
HRT-2	17 September, 1983
HRT-3	09 October, 1983
HRT-4	13 November, 1983
HRT-5	08 February, 1984
HRT-6	24 January, 1985
AMS	29 March, 1985

A description of the HRT and AMS logging methodologies and operating principles can be found in NAGRA (1988). A graphical presentation of the borehole temperature data from these logs is shown in Figure 5.1.

5.2 Temperature Disturbance Around the Borehole and Drilling Fluid Effects

The temperature difference between the borehole drilling fluid and the formation results in a thermal gradient extending from the borehole out into the formation. Exposure of the formation to this gradient will create a temperature disturbance immediately surrounding the borehole. The altered zone may have either a higher or lower temperature than the surrounding formation depending on the relative temperature of the borehole fluid. In order to accurately determine the formation temperature, it is necessary to assess the potential effects of the thermal disturbance. A higher temperature zone around the borehole occurs in cases were the drilling fluid is warmer than the in-situ formation temperature. In contrast, if the drilling fluid temperature is cooler than the formation temperature, a lower temperature zone will result. A simple conceptualization of the disturbed temperature zone would have temperatures gradually increasing or decreasing from the borehole to the undisturbed formation temperature some distance away. A schema of temperature in the formation and temperature of the test interval fluid after shut-in is provided in Figure 5.2. Once fluid is no longer circulating in the borehole, the temperature of the formation adjacent to the borehole will recover to the original formation condition with the rate of change being a function of the thermal gradient and the effective thermal conductivity of the formation fluid and solids. As determined from the thermal flux in the formation, the borehole fluid will eventually achieve temperature equilibrium with the formation providing the temperature of the borehole fluid is not impacted by fluid circulation in the borehole or mixing with non-formation fluid.

If a disturbed temperature zone has developed into the formation as a result of previous borehole activities, the drilling fluid in the borehole will respond to this zone and not to the undisturbed formation temperature. Only temperature data collected after the formation has recovered from the borehole activities and the fluid in the borehole has reached equilibrium with the in-situ formation temperature should be considered representative of the temperature of the undisturbed formation.

In order to develop an understanding of the formation temperature condition during hydraulic testing and geophysical temperature surveys, the activities that occurred in the borehole prior to these events were examined. Table 5.2 provides the following information for the hydraulic tests, (1) the duration of the interval history, (2) the approximate duration of drilling fluid circulation in the test interval, (3) the time between fluid circulation and testing, and (4) the duration of the test. The duration of the history period prior to testing is an indication of the period of time that the test interval may have been exposed to non-formation fluid. The period of time that the borehole was experiencing fluid circulation indicates the length of the history period where the formation was exposed to a maximum temperature differential with the circulating fluid. At the end of fluid circulation, and before testing, the formation starts to recover from the circulation disturbance, therefore, knowing the length of this period is useful in estimating the amount of re-equilibriation to original formation temperature that might have occurred. Finally, the duration of the test period will provide useful information for assessing the expected amount of temperature recovery during testing. Since the data from test 859.1SI did not reflect downhole temperature conditions during testing, it was not included in the table. Table 5.3 shows a similar summary of background information for the temperature logging surveys.

5.3 Interpretation of Temperature Data From HRT and AMS Logs

The fifth and sixth HRT logs and the AMS log were conducted 88 days, 438 days, and 502 days, respectively, after the borehole was completed (see Table 5.3). As seen in Figure 5.1, temperatures recorded by the HRT-6 and AMS logs were almost identical and were 3°C to 4°C warmer than those measured by the HRT-5 log. The temperature difference indicates that the borehole fluid, in the interval surveyed by HRT-5, may have warmed between 3°C and 4°C over the 350 days between HRT-5 and HRT-6. It seems reasonable to assume that the borehole fluid had not yet reached temperature equilibrium with the formation at the time the HRT-5 log was conducted. Since the temperature of the borehole fluid did not change during the period from 24 January, 1985 to 29 March, 1985, it was concluded that the borehole fluid had reached temperature equilibrium with the formation at the time the HRT-6 logging survey was conducted.

The first four HRT logs were run soon after drilling fluid was circulated in the borehole (see Table 5.3). Because insufficient time had elapsed for the drilling fluid in the borehole to come to temperature equilibrium with the formation, the borehole fluid temperatures recorded by these surveys were not considered representative of undisturbed formation temperatures. The discussion in the preceding paragraph demonstrated that the borehole fluid was probably still equilibrating to formation temperature nearly 88 days after fluid circulation in the borehole had ceased. Therefore, temperature equilibrium between the borehole fluid and the undisturbed formation at the time the first four HRT logs were conducted most likely did not exist.

In summary, the temperature log data considered representative of undisturbed formation temperatures consisted of the temperatures measured by the HRT-6 and AMS logs. HRT-6 was completed 438 days after the final drilling of the borehole and the AMS log was completed within 502 days of the end of drilling. These temperature logs were consistent in their results and demonstrate that the borehole fluid had warmed between 3°C and 4°C since HRT-5, some 350 days prior to HRT-6. The time necessary for the temperature disturbance to dissipate and the borehole fluid to reach temperature equilibrium with the undisturbed formation, for conditions in the Weiach borehole, was therefore greater than 88 days and less than 438 days. The Weiach borehole was drilled over a period of 306 days from 10 January, 1983 to 12 November, 1983.

5.4 Interpretation of Temperature Data From Hydraulic Tests

The interval hydraulic tests conducted in the borehole (except test 987.9D) were divided into two groups. Test 987.9D is discussed separately below. Group 1 consisted of those tests conducted from 01 March, 1983 to 04 December, 1983 during the borehole drilling phase. These tests are characterized by a short time period between the end of fluid circulation in the interval and the start of testing. In general, the temperature of the borehole fluid increased during these tests demonstrating the re-equilibrium of the test interval with the temperature of the surrounding formation. A typical response is illustrated in Figure 5.3. The time between the end of drilling fluid circulation in the interval and the start of testing was considered insufficient for the temperature disturbance to have dissipated prior to testing. Therefore, the increase in temperature observed during testing was most likely the result of the borehole fluid responding to a temperature disturbance and not to the undisturbed formation temperature. Extrapolation of this data to a steady-state temperature would have yielded a very uncertain temperature estimate since the data was strongly affected by the altered temperature zone and would not be representative of the undisturbed formation temperature.

Group 2 consisted of those tests conducted from 03 February, 1984 to 21 June, 1984 after the borehole had been capped and inactive for 69 days (see Table 5.1). These tests are characterized by a moderately long period between the completion of fluid circulation in the borehole and the start of testing. The borehole fluid temperatures measured during testing were relatively constant suggesting that the borehole fluid had reached temperature equilibrium with the surrounding formation. This may indicate that the borehole fluid had warmed to an undisturbed formation temperature or that a persistent altered temperature zone was controlling borehole temperatures. Figure 5.4 illustrates a typical temperature response in an isolated test zone. Attempted extrapolations of the Group 1 test data demonstrated that an altered temperature zone can control the thermal recovery of the borehole fluid. In comparing the temperature data from the Group 2 tests and the results of the HRT log conducted on 08 February, 1984 it was evident that the temperature differential increased, the longer the time between testing and the HRT survey. The final Group 2 test (1116.5D) was completed from 19 June, 1984 to 21 June, 1984. The temperature measured by the T2 transducer at shut-in conditions during testing was 57.8°C which lies between the temperatures of 57.1°C and 58.6°C measured at the T2 depth by HRT-5 and HRT-6, respectively. In other words, the borehole fluid at the T2 depth for test 1116.5D increased 0.7°C from 08 February, 1984 to 21 June, 1984 and another 0.8°C from 21 June, 1984 to 24 January, 1985. A reasonable explanation for the observed increase in temperature is that the borehole fluid had not yet reached temperature equilibrium with the undisturbed formation by 21 June, 1984, 222 days after final fluid circulation. This means that (1) the temperatures measured during the Group 2 tests were most likely only representative of a thermal disturbance around the borehole and (2) the range required for the borehole fluid to reach temperature equilibrium with the undisturbed formation is narrowed to greater that 222 days and less than 438 days.

Test 987.9D was a double packer test of the Buntsandstein conducted in the perforated casing on 21 March, 1985, some 494 days after completion of the borehole and final circulation of fluid. The interval was isolated for 537 days by the casing. The temperature recorded by the T2 transducer during this test (53°C) was in agreement with the temperature of 52.8°C measured at the T2 depth by the HRT log completed in January 1985 and the AMS log completed in March 1985. Since these surveys have been determined to be representative of formation temperatures, the borehole temperature at T2 during test 987.9D was considered equivalent to the formation temperature.

5.5 Discussion and Results

Borehole fluid temperatures measured during hydraulic testing and with geophysical logging were examined in order to estimate the undisturbed temperature profile in the Weiach borehole. The geophysical logging surveys included six High Resolution Thermometry logs and one Auxillary Mud Resistivity log. The temperatures measured in the borehole from the four HRT logs and the hydraulic tests conducted from 01 March, 1983 to 04 December, 1983 during and soon after the borehole drilling phase were not representative of formation temperatures. The time between the end of fluid circulation and the testing or logging events was too short for the temperature disturbance around the borehole to have dissipated and the borehole fluid to reach temperature equilibrium with the formation. Most of the remaining interval tests and an HRT log conducted 88 days after fluid circulation measured temperatures in the borehole that were 3°C to 4°C cooler then those recorded by the HRT and AMS logs conducted on 24 January, 1985 and 29 March, 1985, respectively, more than 438 days after final fluid circulation in the borehole. The temperature measured by the T2 transducer during test 987.9D, conducted on 21 March, 1985, matched that recorded by the final HRT/AMS logging surveys run in 1985.

Examination of the temperature data indicated that the temperatures measured during interval testing or by geophysical temperature surveys conducted during drilling or less than 8 months after the borehole drilling phase are not representative of undisturbed formation temperatures. Only the temperature data collected after the borehole had been completed for over about 440 days appeared to be representative. In summary, the temperatures recorded in the borehole by the HRT and AMS logging surveys conducted on 24 January, 1985 and 29 March, 1985, respectively, are considered representative of the formation temperatures and temperature gradient at the Weiach borehole. One hydraulic test, 987.9D in the Buntsandstein, was conducted after a sufficient period of time following drilling to measure an undisturbed formation temperature.

6. EXAMPLE OF APPLICATION OF THE INTERPRETATION METHODOLOGY

This chapter provides an illustration of the application of the interpretation methodology for formation pressure and hydraulic conductivity for a selected test zone (2218.1D) as discussed in BUTLER et al., 1989. Full details on all other test zones are provided in BUTLER et al., 1989.

Test 2218.1D (2211.60 m to 2224.63 m)

Test 2218.1D was a double packer test of the crystalline formation in the Weiach borehole from 2211.60 m to 2224.63 m. The rock type of the interval consisted of biotite-gneiss and biotite-aplite. Several areas of pegmatite are noted as well as areas of strong chloritisation. Fractures are found on average 7 per meter and some zones within the interval are heavily kakiritized such as at 2211.55 m. The testing sequence was performed over a 17 day period from 11 April, 1984 to 28 April, 1984. A pulse injection test (Pi01), three pulse withdrawal tests (Pw01, Pw02 and Pw03), and three slug withdrawal tests (Sw01, Sw02, and Sw03) were completed in the testing sequence. The interval was drilled over 44 hours from 16 October, 1983 to 18 October, 1983. The drilling fluid was traced deionized water. Table 6.1 shows the interval geology, test tool configuration and testing dates.

The pre-test history for this testing sequence begins on 17 December, 1983 at the start of the second period that the annulus was shut-in following the completion of drilling the Weiach borehole. Starting the pre-test history at the second shut-in period was considered reasonable because of the length of the shut-in period during which an average pressure of 373 kPa above annulus pressure was recorded for the uncased crystalline rock. This recovery was considered near formation pressure indicating dissipation of any pressure disturbance around the borehole. This was followed by an open borehole period at annulus pressure for about 26 days. The borehole was swabbed for logging purposes to about 462 m below ground surface on 25 February, 1983. The formation recovered over a period of about 7 days to a fluid level of approximately 400 m below ground surface. The borehole was then filled with fluid to the top of the casing. The borehole was open and several hydraulic tests were performed in the crystalline rock over 18 days. The borehole was swabbed down to approximately 630 m in order to obtain water samples. The fluid removed during the swab was not replaced prior to this testing sequence. Test 2266.8D and a fishing job were performed over 21 days prior to this test with the fluid level in the annulus varying from about 630 m below ground to about 452 m below ground surface. The fluid level was estimated to be 510 m below ground surface at the start of this testing sequence. Several events were combined to develop a pressure history for use in GTFM. The interval pre-test history is shown in Figure 6.1.

Figure 6.2 shows the measured pressure response for the testing sequence. A compliance period was not performed after packer inflation. Because of this, the first test in the sequence (Pi01) is a pulse injection test resulting from the initial shut-in following packer inflation. The pressure was about 20171 kPa at the start of test Pi01. The measured pressure dropped to approximately 17662 kPa before recovering to about 18729 kPa. The tubing was swabbed to about 550 m with the shut-in valve closed. A slug withdrawal test (Sw01) resulted when the shut-in valve was opened. The measured pressure was about 16110 kPa at the start of test Sw01 and recovered to 16139 kPa over 1 hour. The shut-in valve was closed and test Pw01 had a shut-in squeeze of about 75 kPa. The measured pressure recovered to about 65 percent of the assumed formation pressure over 14.8 hours. The tubing was swabbed from 750 m with the shut-in valve closed in preparation for test Pw02. Test Pw02 had an initial pressure of about 15528 kPa and recovered to 67 percent of the assumed formation pressure over 86 minutes. Test Pw03 had an initial pressure of about 15648 kPa and recovered to about 65 percent of formation pressure over 93 minutes. 450 L of water were added to the tubing string prior to slug withdrawal test Sw02 causing the initial pressure for test Sw01 to be about 1430 kPa higher than the initial pressure of test Pw03. Test Sw02 had an initial pressure of about 17075 kPa and the measured pressure increased by about 293 kPa over 21 hours. The average flow rate over the first hour was about 0.15 L min^{-1} and the average flow rate after 3 hours was about 0.08 L min^{-1}. A 550 m swab was pulled with the shut-in valve open for test Sw03. The flow rate during the events after test Sw03 varied from about 0.06 L min^{-1} to 0.04 L min^{-1}. The initial pressure for test Sw03 was about 16408 kPa and recovered to 17489 kPa over 77 hours. The flow rate during Sw03 started at about 0.09 L min^{-1} and decreased to about 0.06 L min^{-1}. Several bailer runs and two swabbing events were performed with the shut-in valve open following test Sw03. The measured pressure response at P1 show some slight communication (several kPa pressure disturbance) with the P2 zone during the swabbing periods throughout the testing sequence. However, the pressure record for the P1 and P2 zones, which showed a differential of over 3000 kPa during most of the pulse tests during the testing sequence, did not indicate significant communication between these zones. The observed response of transducer P1 to a pressure of 20515 kPa during the testing period most likely results from the recovery of the P1 zone to formation pressure from a low pressure disturbance and not P1 - P2 communication. The measured temperatures for the testing sequence are shown in Figure 6.3. Due to the small temperature change during the testing sequence (less than 0.2°C), thermal effects were not included in the simulation.

The testing sequence was simulated with GTFM incorporating the pre-test history. The simulations were run through the third slug withdrawal. The input parameters used in the simulation are shown in Table 6.2. An assumed formation pressure of 21883 kPa was derived by interpolating the Long Term Monitoring formation pressures for Zones 6 and 7 in the crystalline rock to the center of this test interval and correcting the pressure to the P2 transducer depth. P_f could not be determined from analysis of the observed pressure data for this test. Figures 6.4a, 6.4b and 6.4c show the simulated pressure responses for the range of hydraulic conductivity 1.0E-11, 3.0E-11, 1.0E-10 and 3.0E-10 ms^{-1} at specific storages of 2.3E-08, 2.1E-07 and 2.1E-06 m^{-1}. The best fit of the measured pressure responses during the pulse tests varied from a hydraulic conductivity of slightly less than 1.0E-10 ms^{-1} to slightly less than 3.0E-10 ms^{-1} at a specific storage of 2.1E-06 m^{-1}. The best fit during the slug withdrawal tests was consistent at about 2.0E-10 ms^{-1}. Because of relatively consistent range for hydraulic conductivity, the most reasonable fit of the measured data is for a hydraulic conductivity of 2.0E-10 ms^{-1} at a specific storage of 2.1E-06 m^{-1}. Varying the specific storage by one order of magnitude above and below the base case specific storage of 2.1E-07 m^{-1} affected the best-fit hydraulic conductivity by less than a half an order of magnitude.

7. RESULTS

Hydrogeologic interpretations were performed on all analyzable tests in the Weiach borehole. Representative formation pressures were determined from two tests. Formation pressures from each of these testing intervals are reported as equivalent freshwater heads corresponding to the center of the test zone. An estimate of uncertainty in equivalent freshwater head was determined for these two tests based on quantifiable equipment-related uncertainty. Hydraulic conductivities were estimated from 36 tests, and specified with recommended values for 30 tests. The recommended values are based on detailed final analysis. The other estimated values are based on preliminary analysis (GARTNER LEE, 1983/84, 1985a, 1985b) and are reported only in the text of the appendices. Interpretated formation pressures, equivalent freshwater head, and hydraulic conductivities have been presented in table summary form and as depth profiles for the borehole from apparent depths of 188.00 m to 2482.20 m.

7.1 Formation Pressure and Equivalent Freshwater Head

Representative formation pressures were determined from the following tests:

984.2S	Buntsandstein	- Sandstone
1117.5D	Rotliegendes	- Greywacke

The formation pressures and equivalent freshwater heads are presented in Table 7.1. The formation pressures are plotted in Figure 7.1 and the equivalent freshwater heads are plotted in Figure 7.2. Freshwater heads are derived from formation pressures using mean values for true vertical depth and surface elevation and fixed values for barometric pressure (test specific), freshwater density (1000 kgm^{-3}), and gravitational acceleration (9.81 ms^{-2}).

The calculated equivalent freshwater heads are 412.6 m ASL in the Buntsandstein and 452.6 m ASL in the Rotliegendes. Mean surface datum elevation at Weiach is 368.66 m ASL.

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, it is possible to determine formation pressures in intervals which have high hydraulic conductivities and a short borehole history period between drilling and testing. Test 1117.5D was conducted in a high hydraulic conductivity zone at 6.0E-08 ms^{-1}. The history period of about 72 days for test 1117.5D was not included in the test interpretation. The influence of this pressure history was assumed to be minimal given the likely presence of a low permeability mud cake on the borehole wall adjacent to the test interval during the history period. As discussed in Section 4.2.2.4 and in the appendices, the mud cake is expected to be a significant factor in isolating the formation from borehole pressures up to the point of cleaning and testing. A low permeability skin was not used in the test interpretation.

A preliminary evaluation of test 984.2S in Weiach indicates that the zone is of high hydraulic conductivity, between 1.0E-06 ms^{-1} and 1.0E-07 ms^{-1}. However, uncertainty in the interpretation of the measured data resulted in no recommendation of hydraulic conductivity for this depth. However, the formation pressure for this zone is reported with confidence given the high hydraulic conductivity and short (<7 days) history period.

Thermally-induced pressure effects, borehole pressure history effects or poor data records prevented the determination of representative formation pressures and equivalent freshwater heads from the remainder of the hydraulic tests in the Weiach borehole.

7.2 Instrumentation Uncertainties

Each equivalent freshwater head value reported in Table 7.1 has a degree of uncertainty due to instrumentation errors. The uncertainty is displayed graphically for each test with the histograms in Figure 7.3a and 7.3b. Also provided are the mean and standard deviation of the head distributions. If the uncertainty band is defined as two standard deviations about the mean, the average band-width is 3.3 m. The shape of the histograms have the same general appearance as the histogram for the most important input variable for the test. This is true because each test has a dominant input variable, as discussed below.

The partial rank correlations for both tests show measured pressure as the most important input variable. The range used for uncertainty of pressure is based on the accuracy and resolution of a typical transducer. The endpoints of the range (measured value ± 22.8 kPa) are used as the 0.1 and 99.9 percentiles of a normal distribution. This is equivalent to a normal distribution with the measured value being the mean and having a standard deviation of 7.38 kPa. On average, the standard deviation for pressure represents 90 percent of the standard deviation for equivalent freshwater head. The importance of the pressure variable relative to the other input variables could be reduced given tighter accuracy specifications for the transducer. Using the model numbers and the operating specifications of the actual transducers, one could generate a narrower uncertainty band for each test. However, similar to the assumption made for the generic specifications, one would still have to assume that the crystal performed downhole the same way it did in the laboratory.

The second most important input variable for both tests is true vertical depth. As discussed in Section 4.4.1 uncertainty in depth increases with depth by a simple fractional multiplier. Best judgement for the Weiach borehole indicated that a multiple of 0.0011 is reasonable. A uniform distribution ranging from the interpolated depth minus/plus half the uncertainty was assigned to true vertical depth. The standard deviation for the distribution is therefore a multiple (3.2E-04) of the depth. From 980 m to 1120 m the standard deviation increases from 0.31 m to 0.36 m. So throughout the tests, this deviation is less than the standard deviation for transducer measured pressure (7.38 kPa) converted to meters of freshwater head (0.75 m). If in the future, transducer accuracy and resolution ranges are narrowed, the quantification of depth uncertainty would have increased importance and should be examined further.

The remaining three input variables (surface elevation, fluid density, and rock density) are of lesser or no importance to freshwater head uncertainty. Fluid density is not important since it enters the calculations as a multiple of a relatively short distance. This is not the case for water level tests and long-term monitoring, where density is quite important (BELANGER et al., 1988a and BELANGER et al., 1988b).

The uncertainty surrounding the pressure at interval center is dominated by the same variable as equivalent freshwater head. That is, pressure at transducer P2 is the dominant variable. The second most important variable for pressure at interval center is borehole fluid density. Its largest impact accounts for less than 3 kPa variation in pressure at interval center.

7.3 Formation Hydraulic Conductivity and Specific Storage

Hydraulic conductivity was recommended for 30 of 37 analyzed test intervals in the Weiach borehole. Table 7.2 summarizes the hydraulic conductivity, specific storage, and temperature at the end of the testing, determined from each analyzable hydraulic test. Hydraulic conductivities are plotted in Figure 7.4.

Interpreted hydraulic conductivities ranged from 1.0E-06 ms^{-1} to 3.0E-13 ms^{-1}. Zones of high hydraulic conductivity (greater than 1.0E-08 ms^{-1}) were observed at the following true vertical depths:

188 m - 267 m (195.0D and 255.0D)	Malm
822 m - 896 m (859.1SI and 859.1SII)	Muschelkalk
981 m - 990 m (985.3D)	Buntsandstein
1109 m - 1247 m (1116.5D to 1240.1D)	Rotliegendes

The high hydraulic conductivity zones are all contained within the sedimentary section (0 - 2020 m depth) of the Weiach borehole. In general, the tested zones of the crystalline section of the borehole have lower hydraulic conductivity (<1.0E-09 ms^{-1}).

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. The sum of all factors affecting the measured pressure response is considered to produce an uncertainty of about ± one order of magnitude in the interpreted hydraulic conductivity values. Most of these factors have been addressed previously in Section 4.2. The uncertainty in the reported hydraulic conductivity attributed to uncertainty in the estimate of formation specific storage was approximated by determining the best-fit hydraulic conductivity at S_s values one order of magnitude above and below the base case value.

The specific storage values determined for the test zones ranged from 6.2E-05 m^{-1} to 2.1E-07 m^{-1}. The most representative specific storage for a test interval was determined by observing the best-fit of simulations to the measured data for a range of specific storage of about one order of magnitude above and below a base case value at an approximate formation hydraulic conductivity. The base case specific storage is calculated from an assumed representative value of rock compressibility, porosity and fluid compressibility taken from various literature sources. Specific storage was adjusted by varying rock compressibility to obtain the order of magnitude shift above and below the base case value.

7.4 Formation Temperature

Borehole fluid temperatures measured during hydraulic testing and by geophysical logging were examined in order to estimate the undisturbed temperature profile in the Weiach borehole. The geophysical logging surveys included six High Resolution Thermometer logs and one Auxillary Mud Resistivity log. The temperatures measured in the borehole from the four HRT logs and the hydraulic tests conducted from 01 March, 1983 to 04 November, 1983 during the borehole drilling phase were not representative of formation temperatures. The time between the end of fluid circulation and the testing or logging events was too short for the temperature disturbance around the borehole to have dissipated and the borehole fluid to reach temperature equilibrium with the formation. Most of the remaining interval tests and an HRT log conducted 88 days after fluid circulation measured temperatures in the borehole that were 3°C to 4°C cooler then those recorded by the HRT and AMS logs conducted on 24 January, 1985 and 29 March, 1985, respectively, after 438 days of equilibration. The temperature measured by the T2 temperature transducer during test 987.9D, conducted on 21 March, 1985 matched that recorded by the final HRT/AMS logging surveys run in 1985.

Examination of the temperature data in the Weiach borehole indicated that the length of time necessary for the disturbed temperature zone to dissipate and the borehole fluid to reach temperature equilibrium with the undisturbed formation, was greater than 222 days but less than 438 days.

In summary, the temperatures recorded in the borehole by the HRT and AMS logging surveys conducted on 24 January, 1985 and 29 March, 1985, respectively, are considered representative of the formation temperatures and temperature gradient at the Weiach borehole. Only one hydraulic test, 987.9D in the Buntsandstein, was conducted after a sufficient period of time following drilling to measure an undisturbed formation temperature.

Figure 7.5 illustrates the representative formation temperature profile determined for the Weiach borehole and presents a linear approximation through the profile. The equation of the temperature-depth approximation is:

$$T = 0.0468Z + 7.8$$

where T = temperature, °C;
Z = depth, m.

The slope of the linear approximation corresponds to a thermal gradient of approximately 4.7°C/100 m. The maximum difference between this gradient and the representative temperature-depth profile is ± 4°C in the section of the borehole from the depths of 50 m to 2300 m. Below 2300 m to the bottom of the borehole, the gradient of the representative temperatures appears to decrease to about 1.1°C/100 m.

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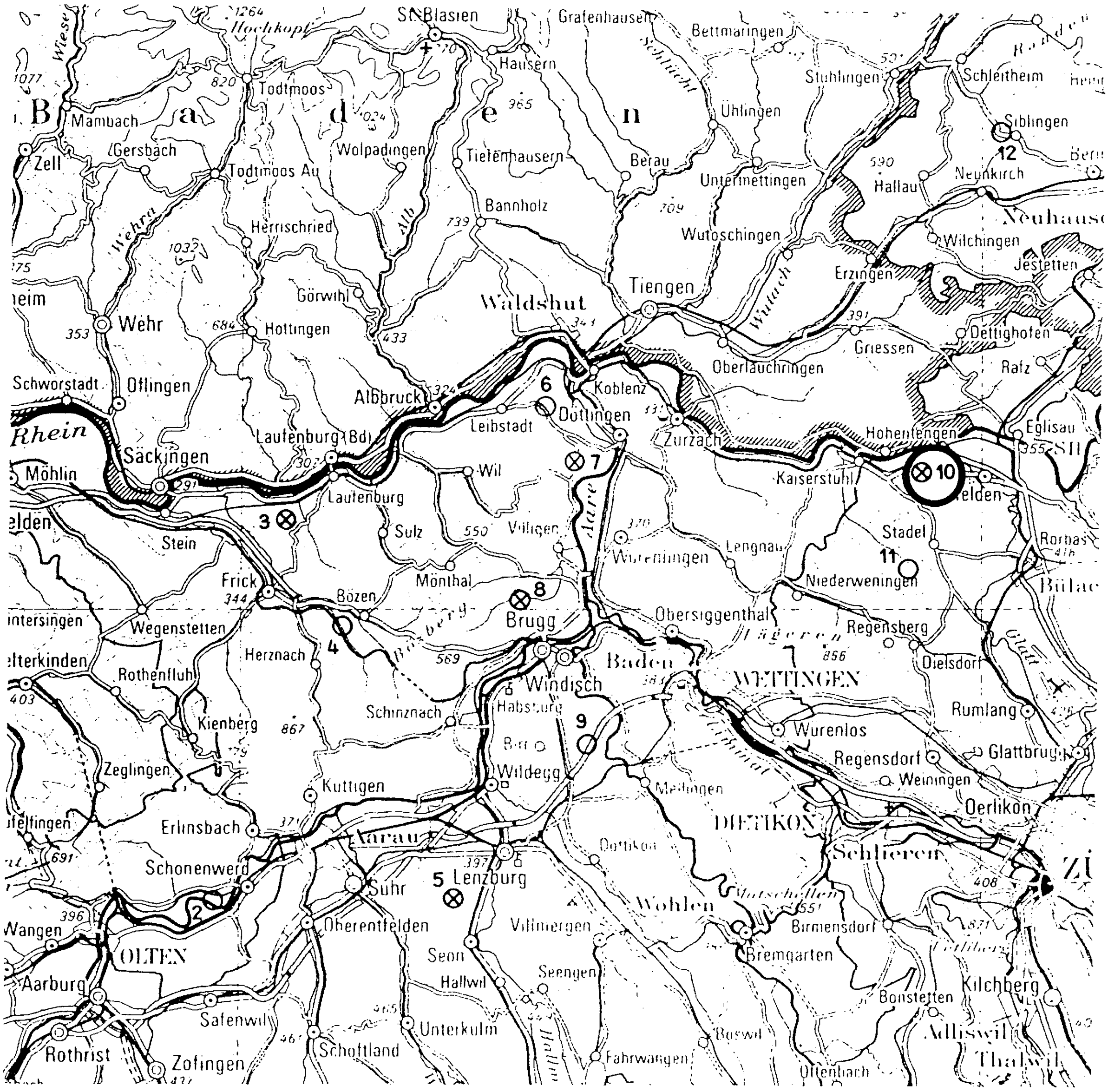


Borehole		Depth
O 1	HAEGENDORF	ca 2400 m
O 2	NIEDERGOESGEN	ca 2250 m
⊗ 3	KAISTEN	1306 m
O 4	HORNUSSEN	ca 1600 m
⊗ 5	SCHAFISHEIM	2006 m
O 6	LEUGGERN	1689 m
⊗ 7	BOETTSTEIN	1501 m
⊗ 8	RINIKEN	1801 m
O 9	BIRRHARD	ca 2350 m
⊗ 10	WEIACH	2482 m
O 11	STEINMAUR	ca 2500 m
O 12	SIBLINGEN	ca 1450 m

LEGEND

O Borehole

⊗ Borehole Completed

0 10 20 km

Figure 1.1 Weiach Borehole Location

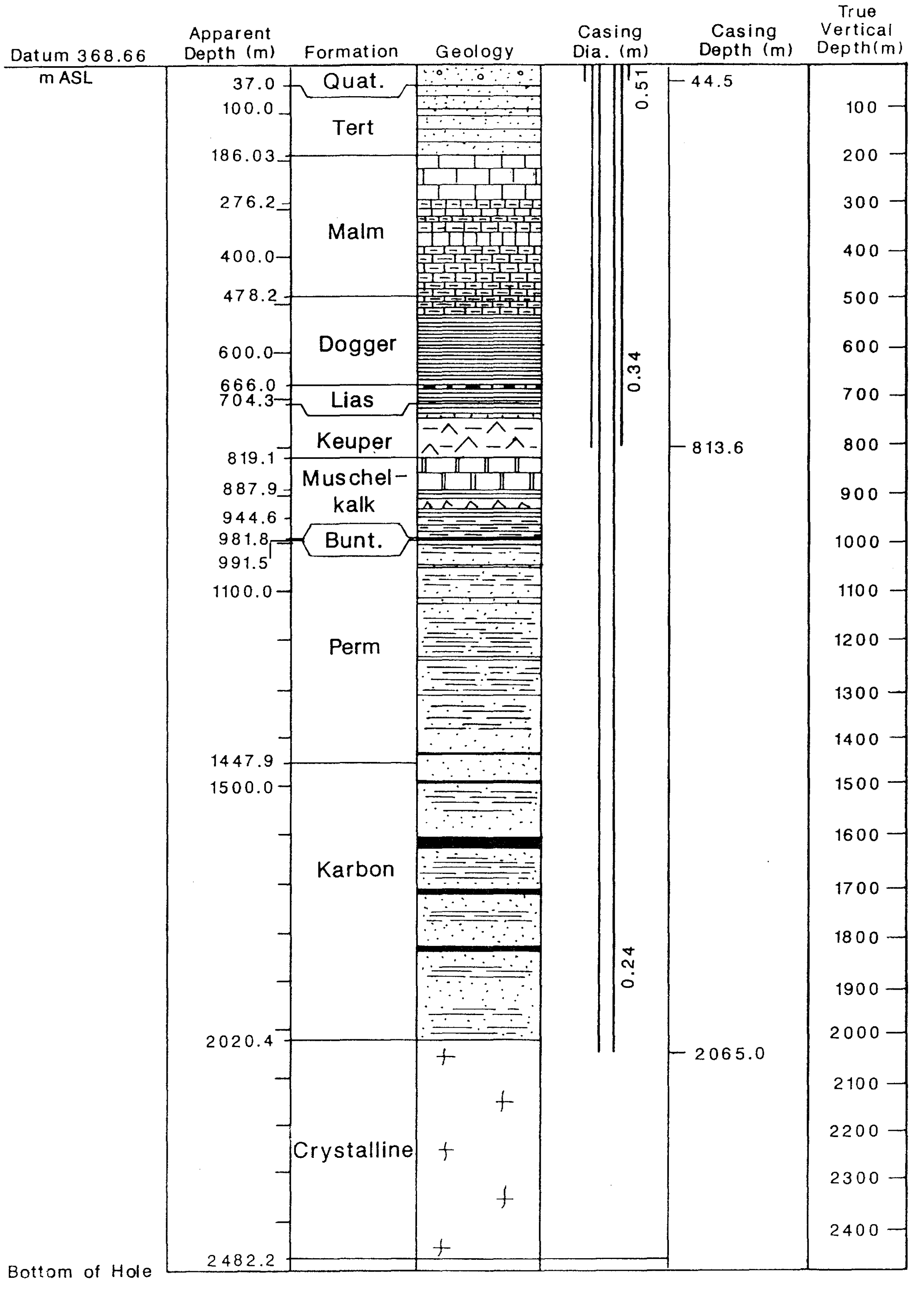


Figure 2.1 Weiach Borehole Geology

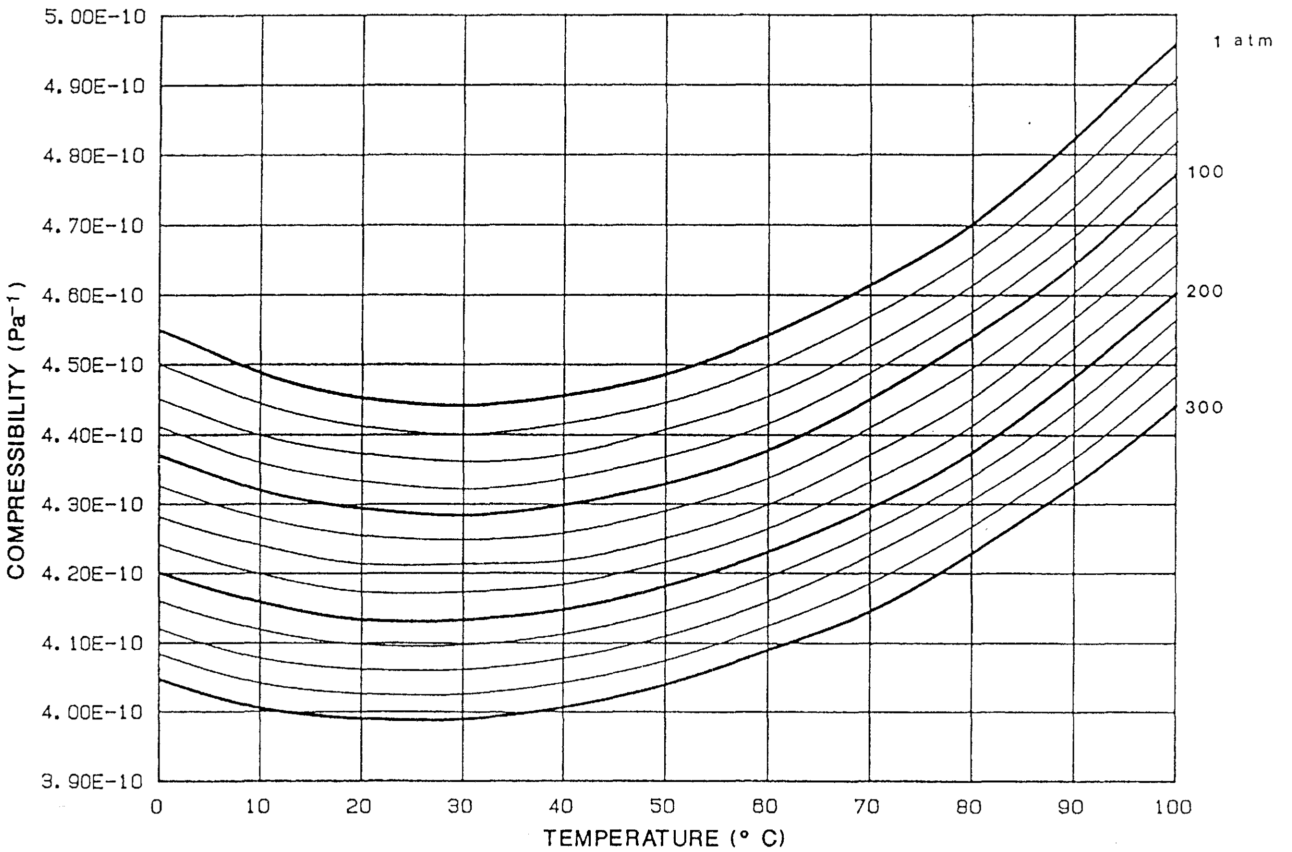


Figure 4.1 Fluid compressibility: Variation with Temperature and Pressure

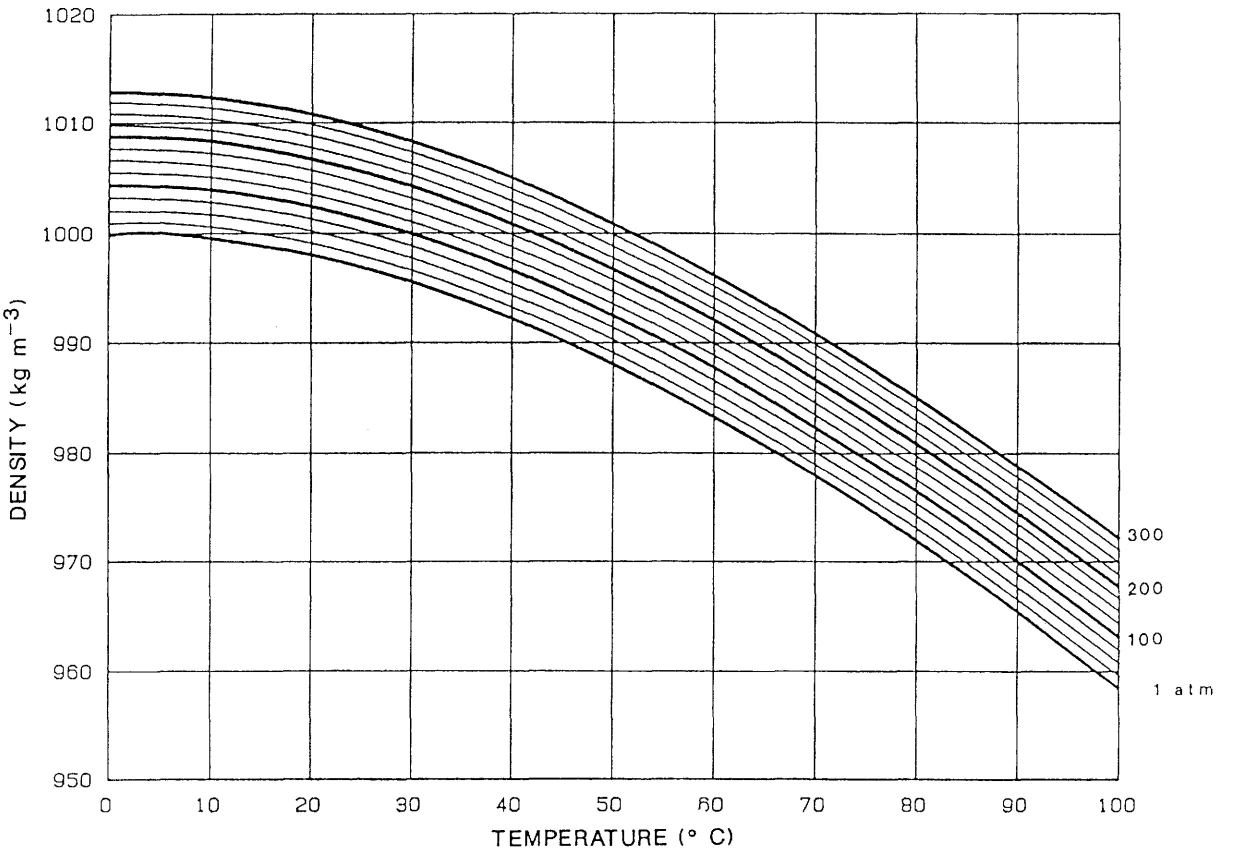


Figure 4.2 Fluid Density: Variation with Temperature and Pressure

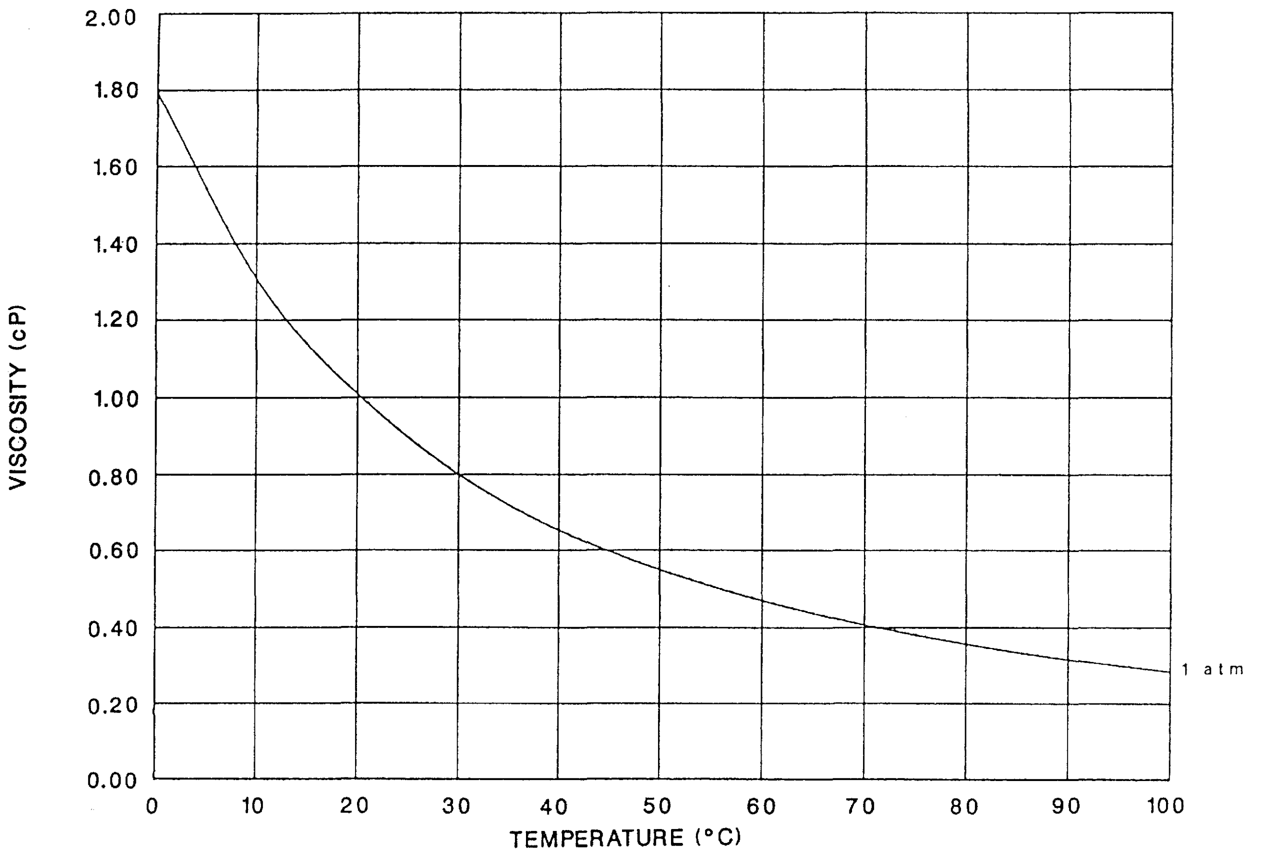


Figure 4.3 Fluid Viscosity: Variation with Temperature

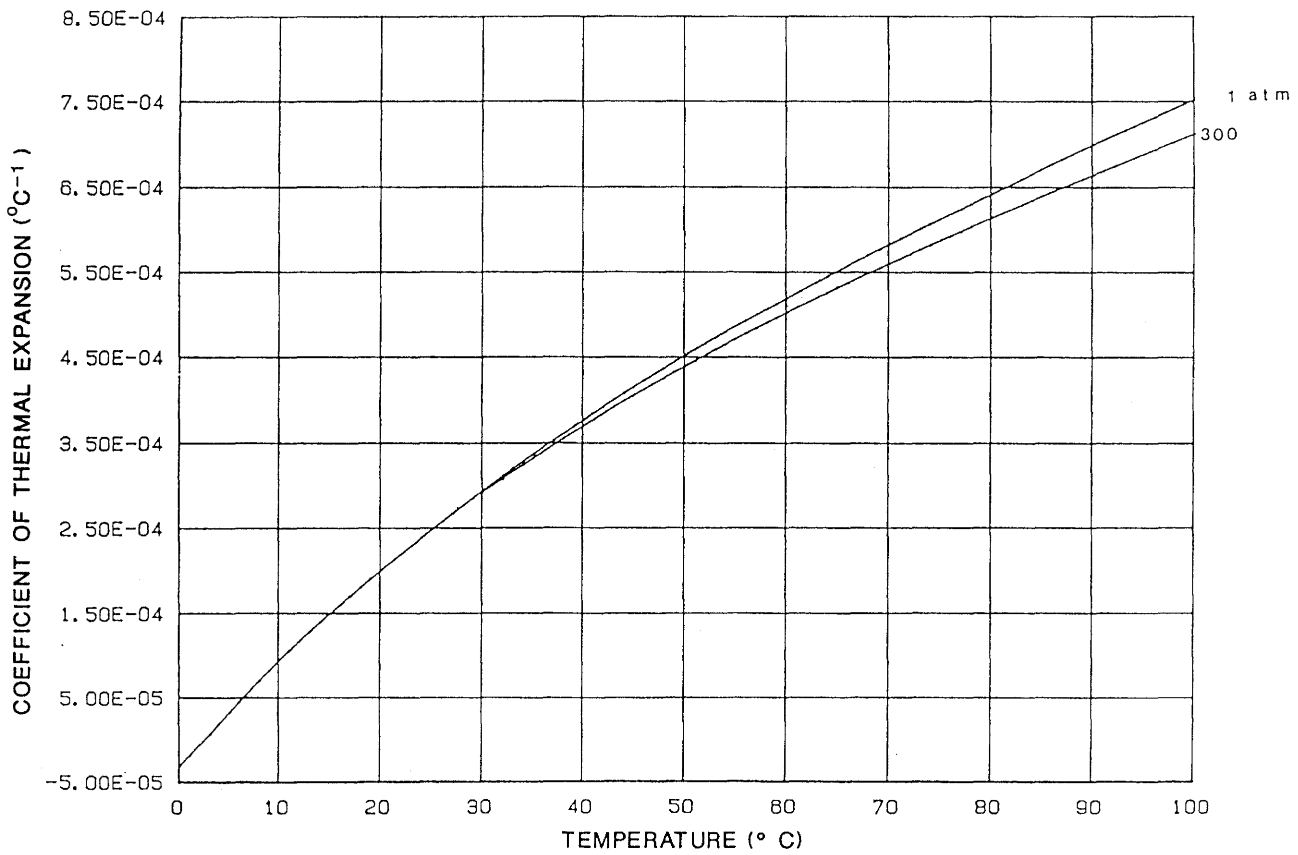


Figure 4.4 Fluid Coefficient of Thermal Expansion: Variation with Temperature and Pressure

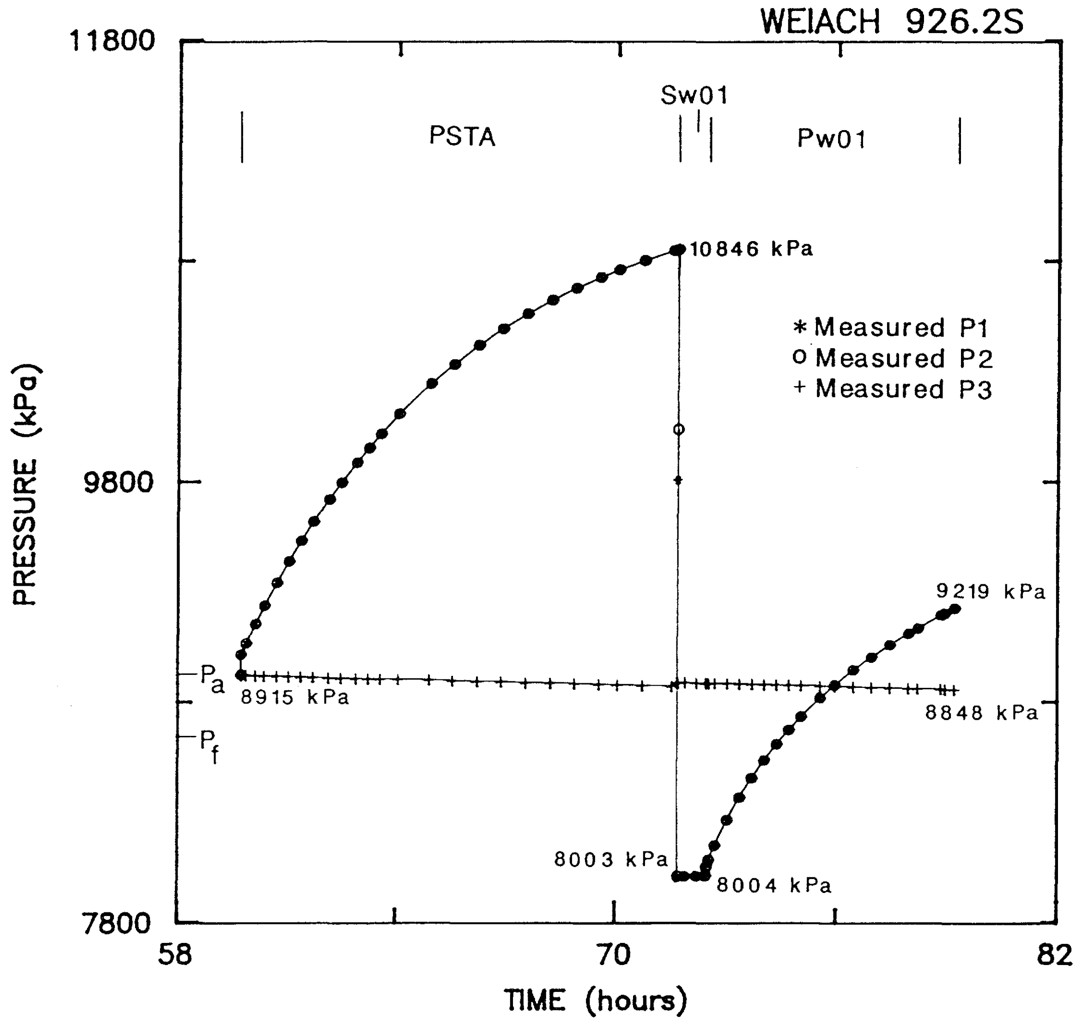


Figure 4.5 Measured Pressure Data for Test Interval 926.2S, Test Sequence Designations, and Starting and Ending Pressures for Each Sequence

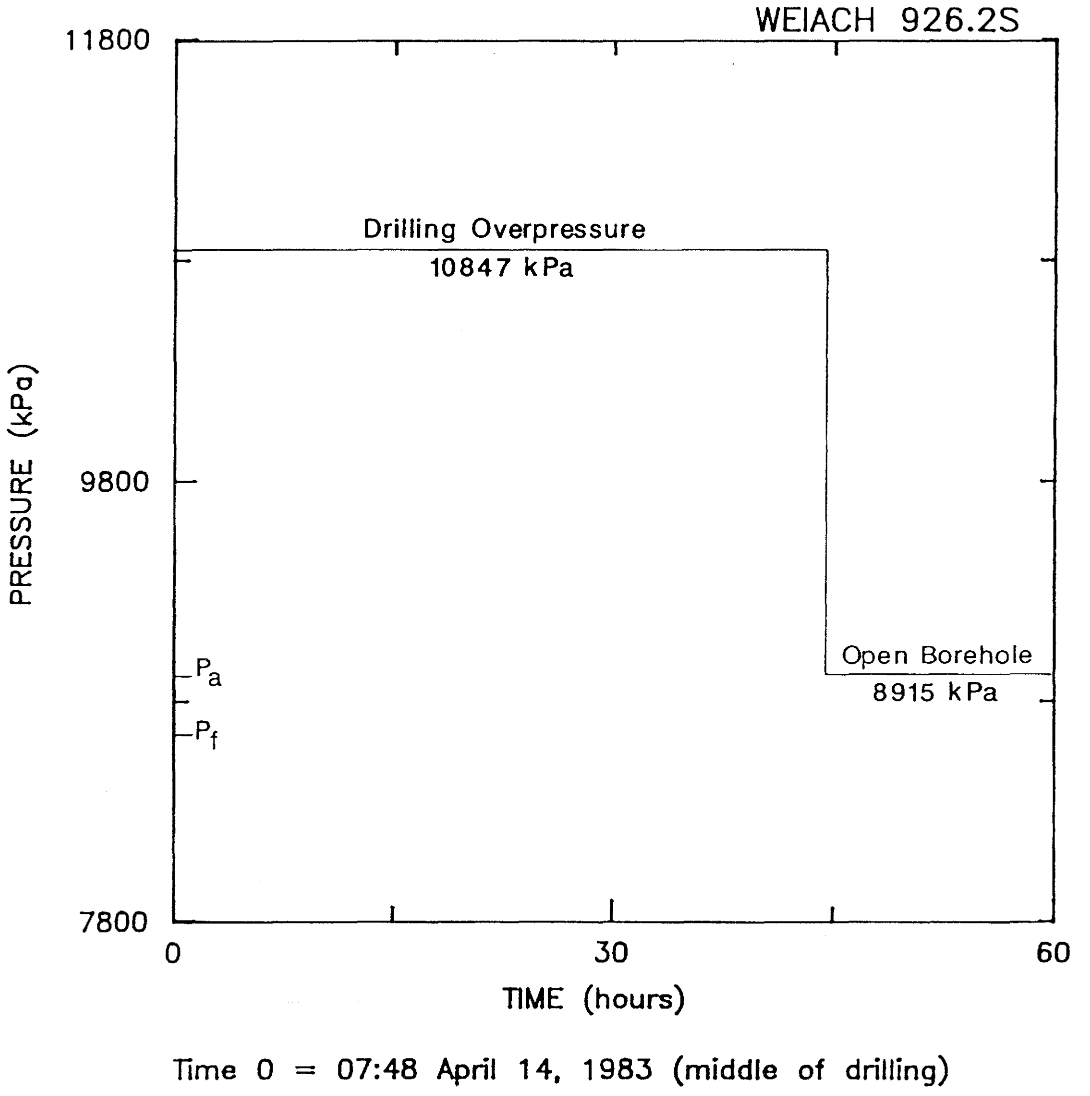


Figure 4.6 Assumed Pressure History on Test Interval 926.2S

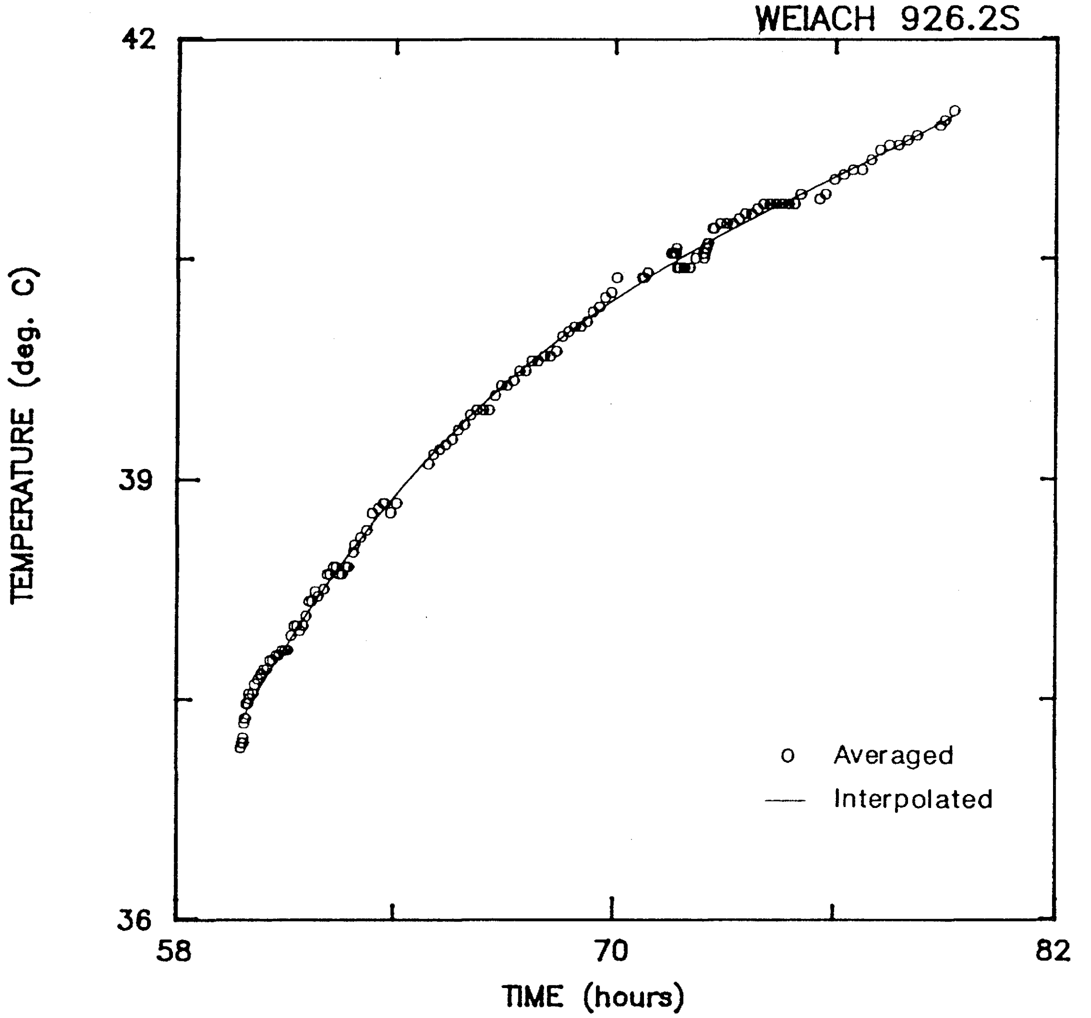


Figure 4.7 Best-Fit Interpolation of the Average Response for the T1, T2 and T3 Temperature Transducers for Test 926.2S

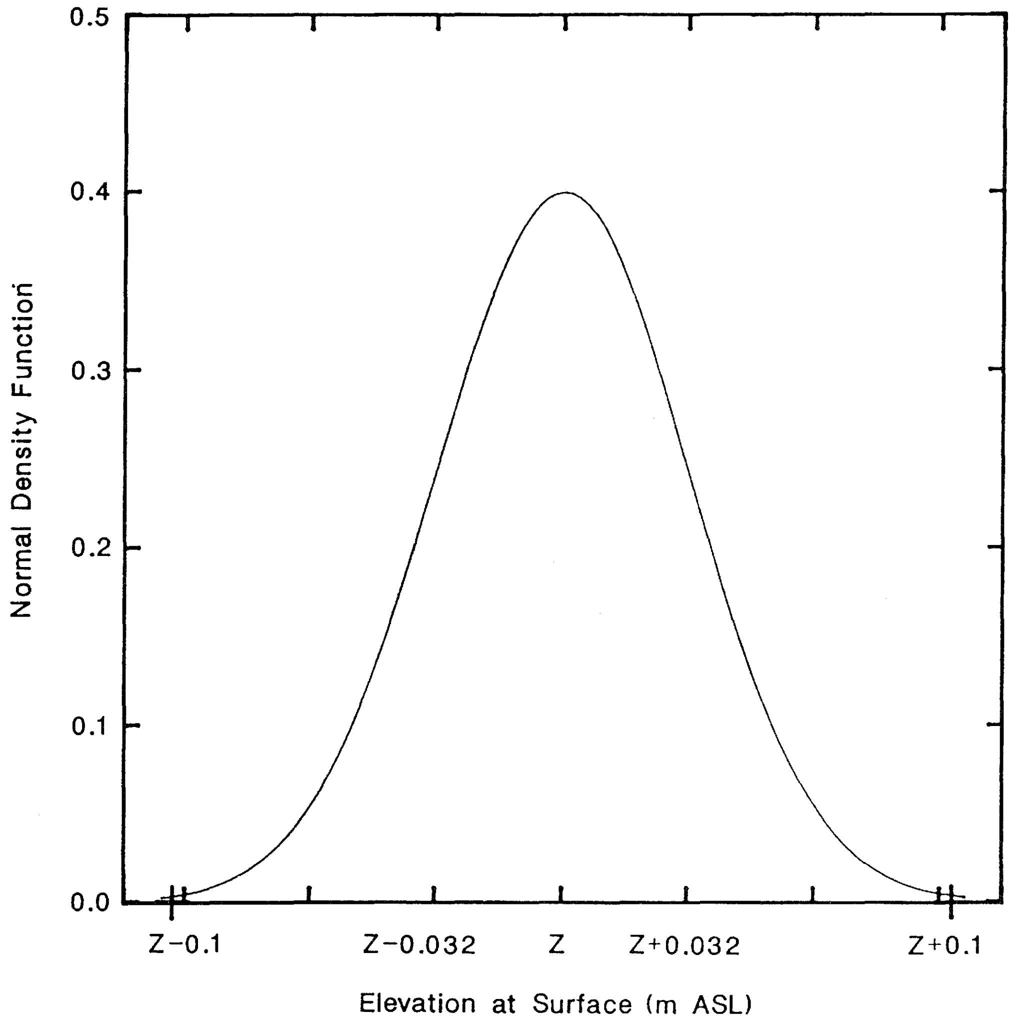


Figure 4.8 Probability Density Function for Elevation at Surface

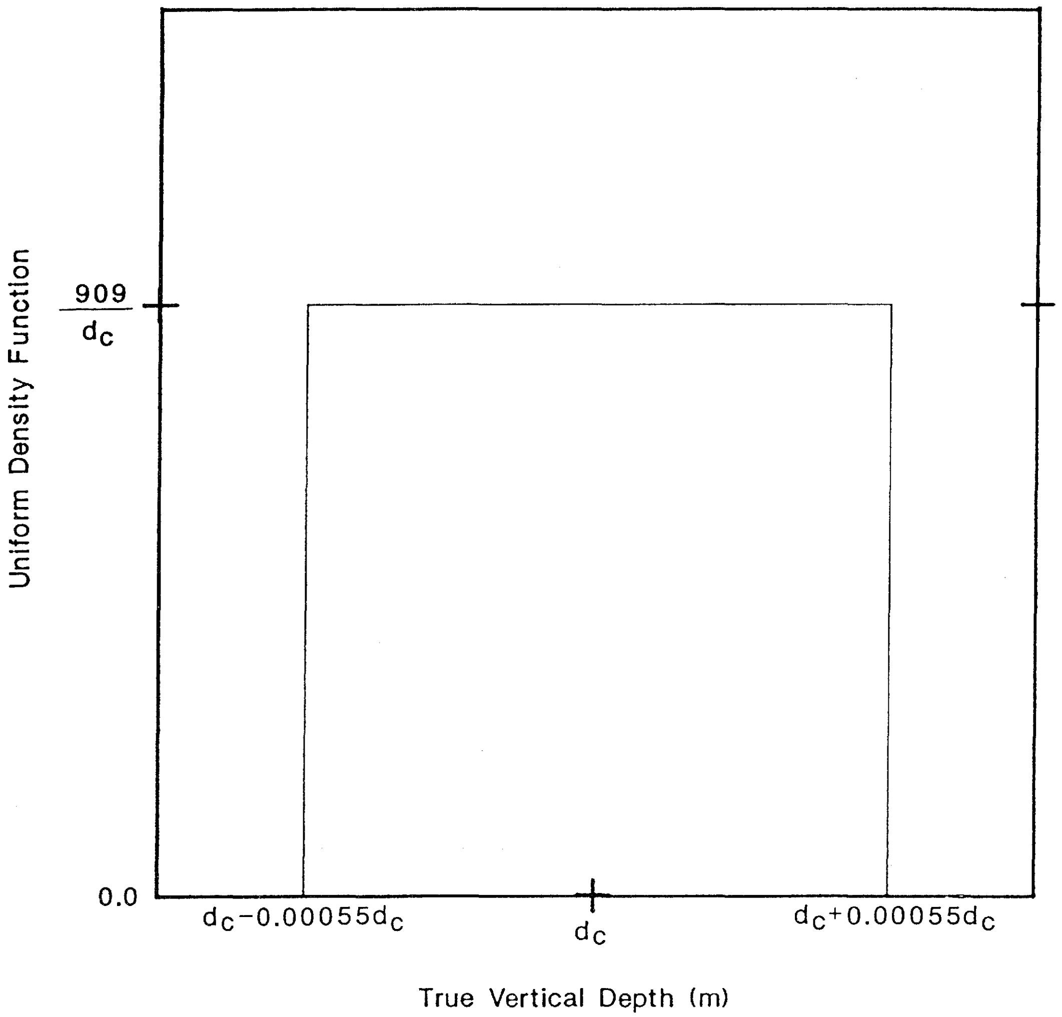


Figure 4.9 Probability Density Function for True Vertical Depth

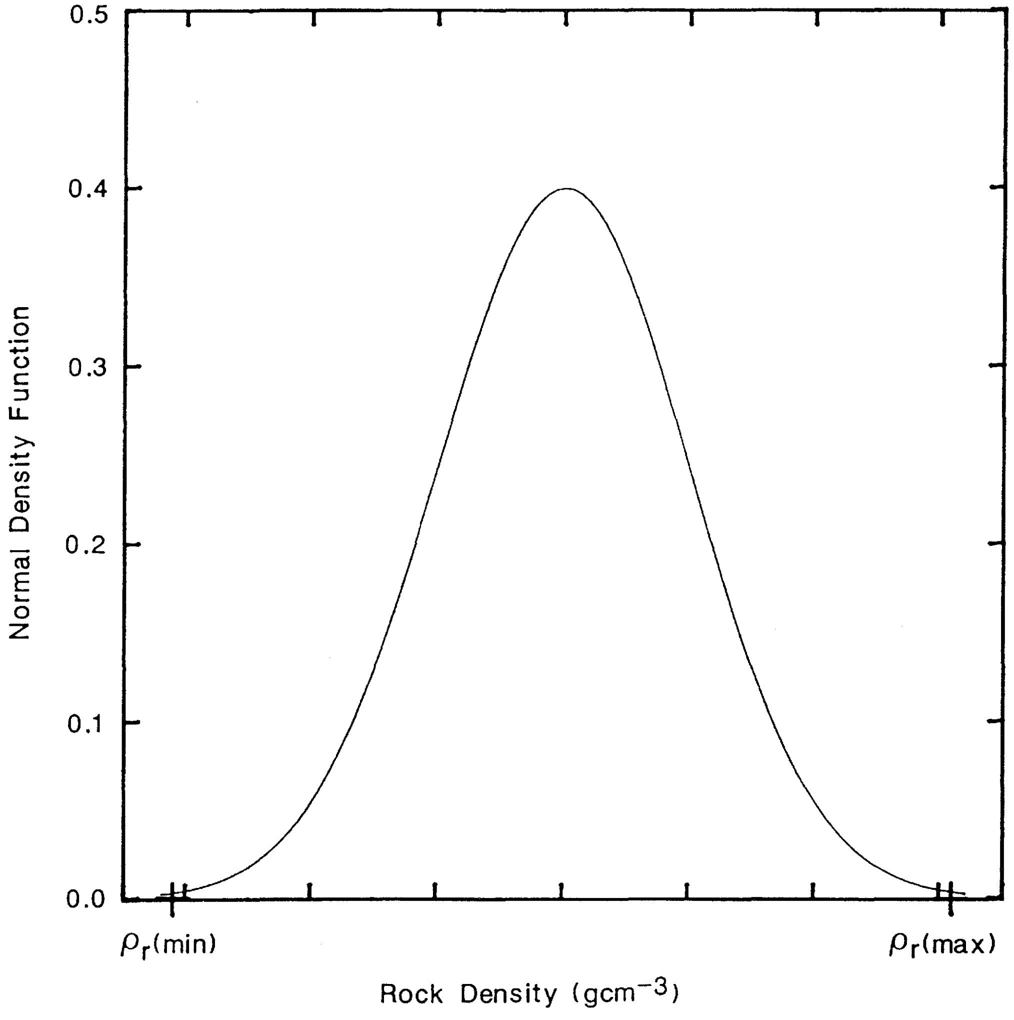


Figure 4.10 Probability Density Function for Rock Density

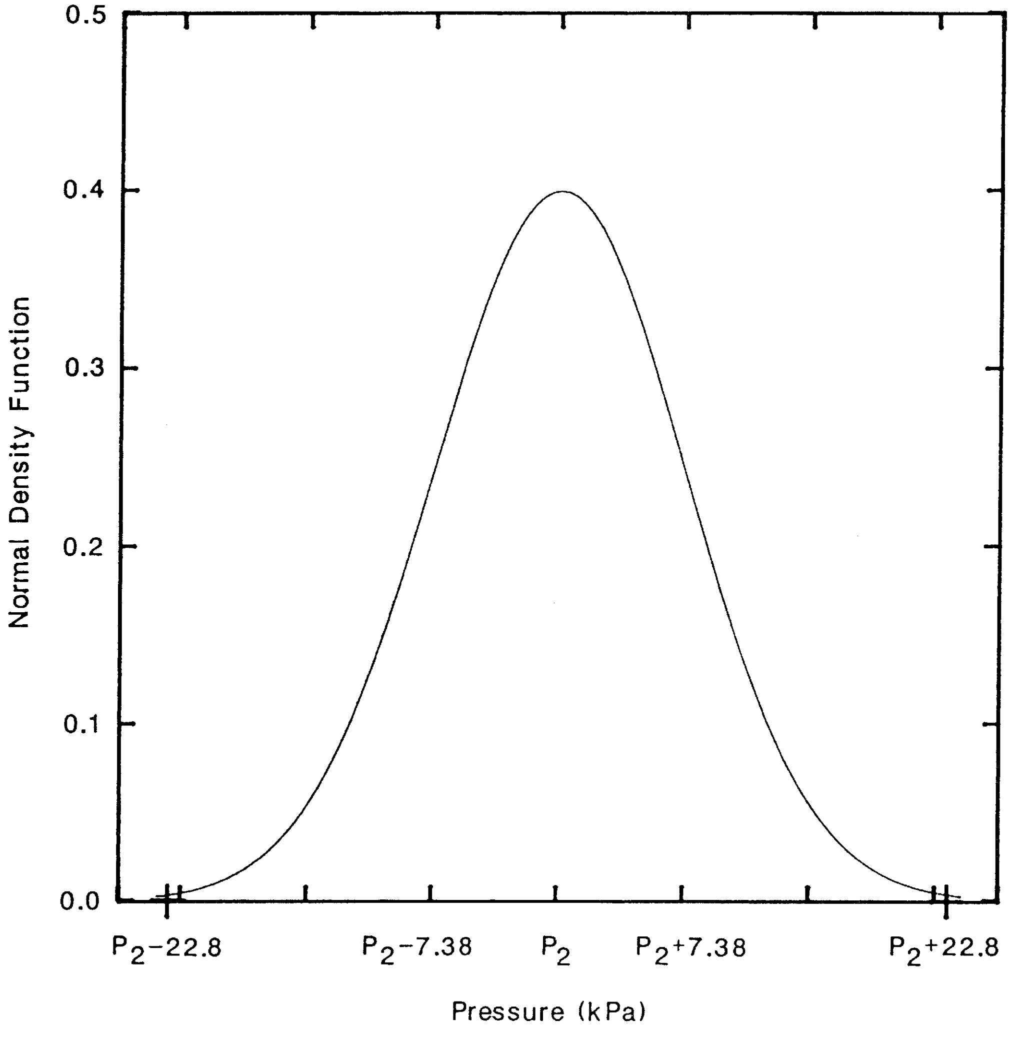


Figure 4.11 Probability Density Function for Pressure

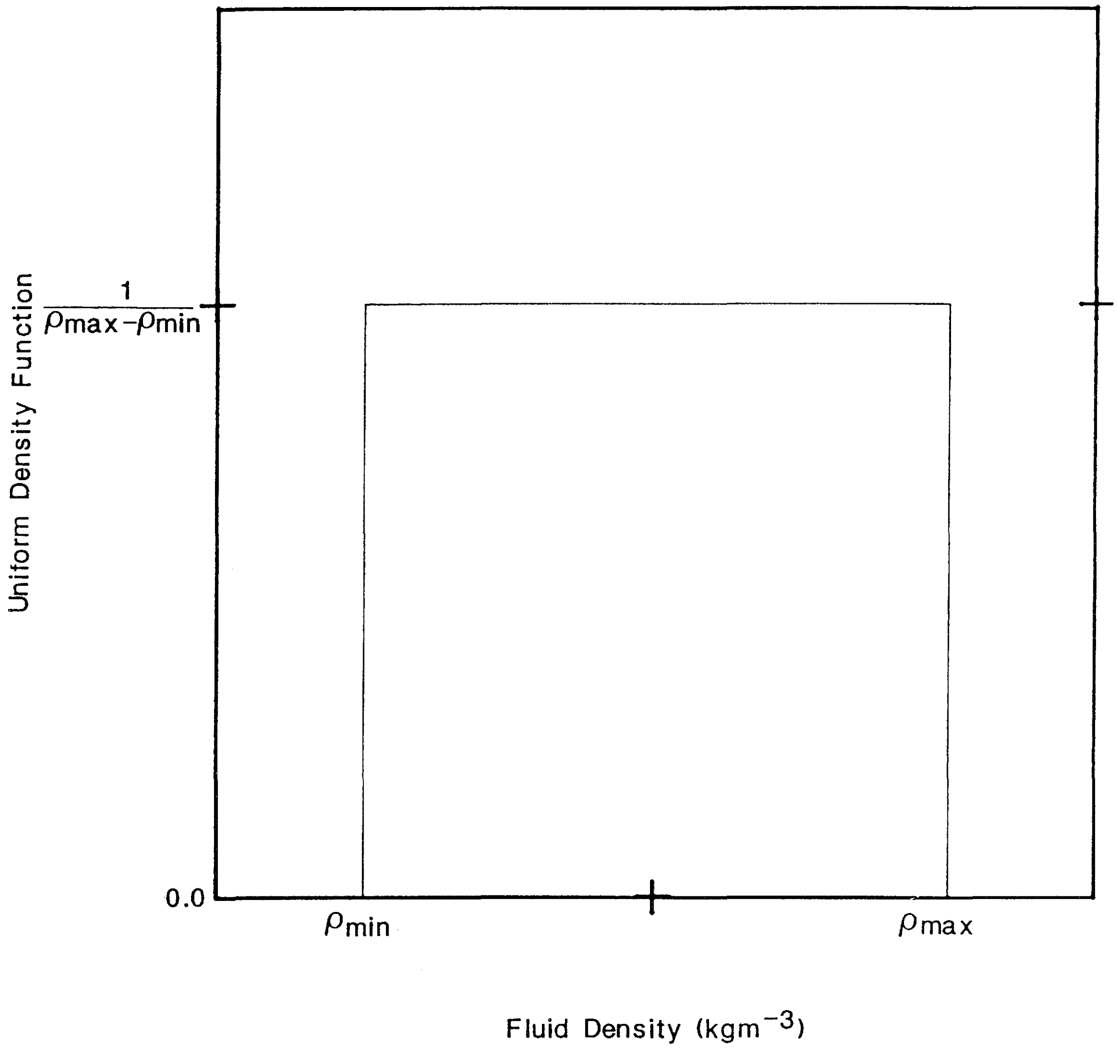
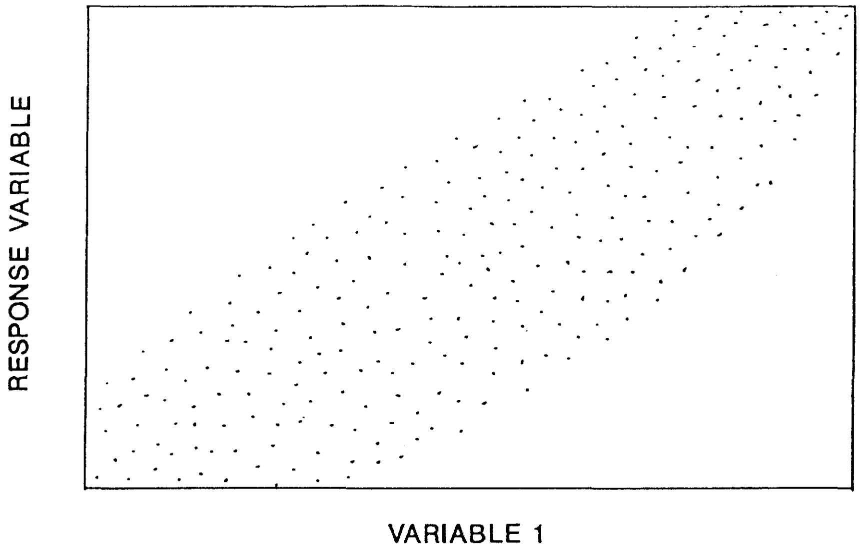


Figure 4.12 Probability Density Function for Fluid Density



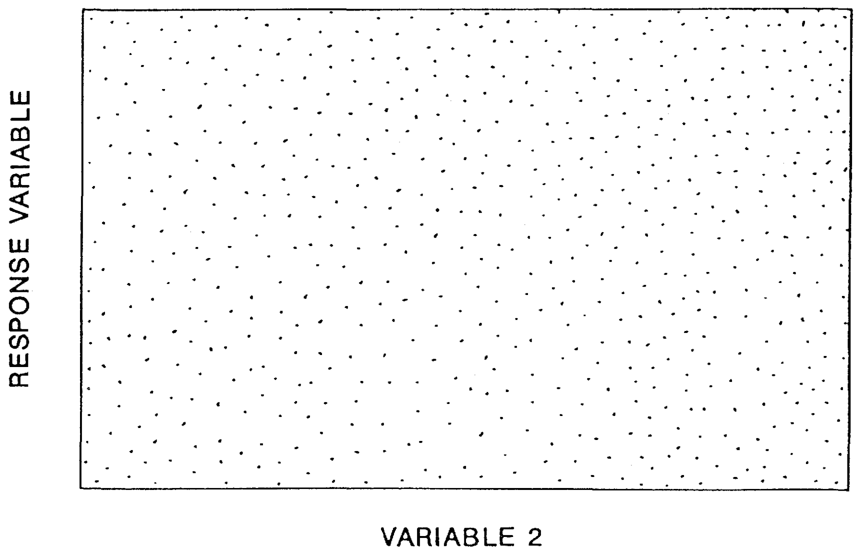


Figure 4.13 Example Scatter Plots of Input Variables 1 and 2 Versus a Response Variable

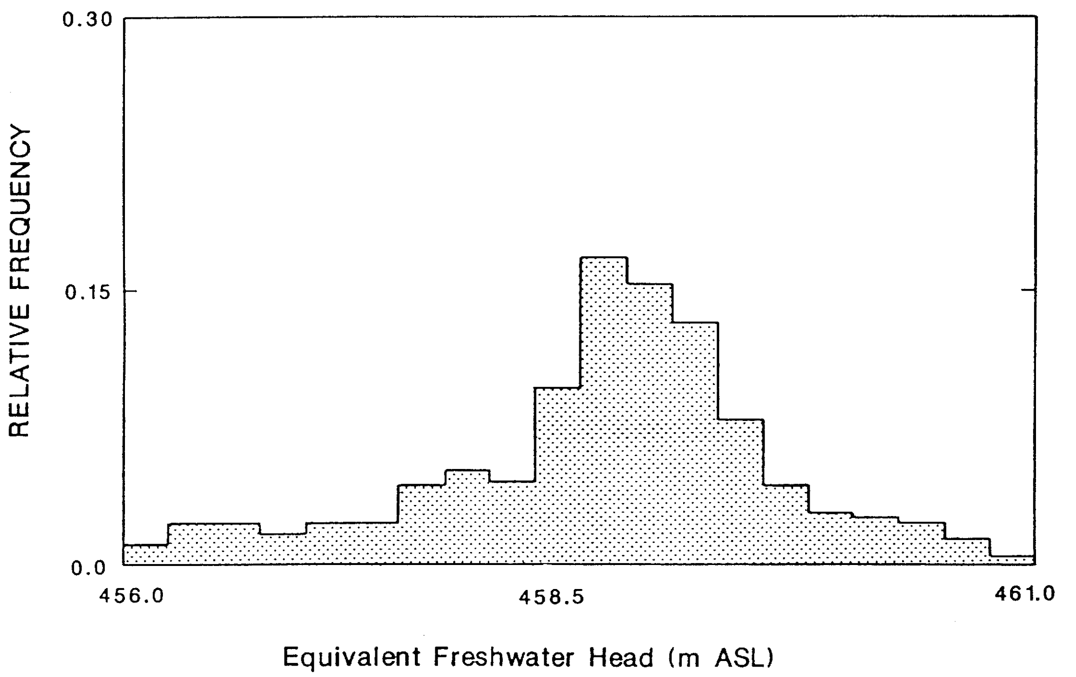


Figure 4.14 Example Histogram Showing Distribution of Equivalent Freshwater Head

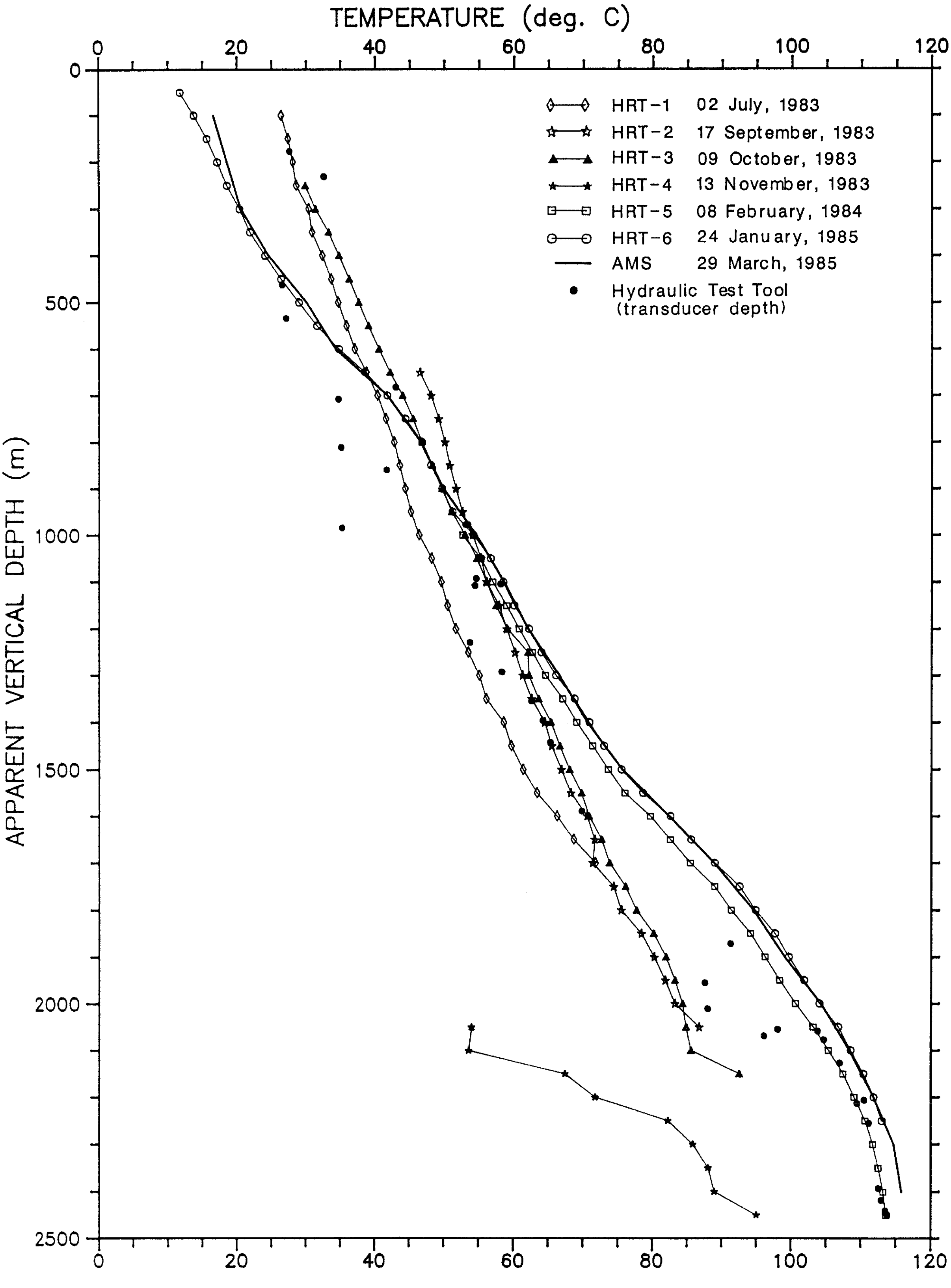


Figure 5.1 Temperature Data Used to Determine the Temperature-Depth Profile in the Weiach Borehole

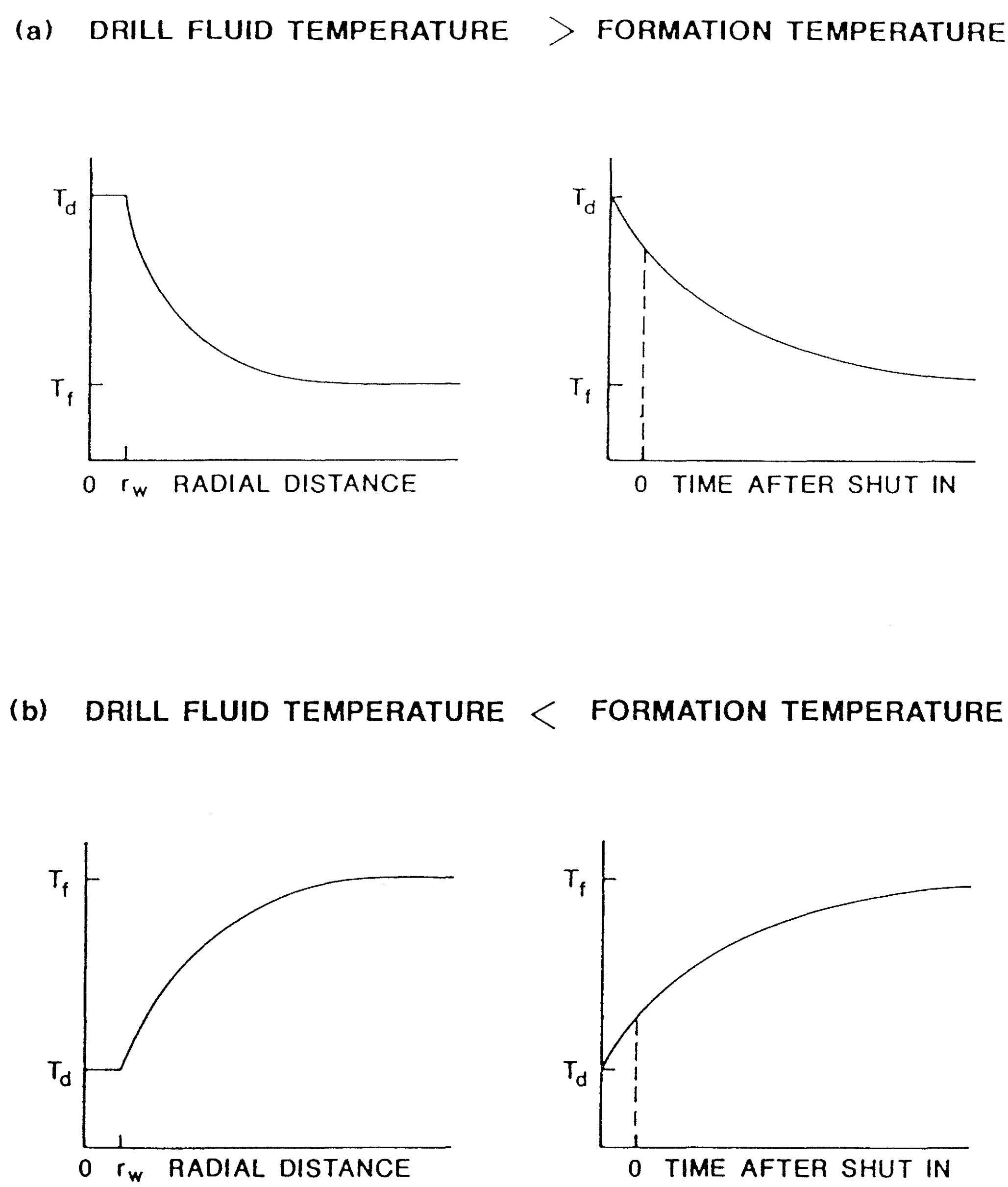


Figure 5.2 Schema of the Temperature Disturbance Around the Borehole and the Test Interval Temperature Response After Shut-in

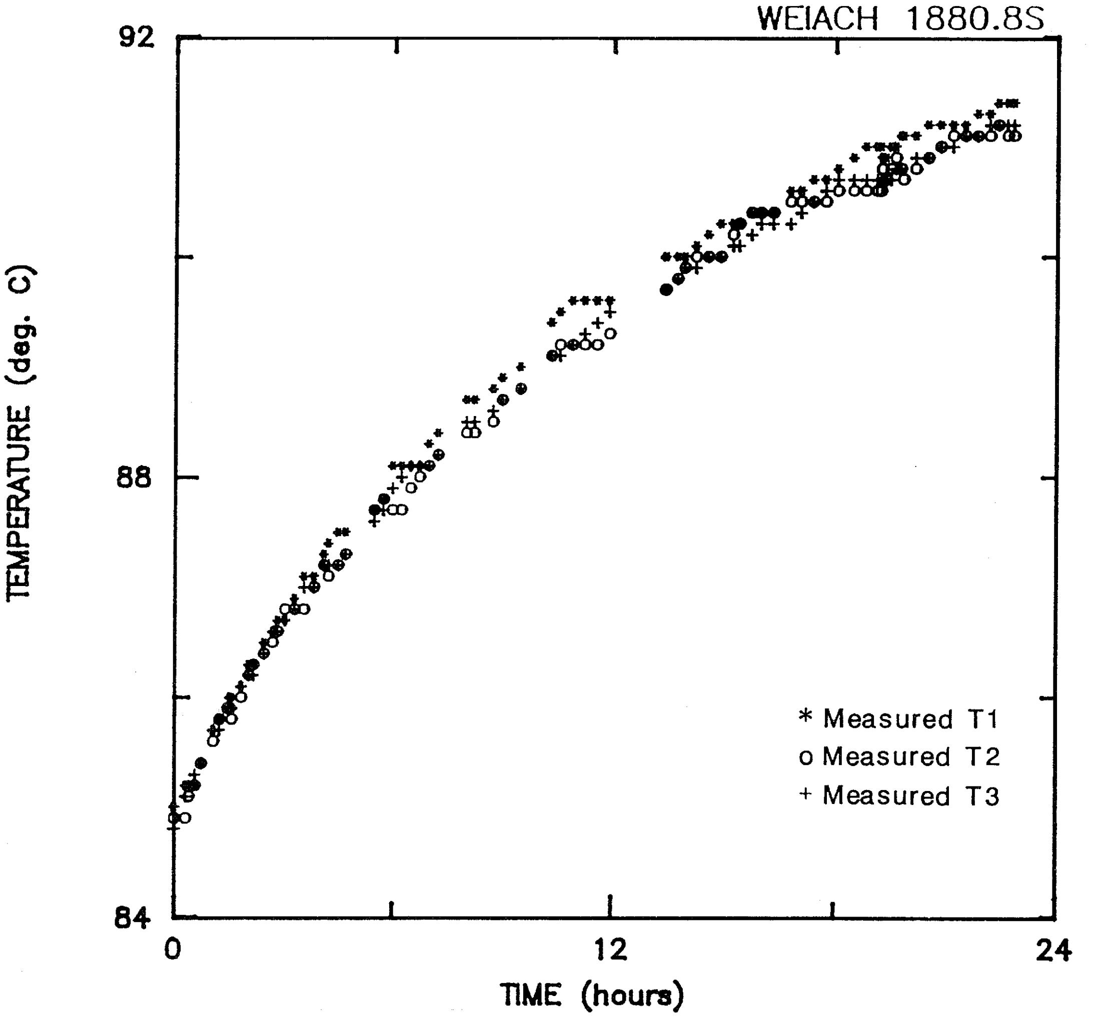


Figure 5.3 Typical Temperature Response Observed for Hydraulic Tests Completed During the Drilling Phase in the Weiach Borehole [Response For Test 1880.8S]

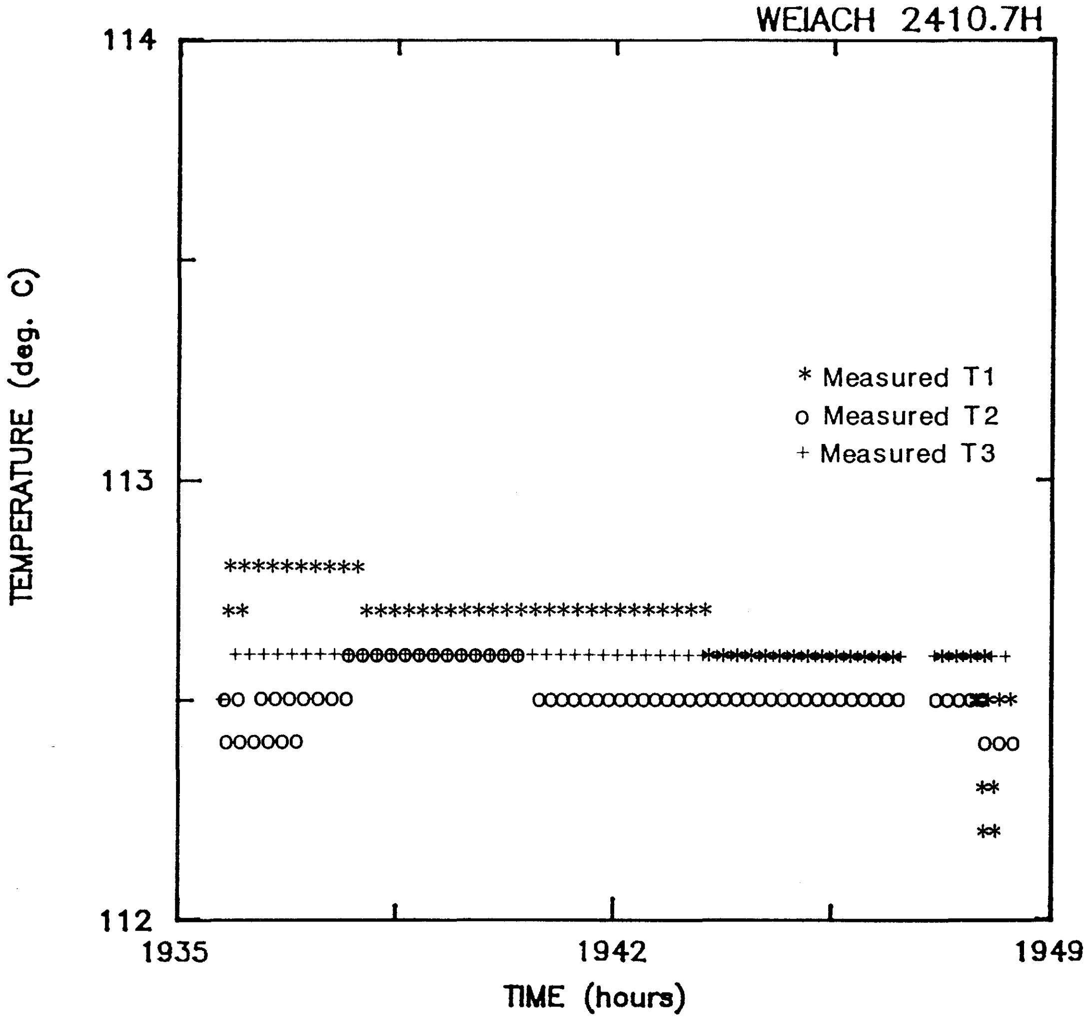


Figure 5.4 Typical Temperature Response Observed for Most Hydraulic Tests Completed After the Drilling and Shut-in Observation Period at the Weiach Borehole [Response for Test 2410.7H]

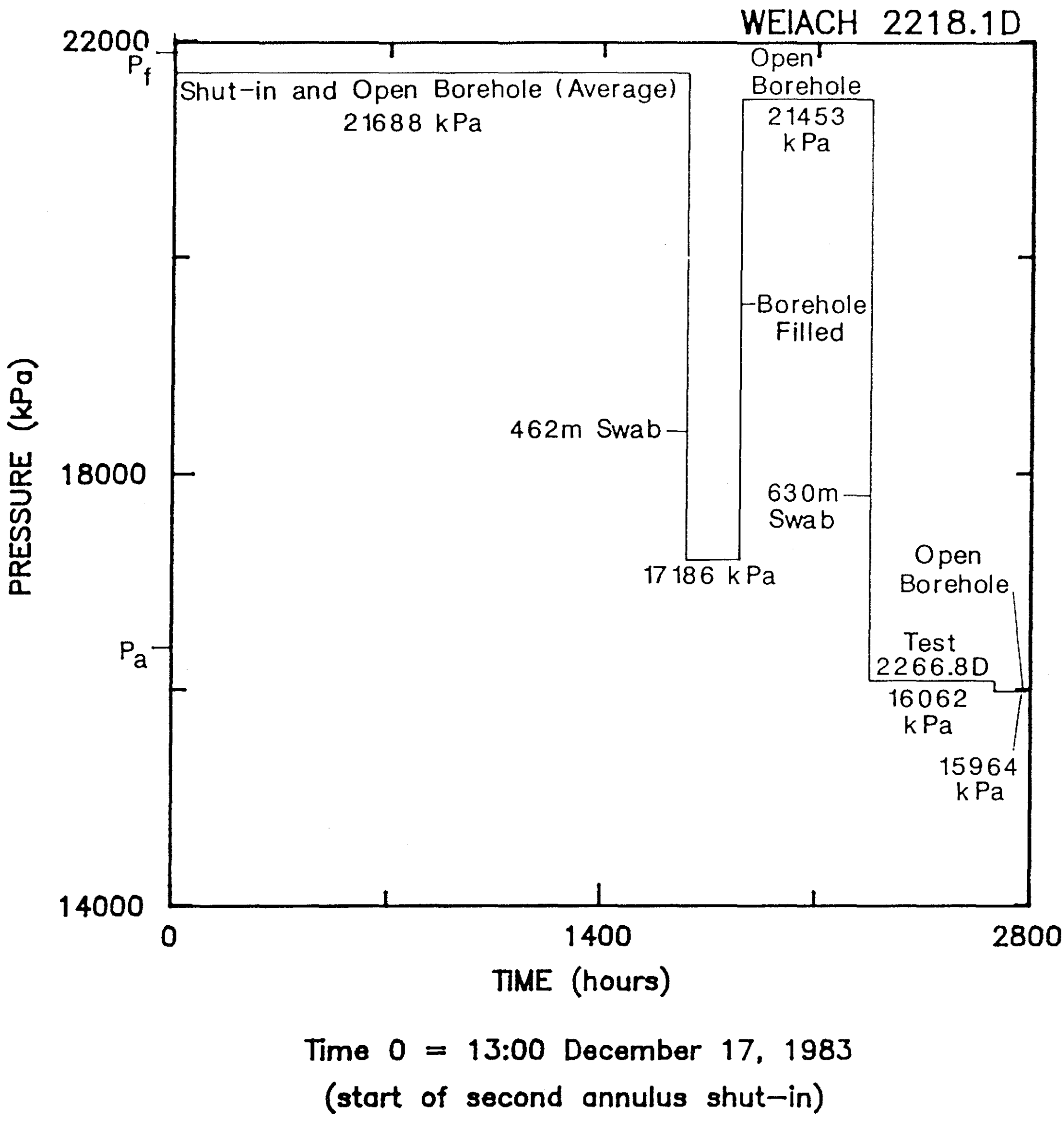


Figure 6.1 Assumed Pressure History on Test Interval From Start of Second Annulus Shut-in

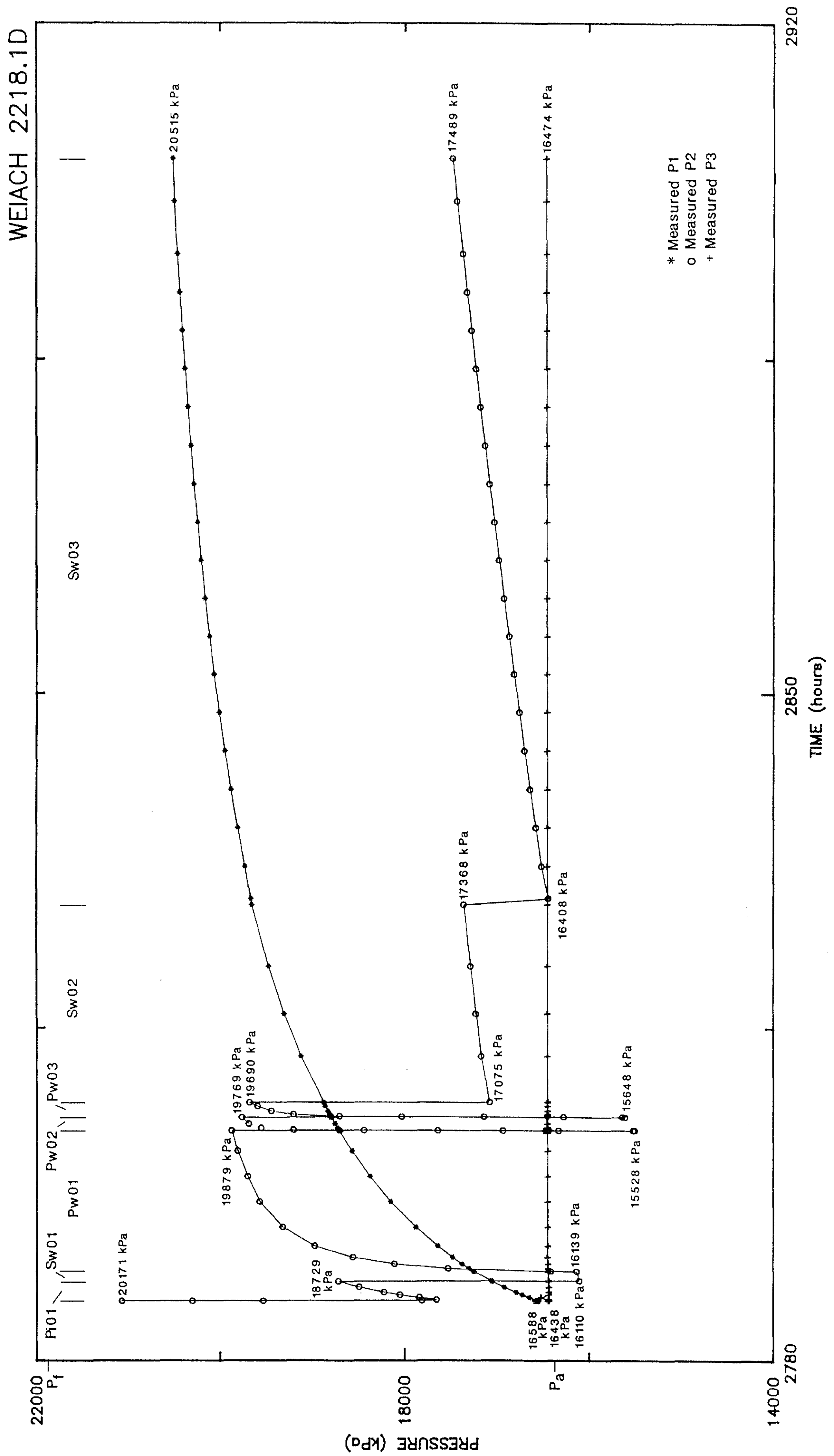


Figure 6.2 Measured Pressure Data for Test Interval, Test Sequence Designations, and Starting and Ending Pressure for Each Test

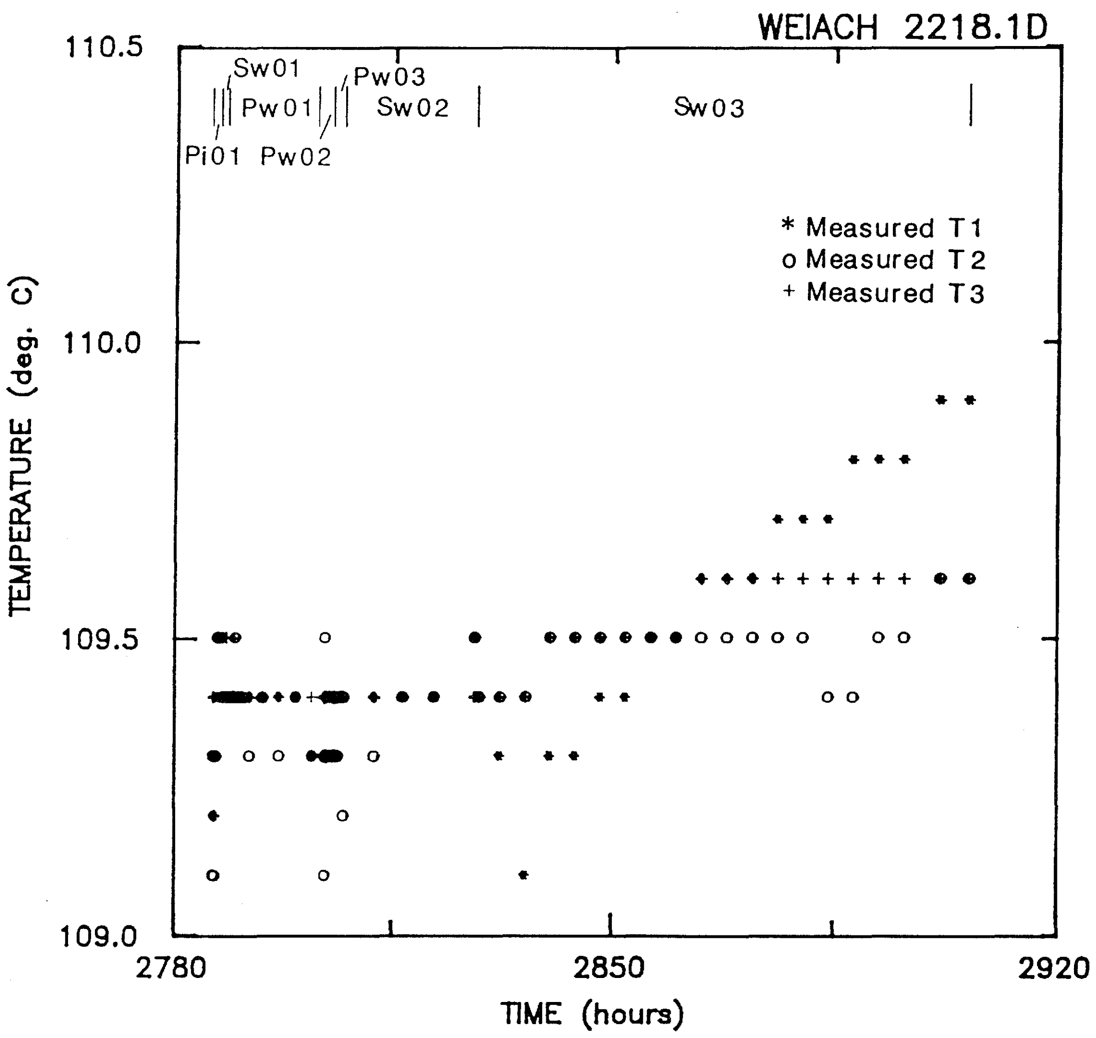


Figure 6.3 Measured Response for the T1, T2, and T3 Temperature Transducers

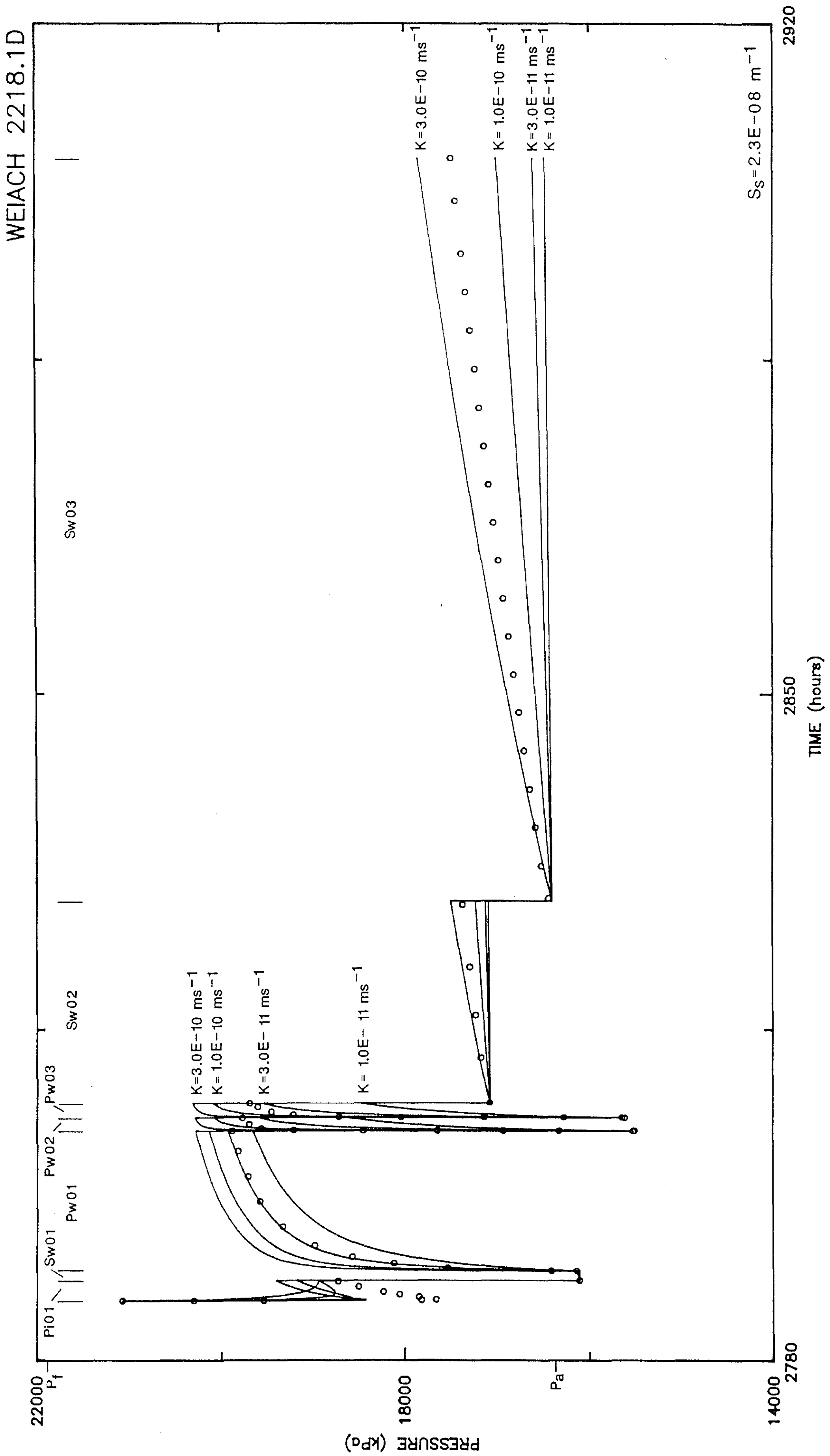


Figure 6.4a Measured (o) and Simulated Pressure Response for the Testing Sequence 2218.1D, Using S_s = 2.3E-08 m^{-1}

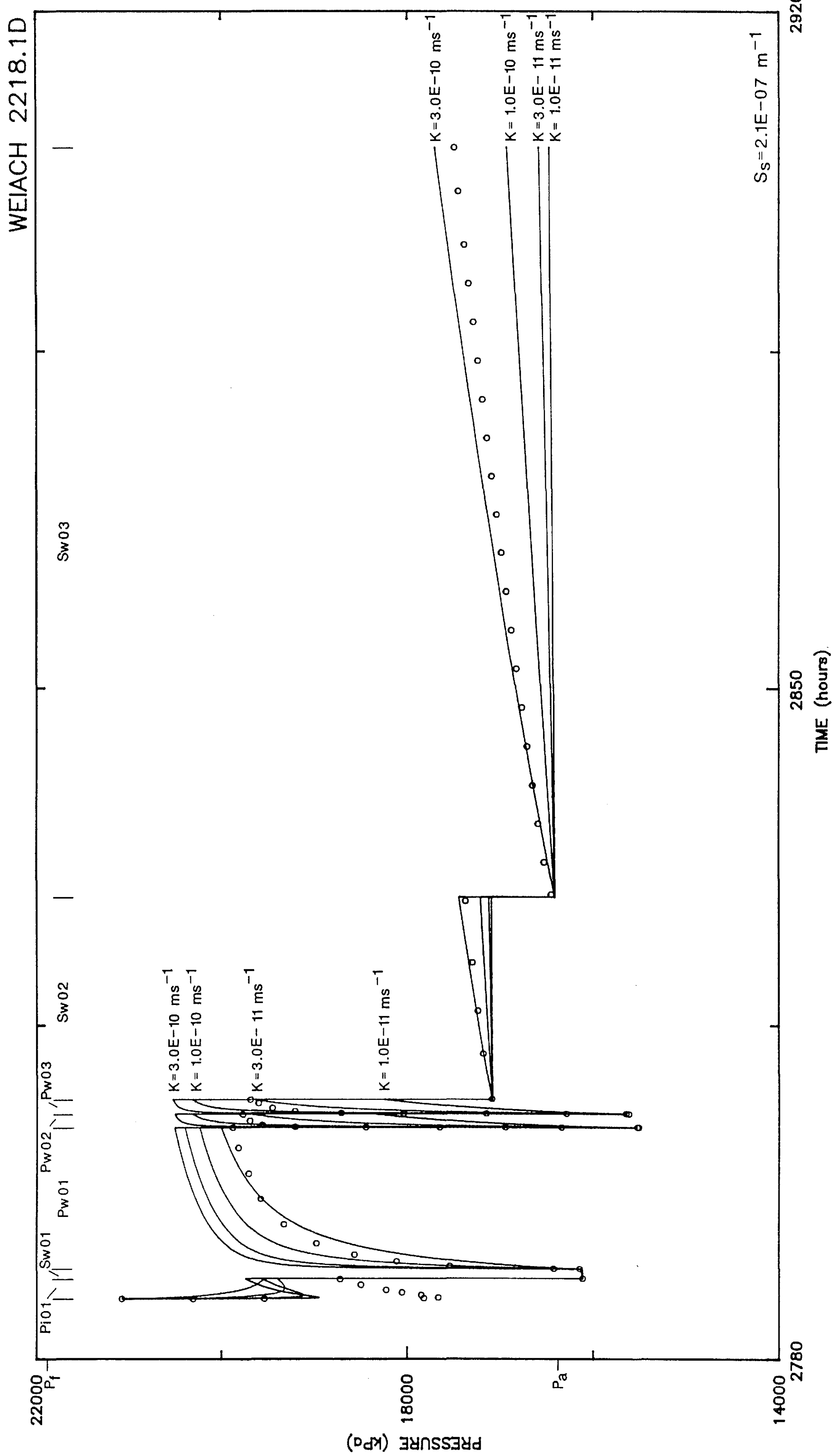


Figure 6.4b Measured (o) and Simulated Pressure Response for the Testing Sequence 2218.1D, Using S_s = 2.1E-07 m^{-1}

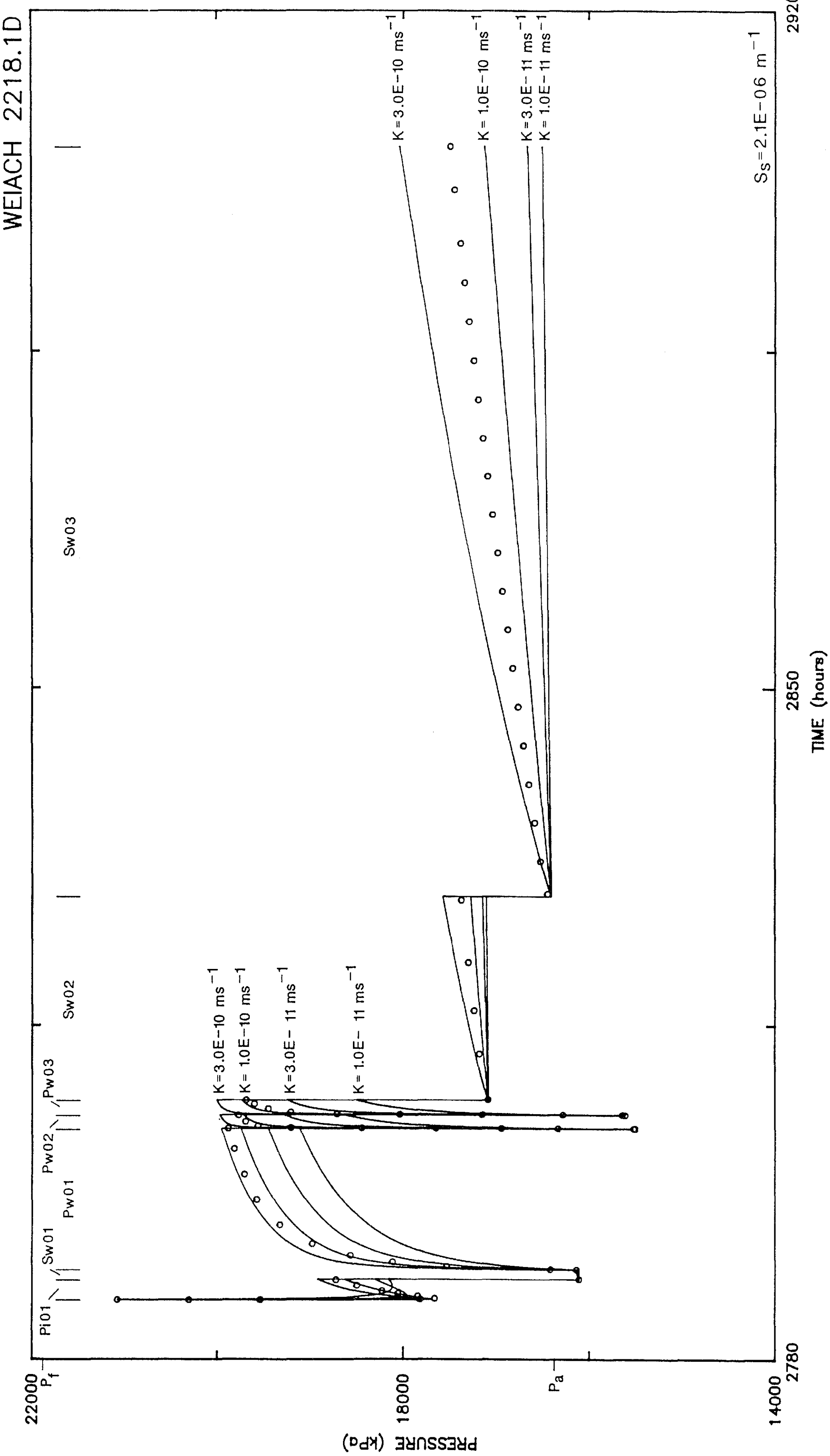


Figure 6.4c Measured (o) and Simulated Pressure Response for the Testing Sequence 2218.1D, Using S_s = 2.1E-06 m^{-1}

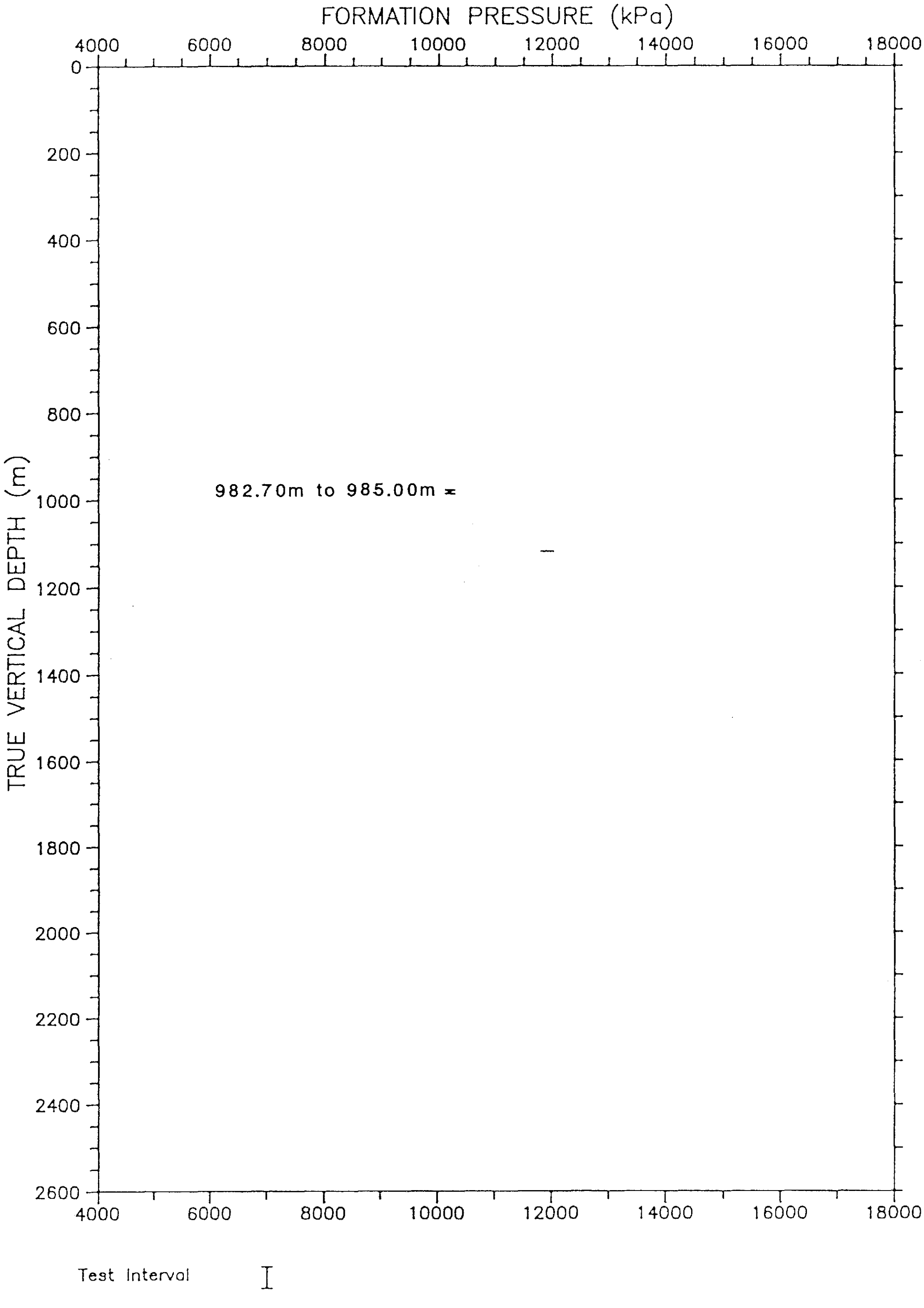


Figure 7.1 Estimated Formation Pressures from Hydraulic Testing at the Weiach Borehole

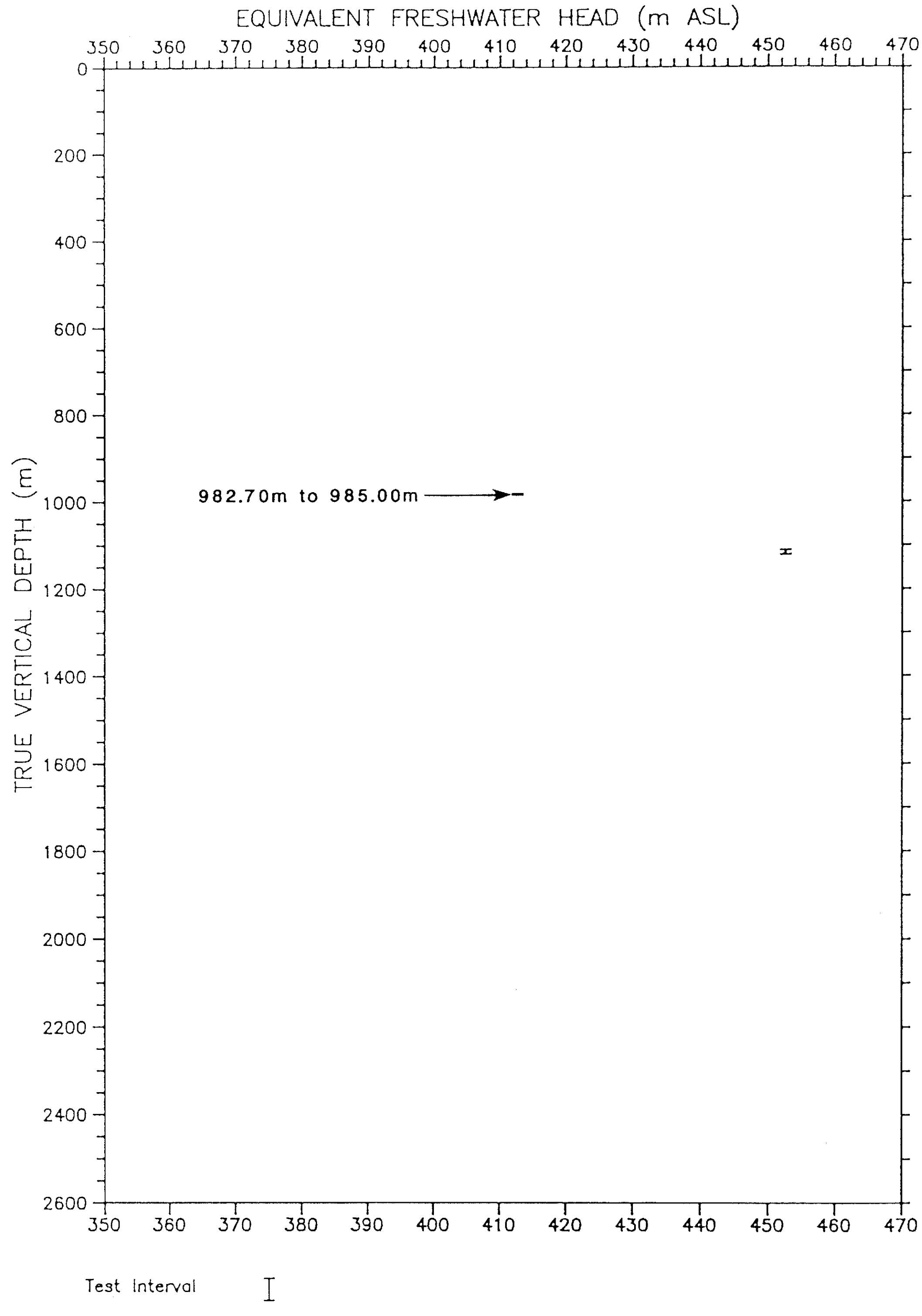
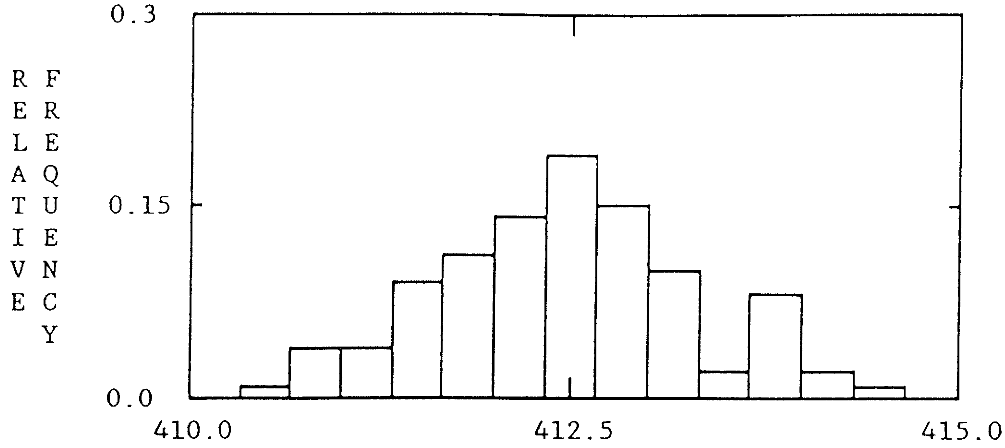


Figure 7.2 Estimated Equivalent Freshwater Heads from Hydraulic Testing at the Weiach Borehole

Test Type and Designation: Single Packer 984.2S



Sample Mean: μ = 412.4 (m ASL)
Sample Standard Deviation: σ = 0.83 (m ASL)
3σ = 2.50 (m ASL)
Width of Each Bin: 0.333 (m ASL)

VARIABLE RANGES

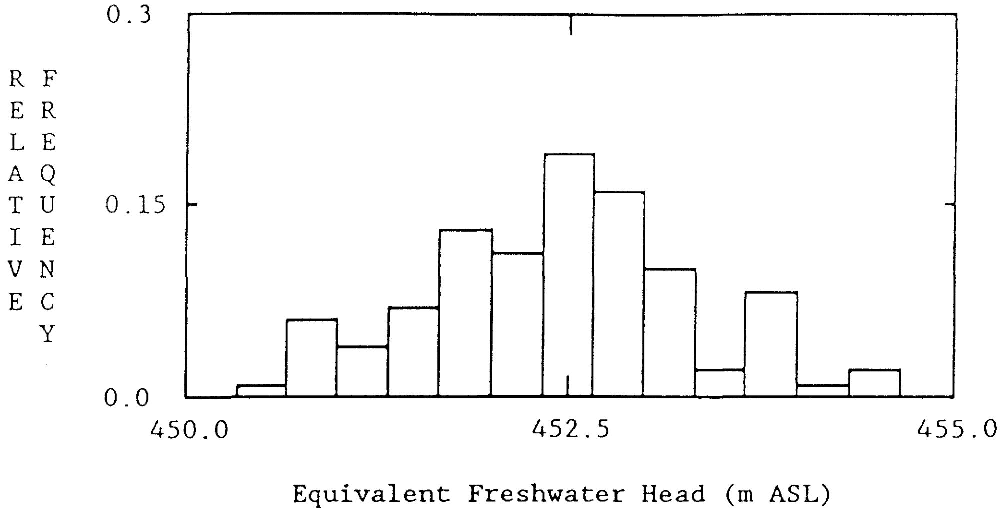
INPUT VARIABLES	MINIMUM	MAXIMUM
Elevation at Surface (m ASL)	368.59	368.74
Average Rock Density (g/cm^3)	2.31	2.66
Depth to Interval Center (m)	983.22	984.49
Pressure at P2 Transducer (kPa)	10095.2	10130.7
Fluid Density of Interval (g/cm^3)	1.000	1.006
OUTPUT VARIABLES		
Equivalent Freshwater Head (m ASL)	410.7	414.5
Pressure at Interval Center (kPa)	10163.8	10199.2
Gravitational Acceleration (cm/s^2)	980.918	980.933

PARTIAL RANK CORRELATIONS

VARIABLE	CORRELATION
Pressure at P2 Transducer	0.98
Depth to Interval Center	-0.94
Elevation at Surface	0.24
Average Rock Density	0.15
Fluid Density of Interval	-0.09

Figure 7.3a Uncertainty in Freshwater Head: Histogram, Statistics, Input, and Correlations for Test 984.2S

Test Type and Designation: **Double Packer 1117.5D**



Sample Mean: μ = 452.4 (m ASL)
Sample Standard Deviation: σ = 0.86 (m ASL)
3σ = 2.57 (m ASL)
Width of Each Bin: 0.333 (m ASL)

VARIABLE RANGES

INPUT VARIABLES	MINIMUM	MAXIMUM
Elevation at Surface (m ASL)	368.59	368.74
Average Rock Density (g/cm^3)	2.30	2.66
Depth to Interval Center (m)	1116.38	1117.83
Pressure at P2 Transducer (kPa)	11762.2	11797.7
Fluid Density of Interval (g/cm^3)	1.012	1.019
OUTPUT VARIABLES		
Equivalent Freshwater Head (m ASL)	450.6	454.5
Pressure at Interval Center (kPa)	11863.8	11899.2
Gravitational Acceleration (cm/s^2)	980.944	980.961

PARTIAL RANK CORRELATIONS

VARIABLE	CORRELATION
Pressure at P2 Transducer	0.98
Depth to Interval Center	-0.95
Elevation at Surface	0.24
Average Rock Density	0.17
Fluid Density of Interval	-0.04

Figure 7.3b Uncertainty in Freshwater Head: Histogram, Statistics, Input, and Correlations for Test 1117.5D

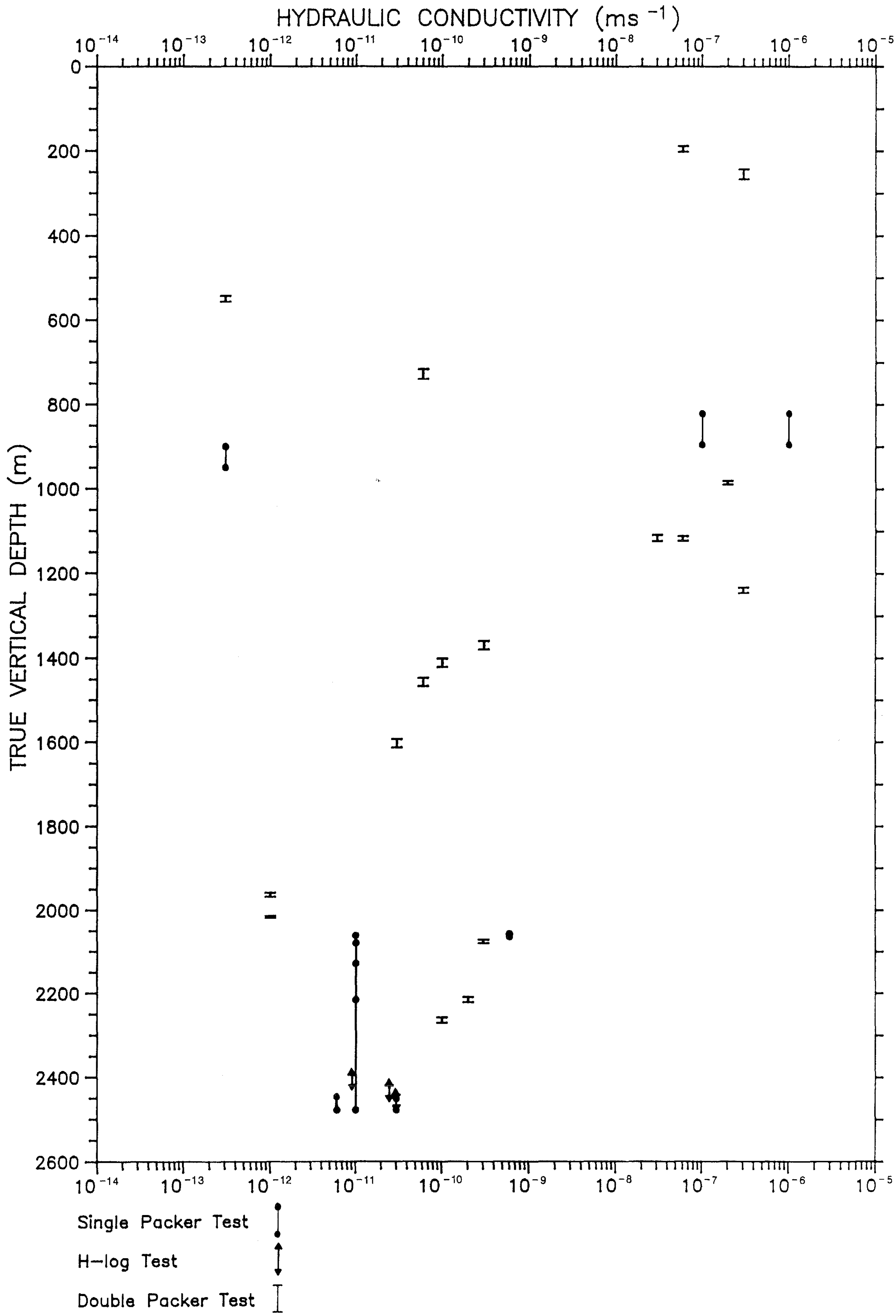


Figure 7.4 Estimated Hydraulic Conductivities from Hydraulic Testing at the Weiach Borehole

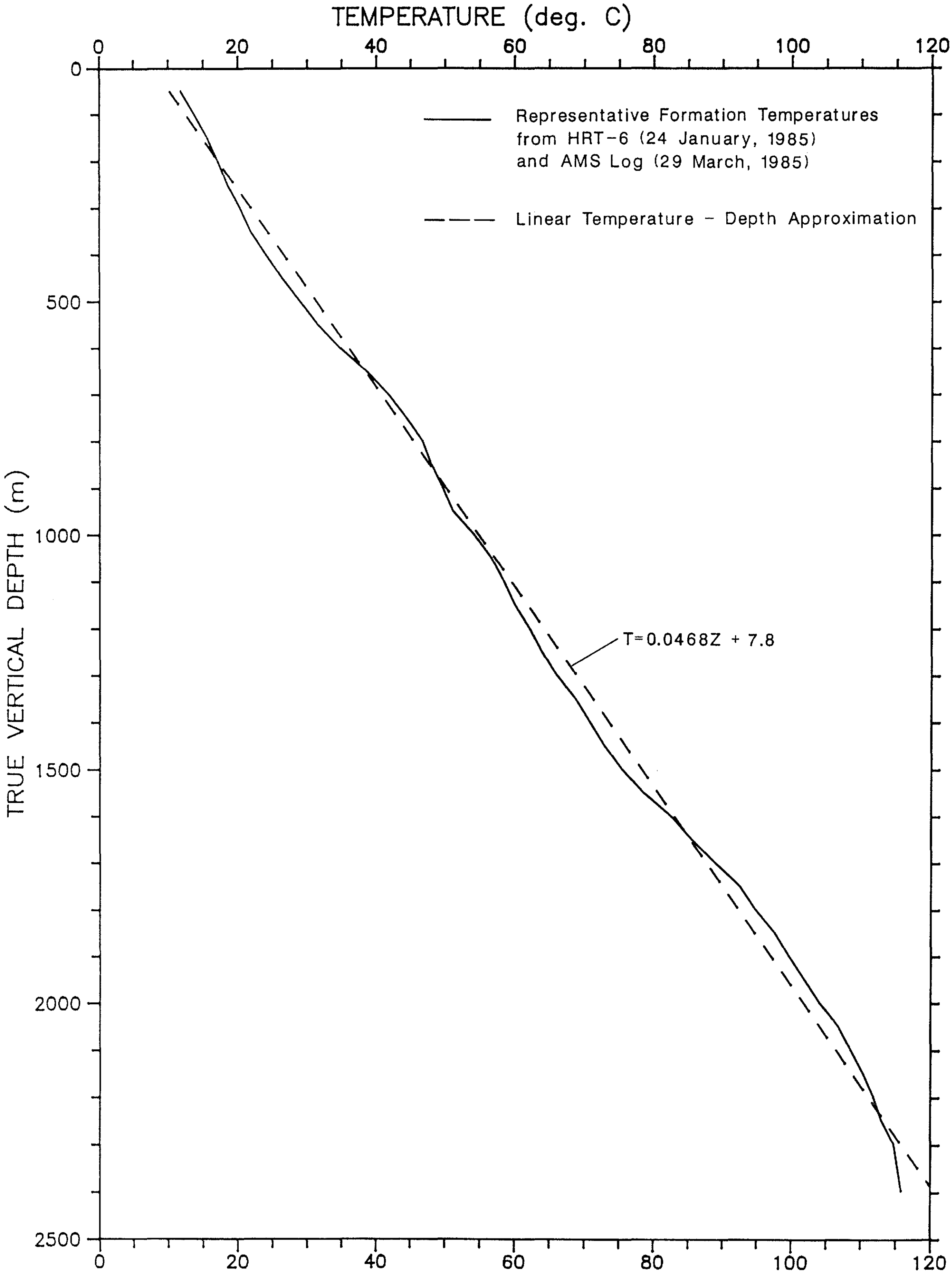


Figure 7.5 Representative Formation Temperatures and Linear Temperature-Depth Approximation Determined for the Weiach Borehole

FRESHWATER DENSITIES IN kgm^{-3} AT
TEMPERATURE (°C) AND PRESSURE (atm)

TEMP. PRESS	0.	10.	20.	30.	40.	50.
1.	999.80	999.50	998.00	995.52	992.16	988.04
25.	1000.90	1000.60	999.10	996.61	993.25	989.12
50.	1002.00	1001.70	1000.20	997.71	994.33	990.30
75.	1003.21	1002.81	1001.30	998.80	995.42	991.38
100.	1004.32	1003.92	1002.41	999.90	996.61	992.46
125.	1005.43	1005.03	1003.51	1001.00	997.61	993.54
150.	1006.54	1006.04	1004.52	1002.00	998.70	994.63
175.	1007.56	1007.15	1005.63	1003.11	999.80	995.72
200.	1008.67	1008.27	1006.64	1004.22	1000.80	996.71
225.	1009.74	1009.29	1007.71	1005.23	1001.85	997.76
250.	1010.82	1010.31	1008.78	1006.24	1002.91	998.80

TEMP. PRESS	60.	70.	80.	90.	100.
1.	983.28	977.90	971.91	965.44	958.41
25.	984.35	978.95	973.05	966.56	959.60
50.	985.51	980.10	974.18	967.68	960.80
75.	986.58	981.26	975.32	968.90	961.91
100.	987.75	982.32	976.47	970.03	963.11
125.	988.83	983.48	977.52	971.16	964.32
150.	989.90	984.54	978.67	972.29	965.44
175.	990.98	985.61	979.72	973.43	966.56
200.	992.06	986.68	980.87	974.47	967.68
225.	993.10	987.75	981.93	975.56	968.80
250.	994.13	988.83	982.99	976.66	969.93

Table 4.1 Temperature and Pressure Effects on Pure-Water Density (Calculated from Data in DORSEY, 1968)

Test Type and Designation: **Single Packer 926.2S**

Geology of test interval: Anhydrite with interbedded dolomite and shale.

Formation: Middle Muschelkalk

Fractures: Average less than one fracture per meter. 1 to 4 fractures per meter in thin interbedded shale and anhydrite layers.

Borehole fluid: Bentonite mud (s.g. 1.24)

Drilled borehole diameter in test interval: 216 mm

Average borehole diameter from caliper: 216 mm

Test interval length: 49.50 m

Apparent depth of test interval: 901.40 m to 950.90 m

True vertical depth of test interval: 901.10 m to 950.60 m

Apparent depth to center of test interval: 926.15 m

True vertical depth to center of test interval: 925.85 m

Apparent depth to pressure transducer P2: 895.59 m

True vertical depth to pressure transducer P2: 895.29 m

Datum elevation at ground surface: 368.66 m ASL

Barometric pressure: 101.9 kPa

Inside diameter of tubing string: 100.5 mm

Annulus pressure at transducer P3: 8915 kPa

Packer inflation pressure above annulus pressure: 9710 kPa

Drilling period of test interval (estimate):

09:50, 10 April, 1983 to 02:54, 16 April, 1983

Mid-point: 07:48, 14 April, 1983

Testing period: 19:32, 16 April, 1983 to 15:00, 17 April, 1983

Test designations and start times:

PSTA 19:32:02, 16 April, 1983
SwO1 07:29:42, 17 April, 1983
PwO1 08:16:03, 17 April, 1983

Time between middle of drilling and start of testing: 2.5 days

Temperature at probe: start of first test: 37.1°C

end of testing: 41.6°C

Table 4.2 Physical Description of the Geology and Testing Conditions at 926.2S

Test Type and Designation: **Single Packer 926.2S**

Formation		
Compressibility	3.0E-10	Pa^{-1}
Porosity	0.10	
Specific Storage	3.3E-06	m^{-1}
Fluid		
Compressibility (at formation temperature and pressure)	4.34E-10	Pa^{-1}
Density (at formation temperature and pressure)	994	kgm^{-3}
Thermal Expansion Coefficient	4.10E-04	$^{o}C^{-1}$
Test Interval		
Length	49.50	m
Diameter (caliper)	0.22	m
Annulus Pressure	8915	kPa
Formation Pressure (calibrated)	not applicable	
Formation Pressure (assumed)	8644	kPa
Conditions of Analysis		
Borehole Pre-Test Pressure History		yes
Thermal Effects		yes

Table 4.3 Parameters Used for Simulation of the Test Interval Pressure Response at 926.2S

Test Designation	Minimum Temperature Measured During Testing (°C)	Maximum Temperature Measured During Testing (°C)
195.0D	26.3	27.5
255.0D	33.3	39.6
479.6D	25.3	26.4
550.0D*	20.8	27.0
699.0D	41.0	43.1
728.0D	32.5	34.6
859.1SII**	35.0	35.0
926.2S	37.1	41.6
984.2S	46.3	53.3
985.3D	30.7	35.5
987.9D (1)	52.8	53.4
1111.0D	54.2	55.3
1116.5D (1)	57.6	58.0
1117.5D	49.3	54.3
1240.1D	52.1	53.7
1303.3D	57.4	59.1
1369.4D	62.1	62.6
1411.1D (1)	63.5	64.0
1456.9D	64.4	64.9
1603.1D	66.3	69.7
1880.8S	84.8	91.4
1965.1D	85.9	87.6
2018.5D	81.2	88.5
2063.3S	91.4	98.0
2077.4D	95.3	96.4
2218.0D (1)	109.1	110.4
2266.8D (1)	110.2	111.4
2272.7S (1)	103.6	104.5
2282.0S (1)	104.3	104.7
2306.9S (1)	106.2	107.0
2350.6S (1)	109.2	109.4
2410.7H (1)	112.4	112.8
2435.8H (1)	112.6	113.1
2458.2H (1)	113.4	113.8
2468.6SI	108.7	113.8
2468.6SII (1)	113.5	113.8

* Temperature measured during the early testing record.
** A single temperature measurement was taken during testing.
(1) Performed after 03 February, 1984.

Table 5.1 Summary of the Minimum and Maximum Temperatures Measured During Interval Hydraulic Testing

Test Designation[1]	Interval History Duration[2] (days)	Duration of Drilling Fluid Circulation[2] (days)	Time Between Fluid Circulation and Testing (days)	Test Duration (days)
728.0D	8.9	7	2	0.2
699.0D	12.8	10	3	0.3
550.0D	22.5	19	3	0.3
479.6D	26.5	23	4	0.2
255.0D	40.0	36	4	0.1
195.0D	47.2	40	7	0.3
859.1SII	15.9	4	12	0.2
926.2S	2.5	2	<1	0.8
984.2S	6.9	6	<1	1.3
985.7D	79.6	77*	2	3.6
1117.5D	71.9	71*	1	0.8
1240.1D	69.7	68*	1	0.5
1303.3D	66.1	64*	2	0.4
1603.1D	48.2	47*	1	0.8
1456.9D	61.6	60*	2	0.6
1411.1D	66.8	65*	2	0.5
1369.4D	70.4	67*	3	0.4
1880.8S	1.5	<1	1	0.9
1111.0D	110.5	109*	1	0.7
1965.1D	17.5	15*	2	0.4
2018.5D	15.6	14*	1	0.6
2063.3S	13.3	11*	2	1.5
2077.4D	14.8	14	1	0.5
2468.6SI	4.1	1	3	18.9
2468.6SII	83.2	1	82	4.5
2458.2H	95.2	5	90	0.2
2435.8H	121.5	6	115	0.3
2410.7H	121.2	6	115	0.5
2350.6S	131.2	9	122	0.8
2272.2S	138.9	15	124	0.8
2306.9S	135.7	11	125	0.8
2282.0S	142.0	14	128	0.8
2266.8D	147.3	15	132	13.9
2218.0D	176.0	25	151	16.9
1116.5D	401.9	183*	219	1.7
987.9D	689.0	194*	495	0.7

1 listed in chronological order
2 from middle of drilling
* fluid circulation was not continuous during period

Table 5.2 Summary of the Interval History, Circulation History, and Test Length for the Hydraulic Test Intervals

Log Type	Logging Date	Time Between End of Circulation and Logging Survey (days)
HRT-1	02 July, 1983	1
HRT-2	17 September, 1983	6
HRT-3	09 October, 1983	<1
HRT-4	13 November, 1983	1
HRT-5	08 February, 1984	88
HRT-6	24 January, 1985	438
AMS	29 March, 1985	502

Table 5.3 Summary of the Length of Time Between the End of Fluid Circulation and the Temperature Logging Surveys

Test Type and Designation: **Double Packer 2218.1D**

Geology of test interval: Biotite-gneiss and biotite-aplite.

Formation: Crystalline

Fractures: Average 7 per meter. Kakiritization present from 2218.69 m to 2224.63 m.

Borehole fluid: Traced de-ionized water

Drilled borehole diameter in test interval: 159 mm

Average borehole diameter from caliper: 174 mm

Test interval length: 13.03 m

Apparent depth of test interval: 2211.60 m to 2224.63 m

True vertical depth of test interval: 2208.80 m to 2221.73 m

Apparent depth to center of test interval: 2218.12 m

True vertical depth to center of test interval: 2215.22 m

Apparent depth to pressure transducer P2: 2205.92 m

True vertical depth to pressure transducer P2: 2203.12 m

Datum elevation at ground surface: 368.66 m ASL

Barometric pressure: 102.4 kPa

Inside diameter of tubing string: 62 mm

Annulus pressure at transducer P3: 16375 kPa

Packer inflation pressure above annulus pressure: 8450 kPa

Drilling period of test interval (estimate):

19:42, 16 October, 1983 to 15:23, 18 October, 1983

Mid-point: 01:10, 18 October, 1983

Testing period: 15:12, 11 April, 1984 to 16:38, 28 April, 1984

Test designations and start times:

Pi01	15:12:06, 11 April, 1984	Pw03	10:34:22, 12 April, 1984
Sw01	17:20:05, 11 April, 1984	Sw02	12:07:12, 12 April, 1984
Pw01	18:20:22, 11 April, 1984	Sw03	09:25:09, 13 April, 1984
Pw02	09:08:09, 12 April, 1984		

Time between middle of drilling and start of testing: 176 days

Temperature at probe: start of first test: 109.3°C

end of testing: 110.4°C

Table 6.1 Physical Description of the Geology and Testing Conditions For Test 2218.1D

Test Type and Designation: **Double Packer 2218.1D**

Formation		
Compressibility	2.2E-10	Pa^{-1}
Porosity	0.005	
Specific Storage	2.1E-06	m^{-1}
Fluid		
Compressibility (at formation temperature and pressure)	4.73E-10	Pa^{-1}
Density (at formation temperature and pressure)	962	kgm^{-3}
Thermal Expansion Coefficient	not applicable	
Test Interval		
Length	13.03	m
Diameter (caliper)	0.17	m
Annulus Pressure	16375	kPa
Formation Pressure (calibrated)	not applicable	
Formation Pressure (assumed)	21883	kPa
Conditions of Analysis		
Borehole Pre-Test Pressure History	yes	
Thermal Effects	no	

Table 6.2 Parameters Used for Simulation of the Test Interval Pressure Response For Test 2218.1D

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 (days)
984.2S	983.85	10181	412.6	N/R	6.9*
1117.5D	1117.10	11879	452.6	6.0E-08	71.9*

* not used in simulation

N/R = no recommendation

Table 7.1 Summary of Formation Pressures and Equivalent Freshwater Heads Determined from Hydraulic Testing in the Weiach Borehole

Test Desig-nation	Apparent Interval Top (m)	Apparent Interval Bottom (m)	True Interval Top (m)	True Interval Bottom (m)	Interval Length (m)	Estimated K (ms^{-1})	Estimated S_s (m^{-1})	Temp. at End of Test (°C)
195.0D	188.00	202.00	188.00	202.00	14.00	6.0E-08	6.6E-07	27.5
255.0D	242.90	267.00	242.90	267.00	24.10	3.0E-07	6.3E-06	34.7
479.6D	472.00	487.20	471.90	487.10	15.20	--	--	26.4
550.0D	543.00	557.00	542.90	556.90	14.00	3.0E-13	5.5E-06	27.0
699.0D	692.00	706.00	691.80	705.80	14.00	P/A	P/A	43.1
728.0D	715.90	740.00	715.70	739.70	24.10	6.0E-11	8.3E-07	34.6
859.1SI	822.00	896.10	821.70	895.80	74.10	1.0E-06	6.2E-05	43.8
859.1SII	822.00	896.10	821.70	895.80	74.10	1.0E-07	6.2E-05	no data
926.2S	901.40	950.90	901.10	950.60	49.50	3.0E-13	3.3E-06	41.6
984.2S	983.00	985.30	982.70	985.00	1.76*	N/R	N/R	51.9
985.3D	981.40	989.97	981.10	989.67	8.57	2.0E-07	2.6E-06	35.0
987.9D	982.00	993.74	981.70	993.44	5.80**	N/R	N/R	52.9
1111.0D	1097.50	1124.50	1097.10	1124.10	27.00	P/A	P/A	55.3
1116.5D	1109.20	1123.79	1108.80	1123.39	5.00**	3.0E-08	8.3E-07	58.1
1117.5D	1112.00	1123.00	1111.60	1122.60	11.00	6.0E-08	8.2E-07	54.3
1240.1D	1233.50	1246.79	1233.10	1246.39	13.29	3.0E-07	6.4E-07	53.6
1303.3D	1296.70	1309.99	1296.30	1309.59	13.29	P/A	P/A	58.1
1369.4D	1359.30	1379.50	1358.90	1379.10	20.15	3.0E-10	2.6E-06	62.5
1411.1D	1401.00	1421.15	1400.60	1420.75	20.15	1.0E-10	1.0E-05	64.1
1456.9D	1446.81	1466.96	1446.31	1466.46	20.15	6.0E-11	2.8E-06	64.8
1603.1D	1593.00	1613.15	1592.20	1612.25	20.15	3.0E-11	2.6E-06	68.4
1880.8S	1876.44	1885.10	1874.84	1883.50	8.66	P/A	P/A	91.3
1965.1D	1960.00	1970.24	1958.20	1968.44	10.24	1.0E-12	2.6E-06	87.4
2018.5D	2015.61	2021.28	2013.61	2019.28	5.67	1.0E-12	8.3E-06	88.1
2063.3S	2059.61	2067.00	2057.51	2064.80	7.39	6.0E-10	2.1E-07	98.0
2077.4D	2072.86	2082.00	2070.66	2079.80	9.14	3.0E-10	2.1E-07	96.0
2218.1D	2211.60	2224.63	2208.80	2221.73	13.03	2.0E-10	2.1E-06	110.4
2266.8D	2260.31	2273.34	2257.21	2270.24	13.03	1.0E-10	2.1E-07	111.0
2272.7S	2063.26	2482.20	2061.06	2477.50	417.20***	1.0E-11	2.1E-06	103.6
2282.0S	2081.80	2482.20	2079.60	2477.50	400.40	1.0E-11	2.1E-06	104.5
2306.8S	2131.34	2482.20	2128.84	2477.50	350.70	1.0E-11	2.1E-06	106.4
2350.5S	2218.84	2482.20	2215.94	2477.50	263.36	1.0E-11	2.1E-06	109.3
2410.7H	2398.23	2423.26	2394.13	2418.13	25.03	9.0E-12	3.0E-06	112.5
2435.8H	2423.26	2448.30	2418.96	2443.70	25.04	2.5E-11	2.1E-07	112.7
2458.2H	2445.71	2470.74	2441.11	2466.14	25.03	3.0E-11	2.1E-07	113.6
2468.6SI	2454.95	2482.20	2450.35	2477.50	27.25	3.0E-11	4.1E-08	113.8
2468.6SII	2454.95	2482.20	2450.35	2477.50	27.25	6.0E-12	2.1E-07	113.6

* Length of Buntsandstein in interval
** Length of perforations
*** Length of uncased borehole in interval
N/R No recommendation
-- Not analysable
P/A Only preliminary analysis; no recommendation

Table 7.2 Summary of Interpreted Hydraulic Conductivities and Specific Storages, and Measured Temperatures From Hydraulic Testing in the Weiach Borehole

A P P E N D I C E S

APPENDICES - Preface

In the following appendices which describe the individual test interpretations for the Weiach borehole, several conventions have been used to present the discussion of testing and the interpreted hydraulic conductivity, formation pressure, specific storage and freshwater head. For those intervals in which formation pressure was accurately determined (not assumed) and freshwater head was calculated from this formation pressure, these values are summarized in Table 7.1. The formation pressure corresponding to a test interval, as reported in an appendix, is for the P2 transducer elevation, unless stated otherwise. These values have been extrapolated to the interval center for the freshwater head calculation and these values are both reported in Table 7.1. The temperature of the formation reported for the test interval is taken from the T2 transducer which is adjacent to P2 and therefore represents the temperature of the fluid around the sensor carrier of the HTT. The recommended hydraulic conductivity and specific storage values for each interval are stated in the text of each appendix and summarized in Table 7.2.

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.

A list of abbreviations with definitions follows this page to familiarize the reader with terminology used in the test discussions.

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 195.0D (188.00 m to 202.00 m) - Malm

Test 195.0D was a double packer test of the Weiach borehole from 188.00 m and 202.00 m, completed with a DST tool. Two drill-stem tests, designated DST01 (consisting of a flow period Sw01 and a shut-in period Pw01) and DST02 (consisting of a flow period Sw02 and a shut-in period Pw02), were performed in the test sequence. The average flow rate during Sw01 was 3.2 L min^{-1} with a pressure recovery of 309 kPa over 1 hour. The reader is referred to GRISAK et al. (1985; pp. 56-60) for a detailed discussion of the pressure response which can be expected during shut-in of an interval. Squeeze effects on a test interval are discussed in this reference. An initial shut-in squeeze of 30 kPa was followed by a recovery within 95 percent of the estimated formation pressure during Pw01. The flow during Sw02 was 3.4 L min^{-1}. Test Pw02 had a recovery to 90 percent of the formation pressure. During the testing sequence, the temperature rose from 26.3°C to 27.5°C. Thermal effects were not included in the simulation due to the high hydraulic conductivity of the interval.

The testing sequence was simulated using GTFM. Diagnostic Horner plots of the shut-in periods indicate that the measured pressure response was affected by a pressure transient or finite boundary which reduced the late time pressure responses. Therefore, a formation pressure of 1630 kPa was determined from the measured pressure data during the middle portion of the build-up periods to minimize pressure disturbance around the borehole and boundary effects. Figure 1 shows the measured and simulated pressure responses for the range of hydraulic conductivity 1.0E-08, 3.0E-08, and 1.0E-07 ms^{-1} for a specific storage of 6.6E-07 ms^{-1}. The most reasonable fit of the measured data is for a hydraulic conductivity of 6.0E-08 ms^{-1} at a specific storage of 6.6E-07 m^{-1}. Varying the specific storage by one order of magnitude higher and lower than the base case specific storage 6.6E-06 m^{-1} results in about half an order of magnitude change in the best estimate of hydraulic conductivity for the interval.

The measured shut-in pressures during tests Pw01 and Pw02 were higher than the simulated pressure responses. Fluid loss to the formation reported while drilling the interval and the 47 day pre-test history could cause a pressure transient which would affect the measured pressure recoveries. Due to this fact, the formation pressure was not calibrated. The change in the fit of the two flow periods could be the effect of mud invasion into the formation. The objective of the first flow period in a DST sequence is usually to clean the formation. A higher degree of confidence should be placed in the hydraulic conductivity based on the simulation of the final DST test (DST02).

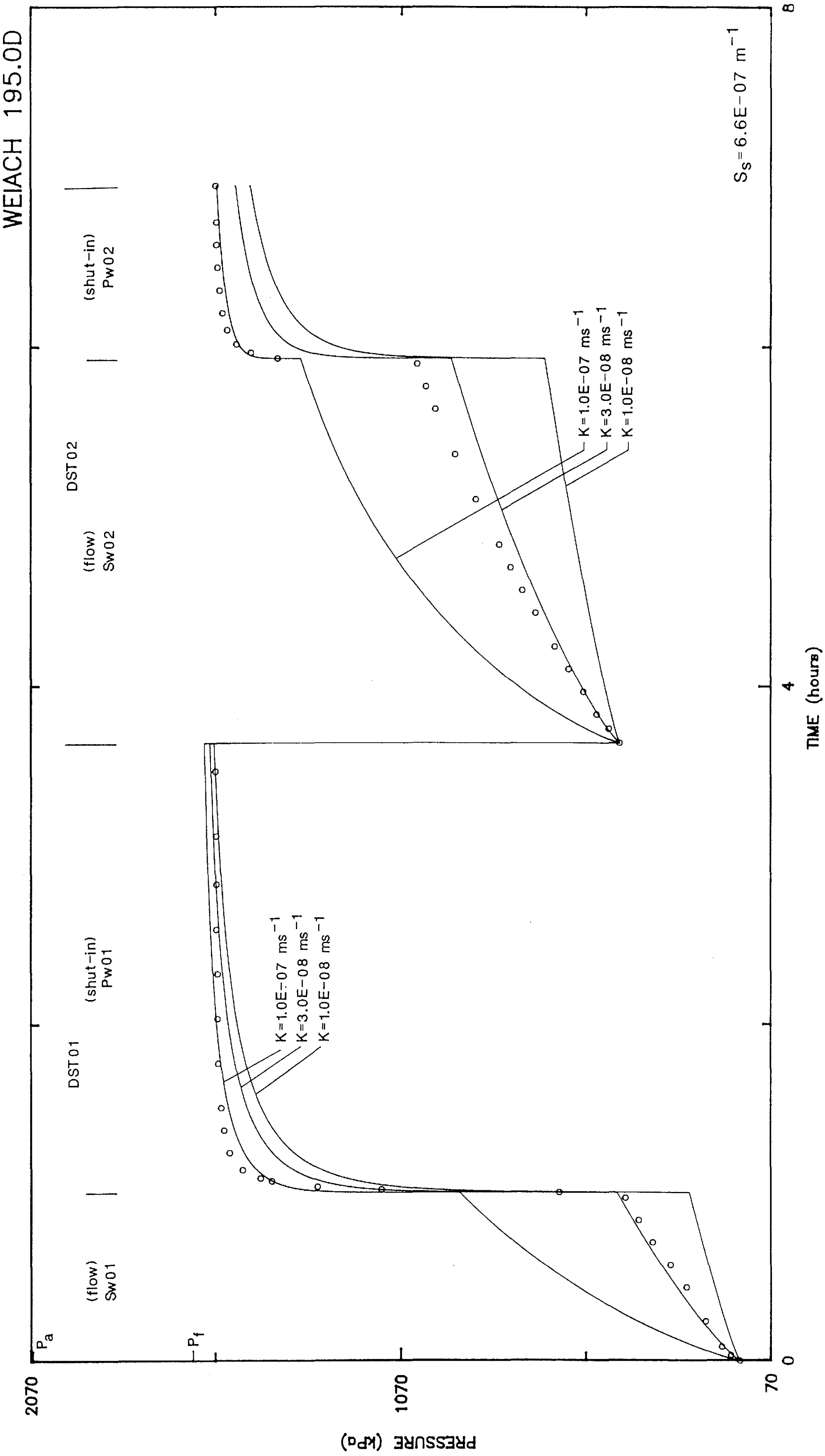


Figure 1 Measured (o) and Simulated Pressure Responses for the Testing Sequence

Test 255.0D (242.90 m to 267.00 m) - Malm

Test 255.0D was a double packer test in the Malm Formation of the Weiach borehole from 242.90 m to 267.00 m, completed with a DST tool. The testing sequence was performed over about 19 hours from 03 March, 1983 to 04 March, 1983. A drill-stem test was completed in the testing sequence. Because of over 13 hours of swabbing of the test interval during the flow period, only the first 2.6 hours of the flow period (Sw01) of the drill-stem test was used in this analysis.

The drill-stem tool used in the testing sequence was equipped with one pressure and one temperature transducer located above the packed-off interval and two external pressure transducers located within the packed-off interval. The measured pressure response of the internal transducers were used for this test analysis. Test Sw01 had an initial pressure of 344 kPa and recovered to a pressure of 2131 kPa over 2.6 hours. During the testing sequence, the temperature ranged from 33.9°C to 38.9°C. Thermal effects were not included in the simulation because the thermal effects on flow test (open tubing string) recovery are not significant. The anomalous temperature response during the flow period does not appear to be explained by movement of fluid past the temperature sensor.

The testing sequence was simulated with GTFM. The formation pressure of 2154 kPa was determined by Horner analysis of the shut-in period of the drill-stem test. The shut-in period was preceded by 13 hours of swabbing the interval. The formation pressure would be influenced by the underpressure transient created from the swabbing period and would not represent the undisturbed formation pressure. The formation pressure of 2154 kPa would not be calibrated for this reason. Figure 1 shows the measured and simulated pressure responses for the range of hydraulic conductivity 1.0E-07, 3.0E-07 and 1.0E-06 ms^{-1} for a specific storage of 6.3E-06 m^{-1}. The most reasonable fit of the measured data is for a hydraulic conductivity of 3.0E-07 ms^{-1} at a specific storage of 6.3E-06 m^{-1}. Varying the specific storage by an order of magnitude higher and lower than the base case specific storage 6.3E-06 m^{-1} results in less than half an order of magnitude change in the best estimate of hydraulic conductivity for the interval.

The measured pressure response dropped by about 30 kPa at approximately 0.35 hours into the flow period. This appears to be a tool related problem and had less than half an order of magnitude affect on the best-fit hydraulic conductivity of 3.0E-07 ms^{-1}.

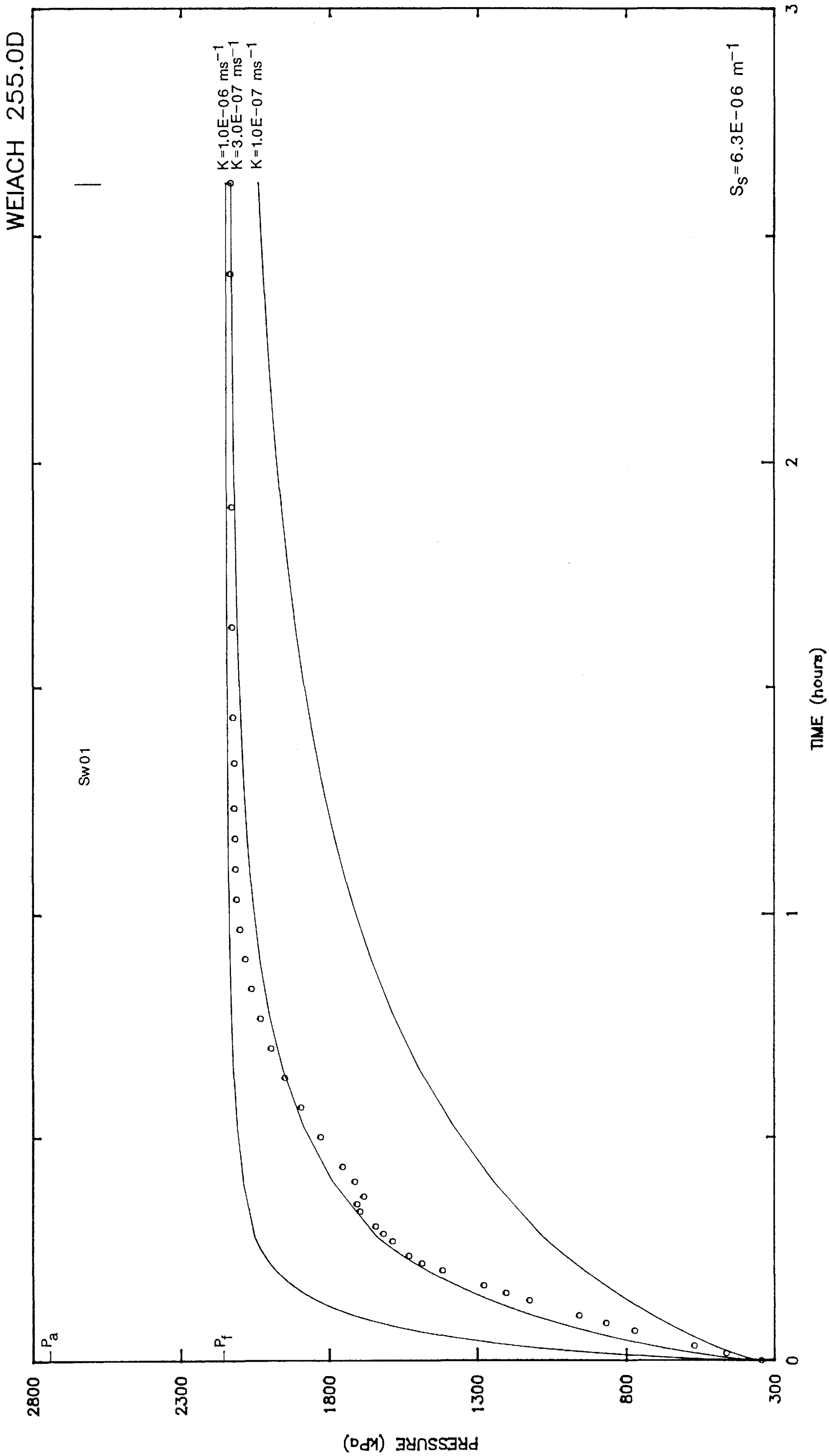


Figure 1 Measured (o) and Simulated Pressure Responses for the Testing Sequence

Test 479.6D (472.00 m to 487.20 m) - Malm/Dogger

Test 479.6D was a double packer test of the Weiach borehole from 472.00 m to 487.20 m, completed with a DST tool. Two drill-stem tests (DST01 and DST02) were conducted in the testing sequence over a 3.9 hour period on 03 March, 1983 using a Lynes DST tool. The measured pressure data for the testing sequence is shown in Figure 1.

The flow periods of DST01 and DST02 had no measurable flow or pressure recovery. The DST01 shut-in period had a recovery of 1 percent of the underpressure from the hydrostatic pressure and DST02 shut-in recovered by 3 percent of the underpressure. A drop in pressure when the shut-in valve was closed for the shut-in periods was probably due to tool movement. There is no indication that the drill-stem tests responded to a formation pressure or pressure transient. Because of this, a hydraulic conductivity based on the test simulations is not provided.

A likely explanation for the poor response of the test interval is that the formation was suffering from mud invasion and reduced permeability.

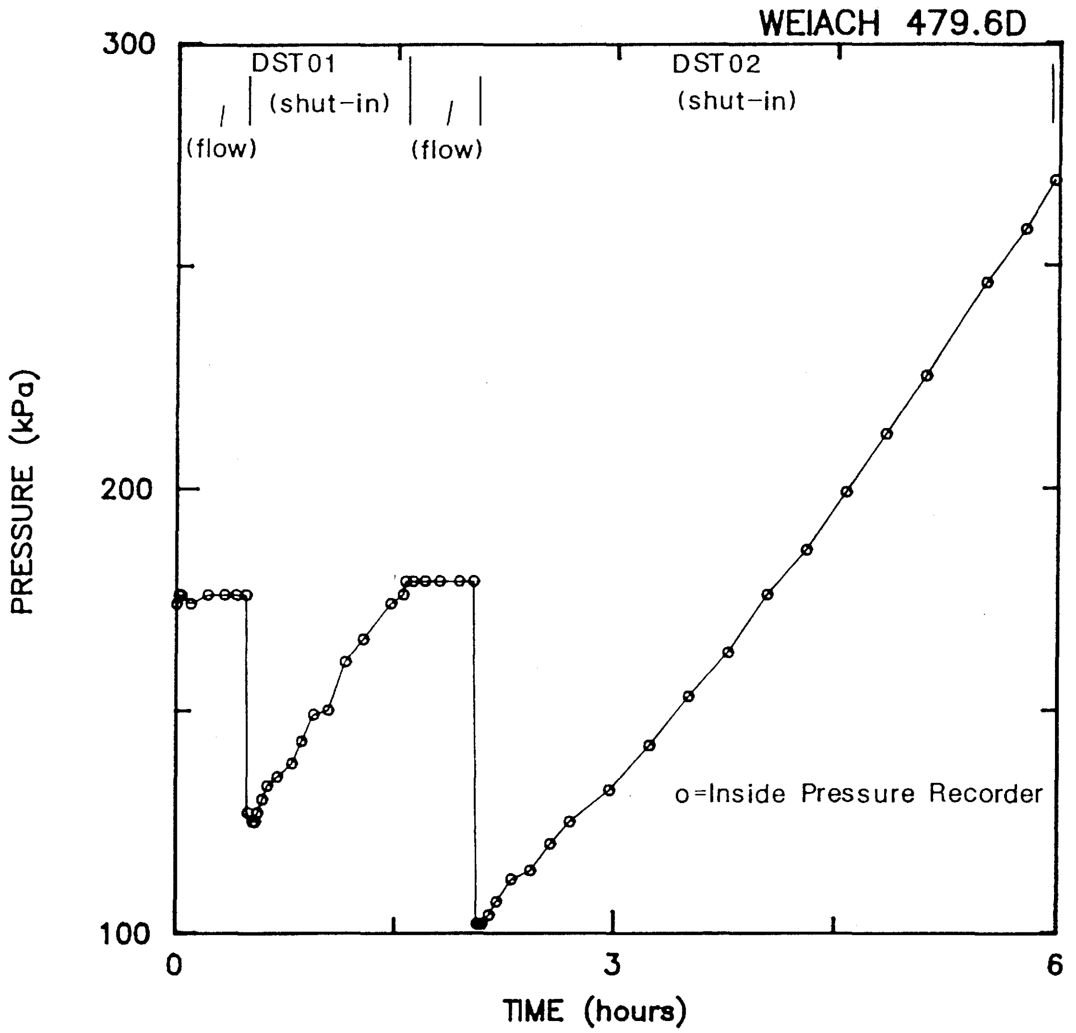


Figure 1 Measured Pressure Data for the Test Interval and Test Sequence Designations for Each Test

Test 550.0D (543.0 m to 557.0 m) - Lower Bäjocien

Lynes GMBH conducted a DST test sequence in the Weiach borehole from 543.0 m to 557.0 m using a DST tool and 4-1/2 inch drill pipe. This was the third in a sequence of eight DST tested intervals from about 820 m to near the top of the borehole.

For the test simulations discussed below, it was assumed that the drill fluid filled the borehole during drilling and that up to the point of testing, the annulus pressure was relatively constant with time.

Formation pressure was estimated by assuming a static fluid level at ground surface and an average fluid density of 1000 kgm^{-3} for the fluid column. Although there is uncertainty in this assumption, it is probably more representative than taking the measured annulus pressure or extrapolated recovery pressure of DST02 (shut-in). This later recovery appears to be only 2700 kPa, from the plot of the pressure recovery data by Lynes.

Temperatures are recorded for the test interval starting 11 minutes into the flow period of DST01. A temperature increase of about 6.2°C is recorded, most of which occurs during DST01 and the flow period of DST02. The temperature change was sufficient at the low hydraulic conductivity of the interval that thermal effects were included in the interpretation of the shut-in recovery tests.

The testing sequence consists of DST01 and DST02, each composed of a flow and shut-in recovery period. Pressure during the first flow period declined from 431 kPa to 371 kPa, likely the result of packer compliance causing a slight increase in the volume of the test zone. This period lasted about 30 minutes. The shut-in valve was then closed and the pressure increased by 1008 kPa over 67 minutes to complete DST01. The available data for the test sequence does not provide any evidence of shut-in squeeze effects. DST02 started with a pressure of 293 kPa in the test interval during the flow period; no recovery in pressure was recorded over 30 minutes. The build-up period saw a pressure increase of 1750 kPa during 240 minutes of monitoring.

The testing sequence was simulated using GTFM to incorporate the pressure history and thermal effects. Simulations were completed for the test sequence at formation hydraulic conductivity of 1.0E-12, 3.0E-13 and 1.0E-13 ms^{-1}. An estimate of the uncertainty in K, by varying specific storage, was completed for an S_s range of 1.0E-06 through 1.0E-05 m^{-1}. The most reasonable estimate of K based on the simulated response is 3.0E-13 ms^{-1} at a specific storage of about 5.5E-06 m^{-1} as shown in Figure 1. The uncertainty in K is half an order of magnitude greater than and less than this estimate based on a variation in specific storage over two orders of magnitude.

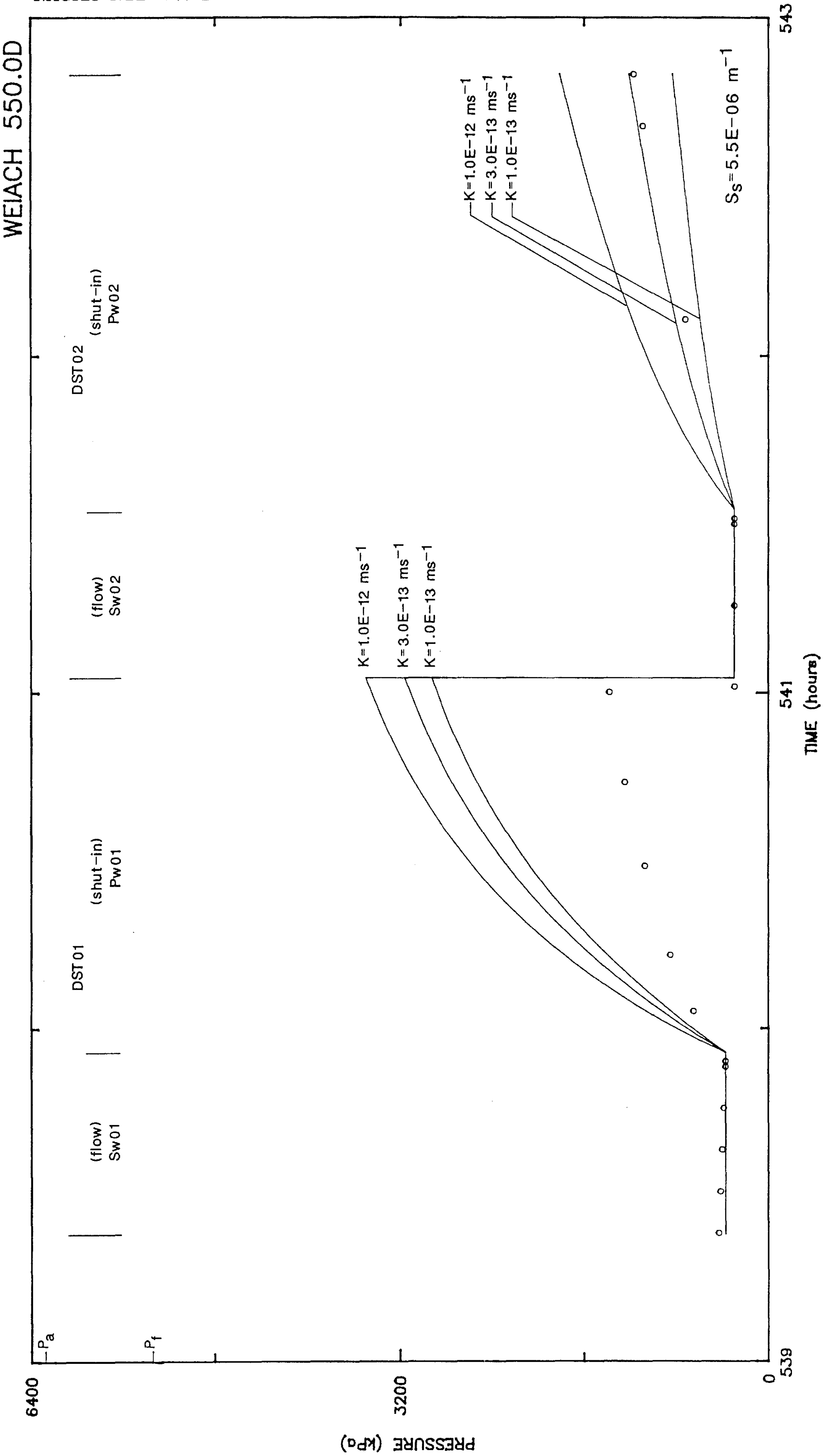


Figure 1 Measured (o) and Simulated Pressure Responses for the Testing Sequence

Test 699.0D (692.0 m to 706.0 m) - Lias/Keuper

Test 699.0D was completed during the drilling phase of the Weiach borehole between depths of 692.0 m and 706.0 m. The equipment used in testing was a Lynes DST tool equipped with inside pressure and temperature recorders and outside pressure recorders. Pressure and temperature data used in the evaluation of this test was taken from the dedicated recorder located inside the DST at a depth of 679 m, about 9 m above the top packer element. This section of the borehole was drilled with bentonite mud of specific gravity about 1.2.

Figure 1 presents the pressure data recorded at 679 m during the sequence of tests in this interval. The temperature increases from 41°C to 43°C with a relatively constant change over time. Pressure is lowered to 202 kPa from 7661 kPa for the start of DST01. During the initial flow period, pressure declined by 69 kPa and after shut-in, pressure increased to the end of DST01. Following DST01, and in preparation for DST02, a pressure pulse was recorded of 800 kPa above the DST01 shut-in recovery pressure. The pressure was then lowered to 220 kPa for the start of the flow period for DST02 and a pressure drop of 108 kPa was recorded across the flow period. The shut-in recovery pressure recovered slowly during the first 40 minutes and then more rapidly to a total recovery of 3534 kPa after 240 minutes.

From a preliminary analysis (GARTNER LEE, 1985a), the hydraulic conductivity was estimated at 1.0E-11 ms^{-1}. A further interpretation of the testing sequence was not attempted for the following reasons:

- the decreasing pressures in the test interval during the flow periods of DST01 and DST02 is an indication of problems of tool performance; perhaps packer slippage causing a change in volume of the test interval.
- the characteristic shape of the shut-in recovery curves for both DST01 and DST02 is incorrect with the early-time pressure recovery rate being less than the late-time recovery; this may be the result of the same tool-related problems which caused a pressure decline during either flow period.

For these reasons outlined above, it was decided that a representative hydraulic conductivity of the formation could not be obtained by simulating the pressure responses.

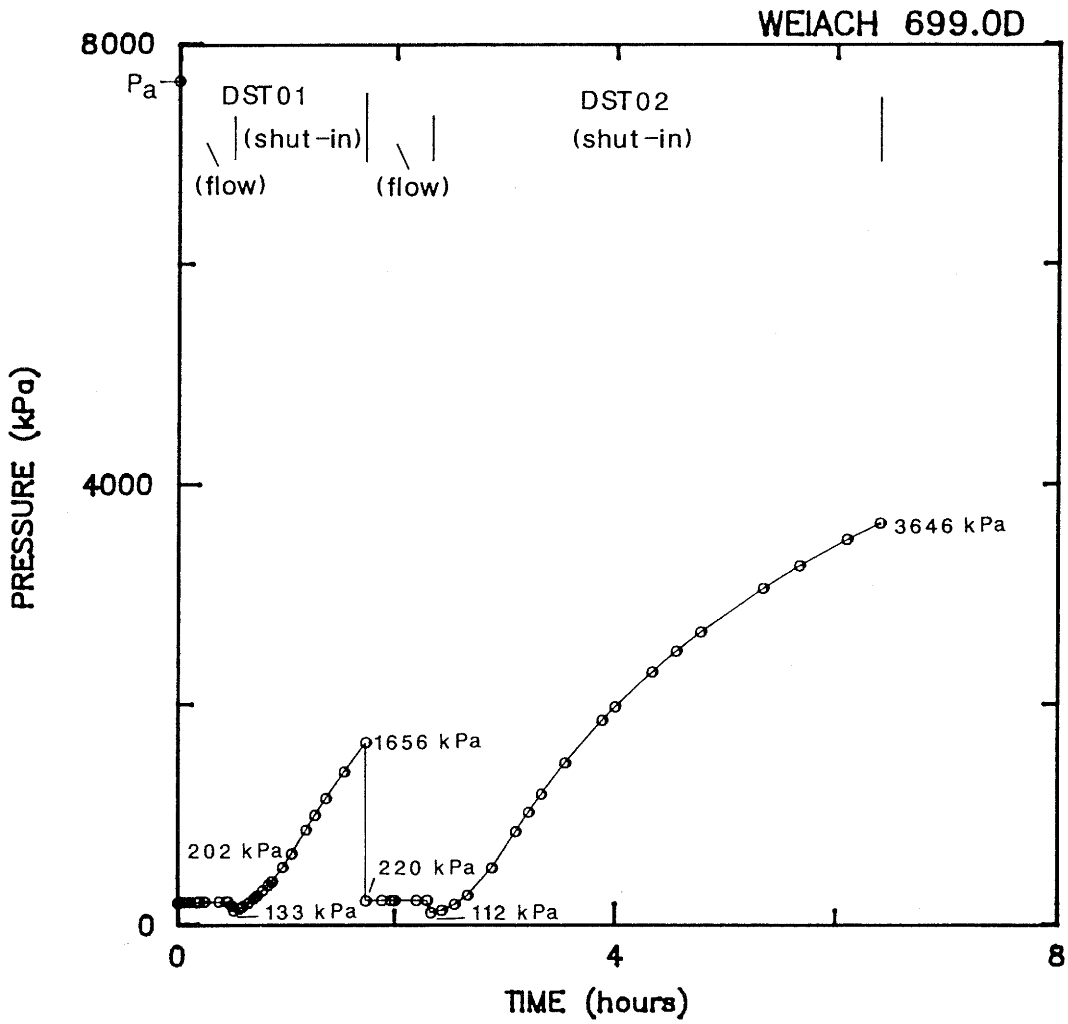


Figure 1 Measured Pressure Data for the Test Interval, Test Sequence Designations, and Starting and Ending Pressure for Each Test

Test 728.0D (715.90 m to 740.00 m) - Keuper

Test 728.0D was a double packer test of the Weiach borehole from 715.90 m to 740.00 m,completed with a DST tool. Two drill-stem tests, DST01 (consisting of a flow period Sw01 and a shut-in period Pw01) and DST02 (consisting of a flow period Sw02 and a shut-in period Pw02) were run on the interval. The pressure in the interval was reduced to 175 kPa from 8197 kPa for the flow period (Sw01) of the first drill-stem test. The average flow rate during Sw01 was 0.42 L min^{-1} and the measured pressure recovered to 206 kPa. Pw01 had a shut-in squeeze of about 537 kPa and a recovery to 81 percent of the assumed formation pressure was recorded over a period of 56 minutes. The tubing was swabbed with the shut-in valve closed prior to Sw02. When the shut-in valve was opened, the interval pressure dropped to 220 kPa. Sw02 recovered to 249 kPa in 44 minutes and had an average flow rate of 0.30 L min^{-1}. Pw02 had a shut-in squeeze of about 326 kPa and a recovery to 92 percent of the assumed formation pressure over a period of 198 minutes. Due to the temperature increase from 32.5°C to 34.6°C during testing, thermal effects were included in the simulation.

The testing sequence was simulated with GTFM incorporating history and temperature effects. An assumed formation pressure of 6800 kPa was derived by matching the measured pressure response for tests Pw01 and Pw02. The formation pressure could not be calibrated due to the pressure transient around the borehole. Figure 1 shows the measured and simulated pressure responses for the range of hydraulic conductivity 3.0E-11, 1.0E-10 and 3.0E-10 ms^{-1} at a specific storage of 8.3E-07 m^{-1}. The best fit of the measured pressure data was for a hydraulic conductivity of approximately 6.0E-11 ms^{-1} at a specific storage of 8.3E-07 m^{-1}. The effects of increasing the specific storage of the formation on the simulated pressure curves are an increased rate of response of the formation during early time and a more rapid dissipation of the pressure transient around the borehole created by the annulus overpressure period. Varying the specific storage by an order of magnitude above and below the base-case specific storage of 8.3E-06 m^{-1} affected the the best fit of hydraulic conductivity by approximately one order of magnitude.

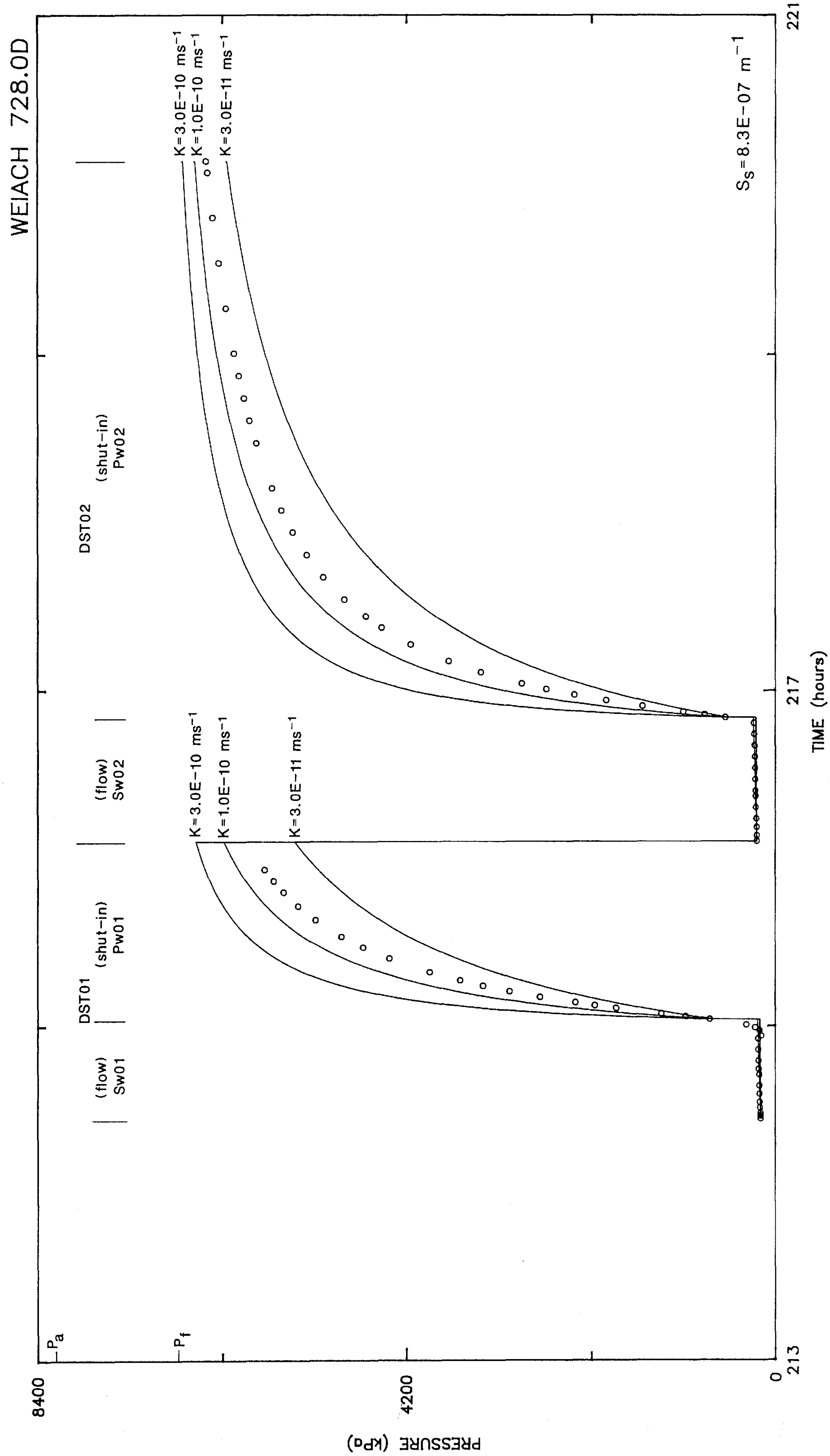


Figure 1 Measured (o) and Simulated Pressure Responses for the Testing Sequence

Test 859.1SI (822.00 m to 896.10 m) - Upper Muschelkalk

Test 859.1SI was a pumping test of the Upper Muschelkalk Formation in the Weiach borehole from 822.00 m to 896.10 m. A pumping drawdown and recovery test was completed in the testing sequence.

The pressure response for the center of the test interval during the testing sequence was determined using the fluid level in the borehole and the estimated density of the borehole fluid. Test PMP1 had an initial static pressure of approximately 8400 kPa with the fluid level in the borehole at about 10 m below ground surface. The pumping rate for the pumping test was initially 12.4 Ls^{-1} and declined to about 3.7 Ls^{-1} after about 1 hour. The fluid level initially decreased to about 134 m below ground surface before increasing to about 110 m below ground surface after reducing the pumping rate. The pumping rate then increased over the next 2 hours to about 5.0 Ls^{-1} causing the fluid level to drop. The pumping rate fluctuated from about 3 to 4 Ls^{-1} for the remaining 67 hours of the pumping test with a short period with the pumping rate reduced to 2.5 Ls^{-1} at approximately 64 hours into test. The fluid in the borehole rose from 110 m below ground surface to about 78 m below ground surface with an increase to 55 m below ground surface corresponding to the reduced pumping rate at 64 hours. The pump was stopped and the test interval was allowed to recover into the open borehole. This period was simulated as slug withdrawal test Sw01. The fluid level rose to about 10 m below ground surface over a period of 1 hour. The fluid then rose 2 m over the next 3 hours before slowly dropping over the next 62 hours by 1.5 m.

The testing sequence was simulated with GTFM. The interpolated pumping rates were used in the simulation to generate a pressure response during test PMP1. The formation pressure of 8400 kPa was taken from the static fluid level prior to the testing sequence. Figure 1 shows the measured and simulated pressure responses for the range of hydraulic conductivity 3.0E-07, 1.0E-06 and 3.0E-06 ms^{-1} at a specific storage of 6.2E-05 m^{-1}. The most reasonable fit of the measured data for test PMP1 was for a hydraulic conductivity of about

7.0E-07 ms^{-1} at a specific storage of 6.2E-05 m^{-1}. The most reasonable fit of the measured data for test Sw01 was for a hydraulic conductivity of 1.0E-06 ms^{-1} also at a specific storage of 6.2E-05 m^{-1}. Varying the specific storage by an order of magnitude higher and lower than the base case specific storage 6.2E-06 m^{-1} results in less than half an order magnitude variation in the hydraulic conductivity. A reasonable range of formation compressibility for dolomite has been calculated to be 5.4E-10 to 2.9E-11 Pa^{-1} based on stress-strain relationships found in TOULOUKIAN et al. (1981). Although the formation compressibility of 6.3E-09 Pa^{-1} chosen for this interval is about one order of magnitude greater than the reported range, it is felt that this variability could be explained in the added compressibility caused by fracturing and jointing of the dolomite and limestone.

The pressure data generated from the measured fluid levels in the borehole and the estimated fluid densities is probably low during the early portion of the pump test and high during the early portion of the recovery. The pressure is low during the early period of test PMP1 due to the temperature of fluid around the tubing in the annulus being estimated too high as a result of using the temperature of the discharge fluid, which is close to the formation temperature of the test interval, to obtain a density for the fluid column in the borehole. In the early portion of the recovery (Sw01), the estimated density and pressure will be high due to the assumption of a fast temperature decrease of the borehole fluid. The borehole fluid actually took a couple of days to cool as indicated by the drop in the fluid level in the borehole at the end of the testing sequence. The uncertainties in the estimated pressure response will affect the estimate of the best-fit hydraulic conductivity slightly but will not change its order of magnitude.

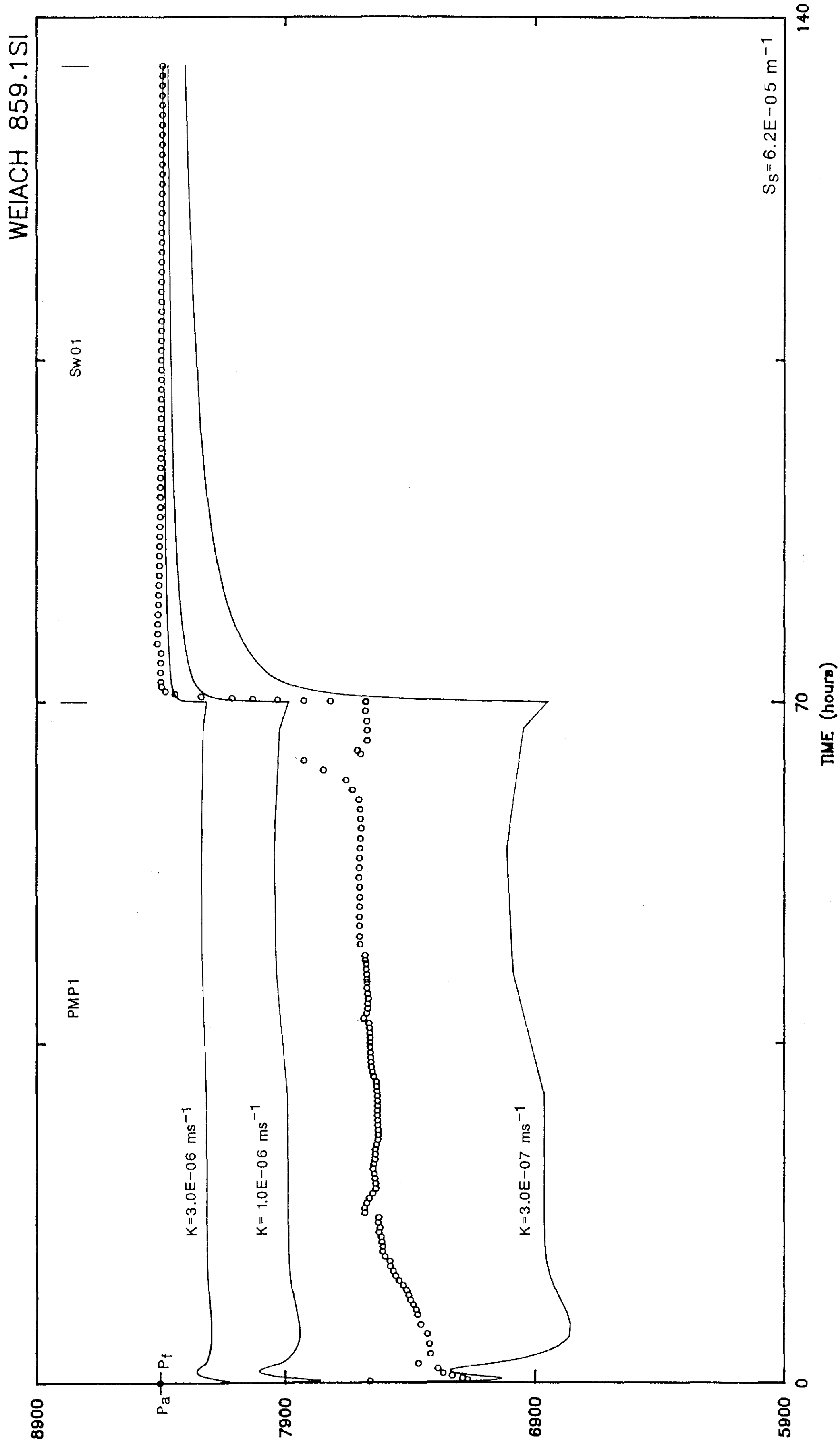


Figure 1 Measured (o) and Simulated Pressure Responses for the Testing Sequence

Test 859.1SII (822.00 m to 896.10 m) - Upper Muschelkalk

Test 859.1SII was a single packer drill-stem test of the Upper Muschelkalk Formation in the Weiach borehole from 822.00 m to 896.10 m,completedwith a DST tool. The testing sequence was performed over a 3.7 hour period from 07 April, 1983 to 08 April, 1983. Two drill-stem tests, DST01 (consisting of a flow period Sw01 and a shut-in period Pw01) and DST02 (consisting of a flow period Sw02 and a shut-in period Pw02), were completed in the testing sequence.

Test Sw01 had an initial pressure of approximately 5162 kPa and recovered to 7754 kPa over 20 minutes. The shut-in valve was closed for test Pw01 causing a squeeze of about 85 kPa. The pressure recovered to about 77 percent of the formation pressure in close to 45 minutes. The shut-in valve was opened and test Sw02 had an initial pressure of 7973 kPa. The pressure recovered to about 8057 kPa in 44 minutes during test Sw02. The shut-in valve was closed for test Pw02 causing a shut-in squeeze of about 58 kPa. The shut-in squeeze was not used because it caused a pulse injection for the highest hydraulic conductivity used in the simulation. The pressure during test Pw02 was stable over 110 minutes at about 8115 kPa.

The testing sequence was simulated with GTFM. Figure 1 shows the measured and simulated pressure responses for the range of hydraulic conductivity 3.0E-08, 1.0E-07 and 3.0E-07 ms^{-1} at the most reasonable specific storage for the test interval of 6.2E-05 m^{-1}. The formation pressure used was 8115 kPa indicated by the stable recovery of test Pw02. The pressure transient at the end of the final shut-in recovery was approximately 17 kPa at a depth of 2 m into the formation. Although the pressure transient was minor in extent, the formation pressure determined using GTFM by matching to the shut-in recovery of test Pw02 is reported only as an assumed pressure. Compared to the preliminary tests on this zone (859.1SI), the freshwater head of 374.6 m ASL estimated for this test appears to be anomalously high, for the following reasons. The approximate hydraulic head for test 859.1SI is 358 m ASL, at least 10 m below ground surface. From our estimation, this hydraulic head represents an equivalent freshwater head of about 364 m ASL. This indicates that the freshwater head from test 859.1SII is about 10 m too high. Nagra has made the suggestion that this discrepancy could be caused by an out-of-calibration transducer on the test tool. We believe that the discrepancy may be this or may be caused by an error in reporting the location of the inside pressure recorder in the DST report.

The most reasonable fit of the measured data was for a hydraulic conductivity of 1.0E-07 ms^{-1} at a specific storage of 6.2E-05 m^{-1}. Varying the specific storage by an order of magnitude higher and lower than the base case specific storage 6.2E-06 m^{-1} results in less than half an order magnitude variation in the best fit hydraulic conductivity. As has been discussed in test 859.1SI, a reasonable range of formation compressibility for dolomite has been calculated to be 5.4E-10 to 2.9E-11 Pa^{-1} based on stress-strain relationships found in TOULOUKIAN et al. (1981). Although the formation compressibility of 6.3E-09 Pa^{-1} chosen for this interval is about one order of magnitude greater than the reported range, it is felt that this variability could be explained in the added compressibility caused by fracturing and jointing of the dolomite and limestone.

The best-fit simulated response was higher than the measured data during the early portion of test Sw01. The aperture may have been clogged during test Sw01 causing the measured pressure response to be low. The hydraulic conductivity of the measured test Sw01 appears to change throughout the test as indicated by the inflection points in the pressure response. The shut-in portion of test DST01 and all of test DST02 do not appear affected.

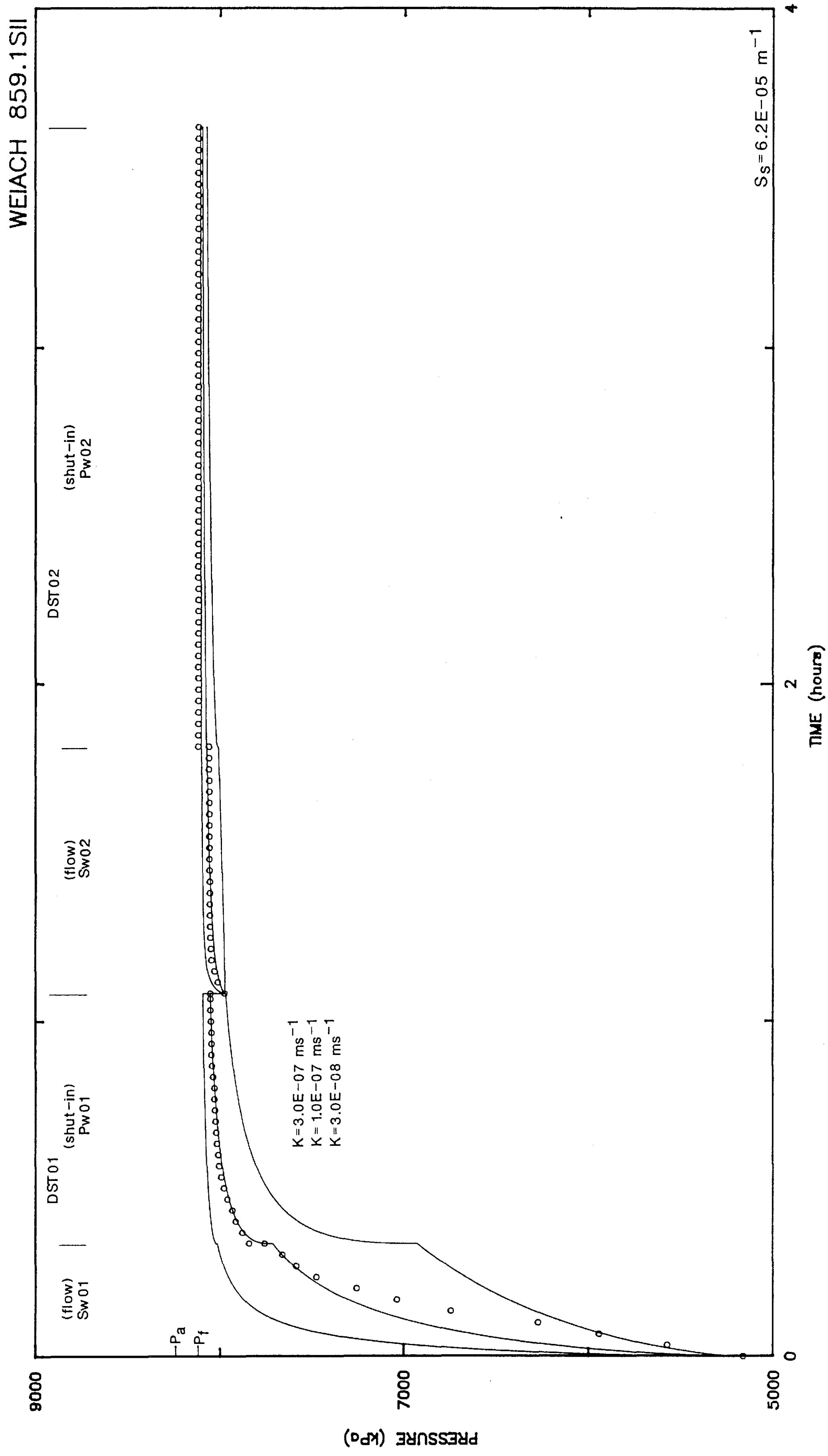


Figure 1 Measured (o) and Simulated Pressure Responses for the Testing Sequence

Test 926.2S (901.40 m to 950.90 m) - Middle Muschelkalk

Test 926.2S was a single packer test of the Middle Muschelkalk Formation in the Weiach borehole from 901.40 m to 950.90 m. A pulse injection test (PSTA), a slug withdrawal test (Sw01), and a pulse withdrawal test (Pw01) were completed in the testing sequence. An initial shut-in squeeze of about 88 kPa occurred when closing the shut-in tool. The measured pressure reached 10846 kPa over a period of 12 hours. A 100 m swab was pulled with the shut-in valve closed prior to test Sw01. Test Sw01 exhibited a measured pressure change of 1 kPa indicating essentially no flow over a 1 hour period. A shut-in squeeze of about 36 kPa preceded test Pw01 which had a measured pressure increase to 9219 kPa over a period of 7 hours. Due to the temperature change of 4.5°C during the test sequence and the apparent low K of the test zone as indicated by the shut-in recovery rates, thermal effects were included in the simulation.

The testing sequence was simulated with GTFM incorporating history and thermal effects. A formation pressure of 8644 kPa was estimated by extrapolating the equivalent freshwater head determined for the center of the Long Term Monitoring test interval from 824.5 m to 829.5 m to the P2 pressure transducer depth of this test interval. Figure 1 shows the measured and simulated pressure responses for the range of hydraulic conductivity 3.0E-14, 1.0E-13, 3.0E-13, 1.0E-12 and 3.0E-12 ms^{-1} at a specific storage of 3.3E-06 m^{-1}. For the base-case specific storage of 3.3E-06 m^{-1}, the most reasonable fit of the measured data for test PSTA is for a hydraulic conductivity of 2.0E-13 ms^{-1} and for a hydraulic conductivity of 3.0E-13 ms^{-1} for test Pw01. Test Sw01, with an insignificant pressure response, was fit with each of the K's. Varying the specific storage by an order of magnitude above and below the base-case specific storage of 3.3E-06 m^{-1} affected the best-fit hydraulic conductivity by about one order of magnitude.

The higher hydraulic conductivities had the lower simulated pressure responses during test PSTA and higher pressure responses during test

Pw01. Because of the strong temperature increase after the shut-in for test PSTA, the pressures in the interval increased even though the initial shut-in pressure is believed to be higher than the formation pressure. The dominance of thermally-induced pressure increases results in higher simulated pressures for the lower hydraulic conductivities. For test Pw01, the initial pressure is believed to lie below the formation and the temperature increase while significant is less dominant. Therefore, for test Pw01 the simulated pressure response is higher initially for the higher hydraulic conductivities. Due to the strong thermal effects and low hydraulic conductivity, the formation pressure could not be calibrated for this test interval.

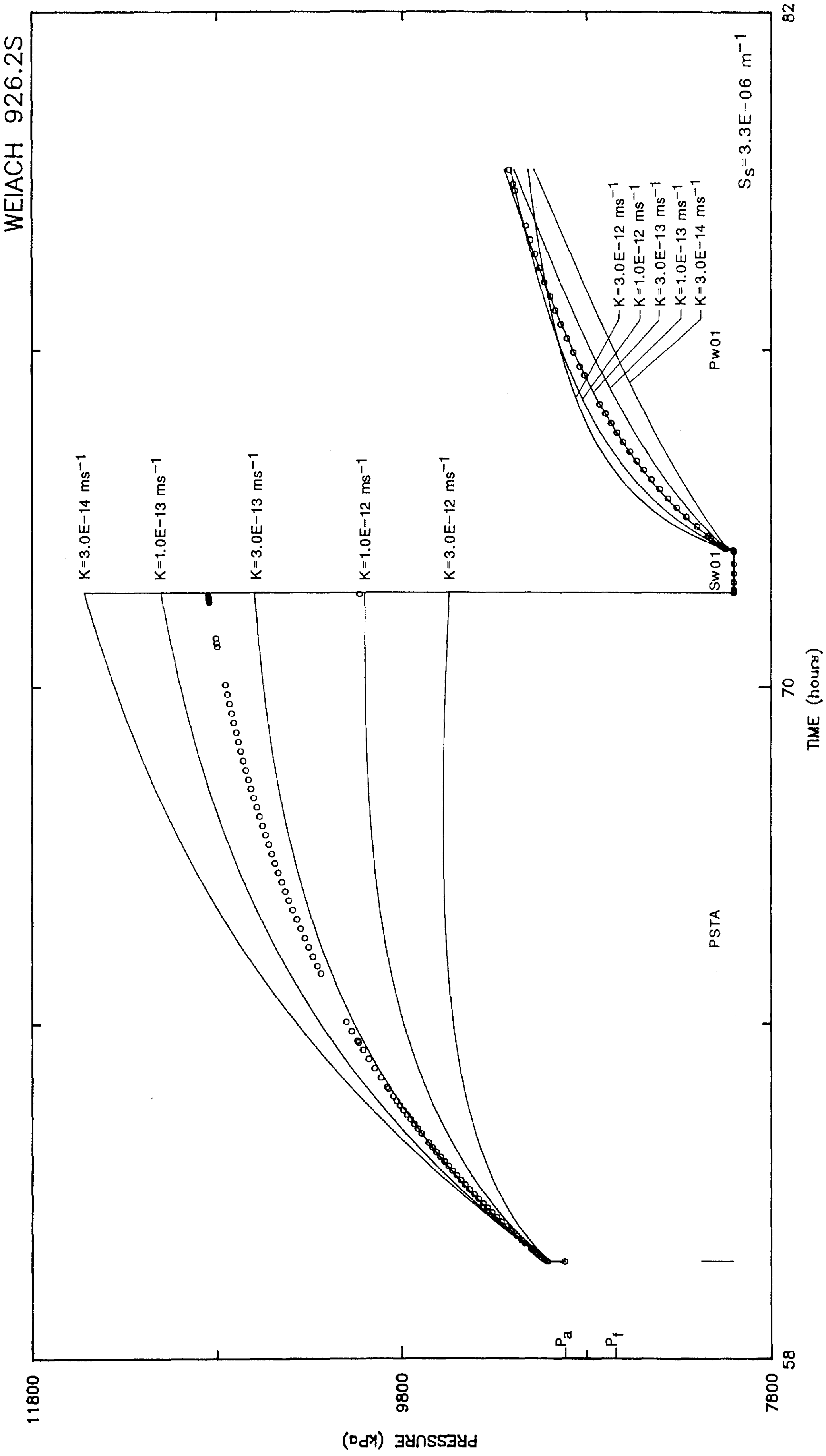


Figure 1 Measured (o) and Simulated Pressure Responses for the Testing Sequence

Test 984.2S (983.00 m to 985.30 m) - Buntsandstein

Test 984.2S was a single packer test of the top of the Buntsandstein. The hydraulic tests consisted of a static recovery (PSTA), three pumping periods designated, PMP1, PMP2 and PMP3, two slug withdrawal tests, Sw01 and Sw02, and two pulse withdrawal tests, Pw01 and Pw02. PSTA recovered to 10105 kPa. The pressure decreased to 8583 kPa during PMP1. The flow rates were unavailable for PMP1. Pw01 had an initial shut-in squeeze of about 120 kPa and recovered to within 6 kPa of the estimated formation pressure. The first 45 minutes (PMP2) of the second pumping period had an initial rate of 50 L min^{-1} which decreased to 19 L min^{-1}. The pumping rate was then set at 11 L min^{-1} for the rest of the pumping period. This was simulated as a separate pump test, PMP3. The measured pressure during PMP3 stabilized at approximately 7965 kPa. Pw02 had a shut-in squeeze of 31 kPa and recovered to 93 percent of formation pressure. No flow rate was given for Sw02. Thermal effects were not included in the simulation due to the high hydraulic conductivity of the interval.

The testing sequence was simulated using GTFM. Due to the high hydraulic conductivity of the sandstone compared to the anhydrite at the top of the test interval, the interval thickness used was 1.76 m, which was the length of penetration of the Buntsandstein. The measured pressure response during PMP1 was used for history purposes due to the lack of flow rate data. The pumping rate during PMP2 was simulated as a linearly decreasing rate over the period of the test. Test PMP3 was simulated with a constant pumping rate of 11 L min^{-1}. Figure 1 shows the measured and simulated pressure responses for the range of hydraulic conductivity 5.5E-07, 2.0E-06, and 5.5E-06 ms^{-1} at a specific storage of 1.5E-06 m^{-1}. A calibrated formation pressure of 10113 kPa was determined by Horner analysis of tests PSTA and Pw01. This agrees closely with the formation pressure of 10115 kPa determined by GTC (Hydraulic Test Analysis of Buntsandstein Aquifer Test, May 30, 1983). The most reasonable fit of the measured data for hydraulic conductivity is between 1.0E-06 ms^{-1} and 5.5E-07 ms^{-1} at a specific storage of 1.5E-06 m^{-1}. Varying the specific storage by two orders of magnitude affected the best-fit hydraulic conductivity by less than half an order of magnitude.

The lack of interval history in the simulation caused the simulated pressure response during PSTA to recover sharply. The effects of the history period were short in duration as the interval recovered to within less than 8 kPa of formation pressure during both PSTA and Pw01. There is considerable uncertainty in the pumping rate during tests PMP2 and PMP3, resulting in a range of uncertainty in the hydraulic conductivity between 5.5E-07 and 1.0-06 ms^{-1}. An inspection of Figure 1 could lead to the presumption that the pumping rate used in test PMP2 should be increased to produce more drawdown during PMP2 and a flatter drawdown during PMP3. However, since only the starting (50 L min^{-1}) and ending (19 L min^{-1}) pumping rates for PMP2 were recorded, and only the 'average' pumping rate (11 L min^{-1}) for PMP3 was recorded, further refinements of the simulated fit would have to be used on speculations rather than actual data. The magnitude of drawdown during test PMP3 is the best indication of the formation properties with some uncertainty derived from the pumping rate data for PMP2 and PMP3. There is, however, little uncertainty in the order of magnitude correctness of the hydraulic conductivity. An additional concern in simulating this test sequence was the partial penetration (1.76 m) of the test interval into the Buntsandstein (5.66 m). Assuming that the total thickness of the Buntsandstein was contributing to the pressure response decreased the best fit of hydraulic conductivity by a factor of 3.

An equivalent freshwater head of 412.64 m ASL was calculated for the center of the test interval. There is a standard deviation of 0.83 m ASL around the mean, 412.4 m ASL. The variables that predominantly cause the uncertainty in the equivalent freshwater head are the pressure at the P2 transducer and true vertical depth. Uncertainty of pressure at P2 is based on the combined accuracy and resolution specifications for a generic HTT transducer, ± 22.8 kPa. Using the endpoints as the 0.1 and 99.9 percentiles of a normal distribution is equivalent to a normal distribution having a 7.38 kPa standard deviation. Converting pressure to meters of freshwater head (7.38/g = 0.75), the transducer specifications can account for about 90 percent of the uncertainty of freshwater head. Since the distribution for true vertical depth is uniform, its standard deviation is 0.37 m. Although not as pronounced as the pressure at the P2 transducer, the effect of the uncertainty around true vertical depth is not insignificant.

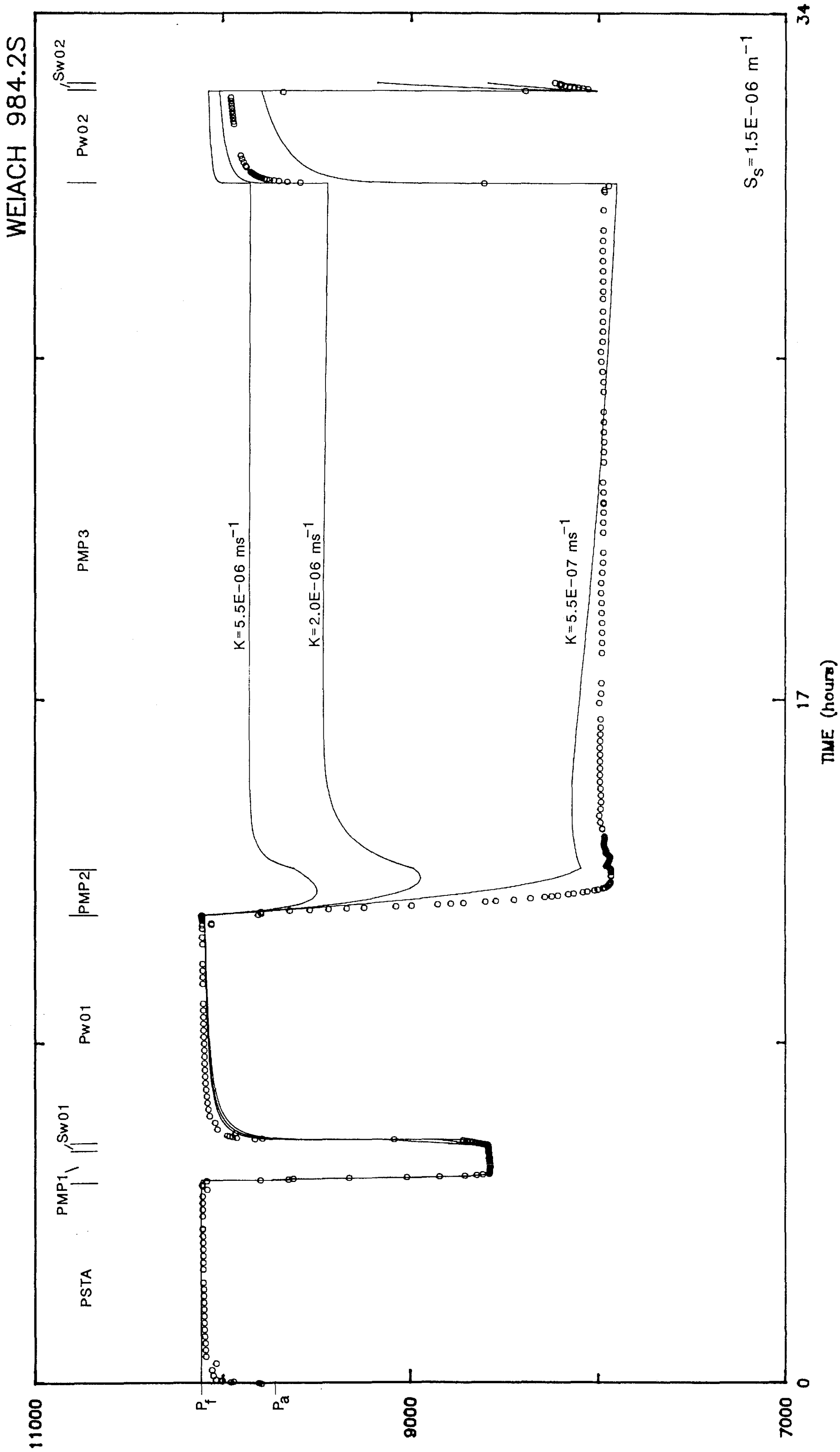


Figure 1 Measured (o) and Simulated Pressure Responses for the Testing Sequence

Test 985.3D (981.40 m to 989.97 m) - Buntsandstein

Hydraulic testing involving pumping tests was completed in the interval from 981.40 m to 989.97 m of the Weiach borehole from 14 July, 1983 to 19 July, 1983. A DST tool was used to isolate the formation. The formation pressure was assumed to be 2445 kPa based on observed pressure recovery data which is presumably low due to the underpressure caused by the low pressure history period over 81 days and the pumping during test Qw01. The location of the pressure transducer at 750 m above the interval center does not affect the interpretation of the test and only results in the assumed formation pressure being unrepresentative of the pressure at the test interval depth.

The first pumping period (Qw01) was conducted for about 12 hours from 15 July, 1983 until 09:27 on 16 July, 1983. The pressure declined from about 2410 kPa to about 730 kPa during pumping. During this pumping period, the annulus level declined approximately 3 m. Qw01 was terminated to check the annulus level response which continued to drop throughout the testing sequence. The water level in the tubing was at 667 m below ground surface before recovery. Recovery of the fluid level (Rw01) was monitored for about 4.5 hours until 14:05 on 16 July, 1983. During Rw01, the pressure increased about 1715 kPa to 2445 kPa. Test Qw02 was conducted for approximately 71 hours, from about 14:10 on 16 July, 1983 until 12:30 on 19 July, 1983. During Qw02, the pressure declined and fluctuated primarily between 700 kPa and 850 kPa, principally in response to changes in pumping rates. The CWL recorder was located 246 m below the top of the tubing, 13 m above the pump, and 750 m above the interval center. Thus, the measured pressure and temperature are not representative of the formation. Additionally, the CWL was located near the pump, so temperature effects from the pump and density effects as fluid is pulled from the borehole may have influenced the pressure responses. This effect was assumed to be negligible in the simulations.

Simulation of the history and testing sequence was completed using GTFM to allow incorporation of history effects. Temperature effects were not included in the simulations because the interval was not shut-in during testing, therefore the pressure response from temperature effects was assumed to be negligible. Incomplete documentation of the change in pumping rate during the testing sequence required the use of interpolated pumping rates in the simulations. Often the field records that were provided for the test did not contain measured pumping rates corresponding to changes in the pressure-time record. Sensitivity analysis of the pumping rate showed that the rate was relatively high (30 L min^{-1}) for an initial period of about 1 hour and then the rate was significantly reduced on each of the pump tests (Qw01 and Qw02). The incomplete data on pumping rate changes introduced significant uncertainty into the determination of the rates and also into the determination of a final K for the formation. The interpolated rates produce a K value similar to the K from the average pumping rates. However, the fit of the initial pressure response during the pumping period is significantly degraded when using the average pumping rate as compared to the interpolated rate.

Simulations completed for the hydraulic conductivities of 1.5E-07, 2.0E-07, and 2.5E-07 ms^{-1} and for a specific storage of 2.6E-06 m^{-1} are shown in Figure 1. The simulations were terminated prior to the end of the P2 readings due to inadequate pumping rate data. From the fit of the pumping tests, the most reasonable hydraulic conductivity of the test zone is 2.0E-07 ms^{-1}. The effect of varying specific storage over about one and a half orders of magnitude should result in less than half an order of magnitude uncertainty in the final estimate of K for the test zone.

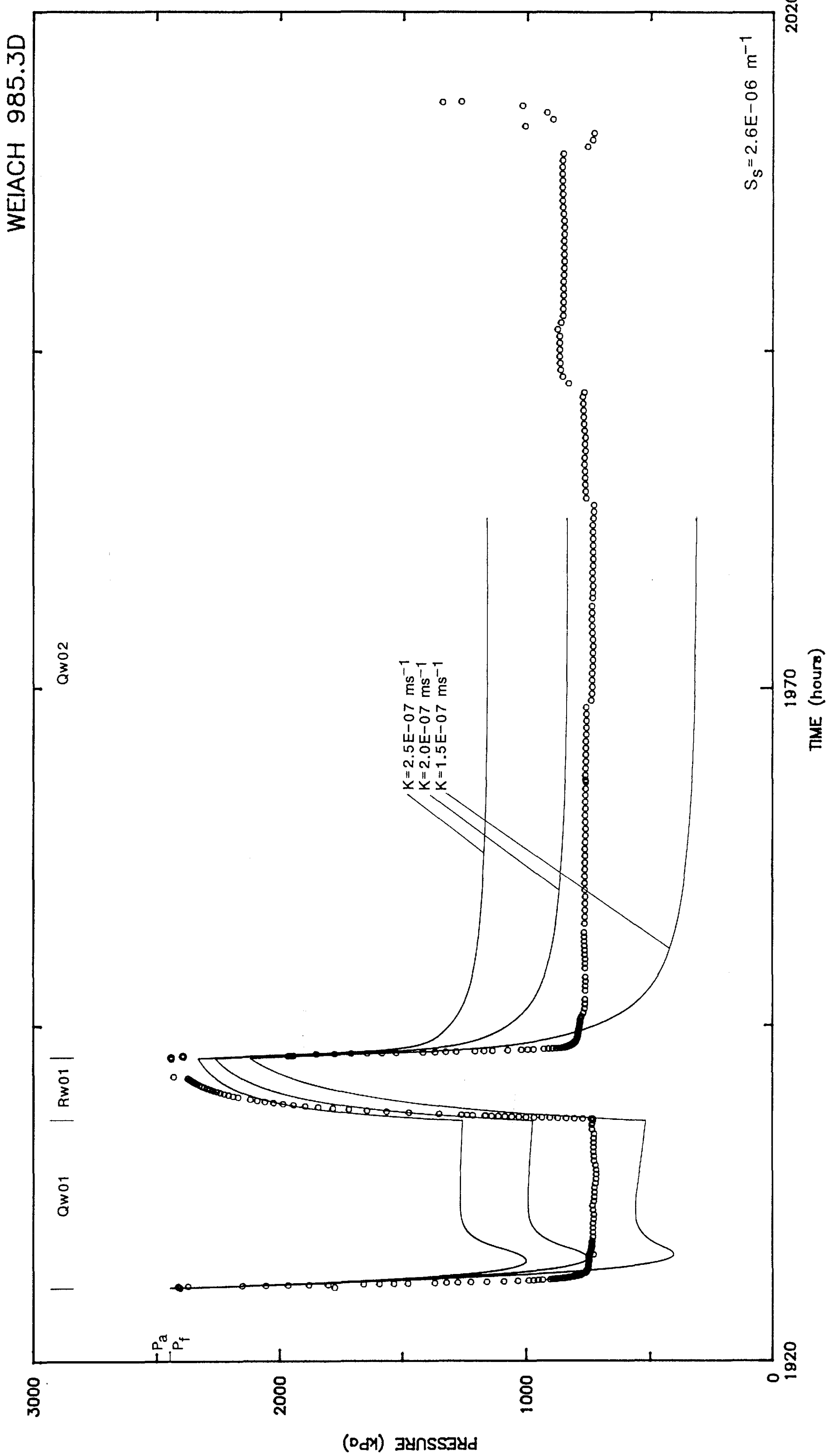


Figure 1 Measured (o) and Simulated Pressure Responses for the Testing Sequence

Test 987.9D (982.00 m to 993.74 m) - Buntsandstein

Test 987.9D was a double packer test of the Buntsandstein Formation in the Weiach borehole from 982.00 m to 993.74 m.

Test Pi01 had an initial pressure of about 10352 kPa. The measured pressure decreased to about 9962 kPa in approximately 4 minutes before increasing to 9975 kPa over a period of 16.4 hours. Due to the temperature change of 0.1°C during the testing sequence, thermal effects were not included in the analysis. It should be noted that the pressure in the P1 zone increased from 10146 kPa to 10282 kPa during the Pi01 test period and that the P3 pressure measured approximately 9551 kPa. The pressure change at P1 should not affect the response in the test interval.

The testing sequence was simulated with GTFM incorporating the pre-test history. The interval length of 5.8 m corresponds to the total length of the perforations within the testing interval. This test interval was isolated from borehole pressures by casing for about 537 days. The interval was then perforated from 984 m to 985 m and 986.5 m to 991.3 m. A formation pressure of 10119 kPa was determined by correcting the calibrated formation pressure of 10113 kPa from test 984.2S to the P2 depth of this test interval. Simulations of the test were completed for the range of hydraulic conductivity 3.0E-08, 1.0E-07 and 3.0E-07 ms^{-1} at specific storages of 8.3E-07, 8.3E-06 and 8.3E-05 m^{-1}. The measured and simulated pressure responses are shown in Figure 1. Due to the poor fit of the measured data, a hydraulic conductivity for the formation is not reported here. From a fit of the simulations to the late time data, the hydraulic conductivity of 1.0E-07 ms^{-1} seems likely. However, given the uncertainty in the simulations a K is not recommended. The reader is referred to the test write-up for this interval in BUTLER et al. (1989) for a discussion of testing problems.

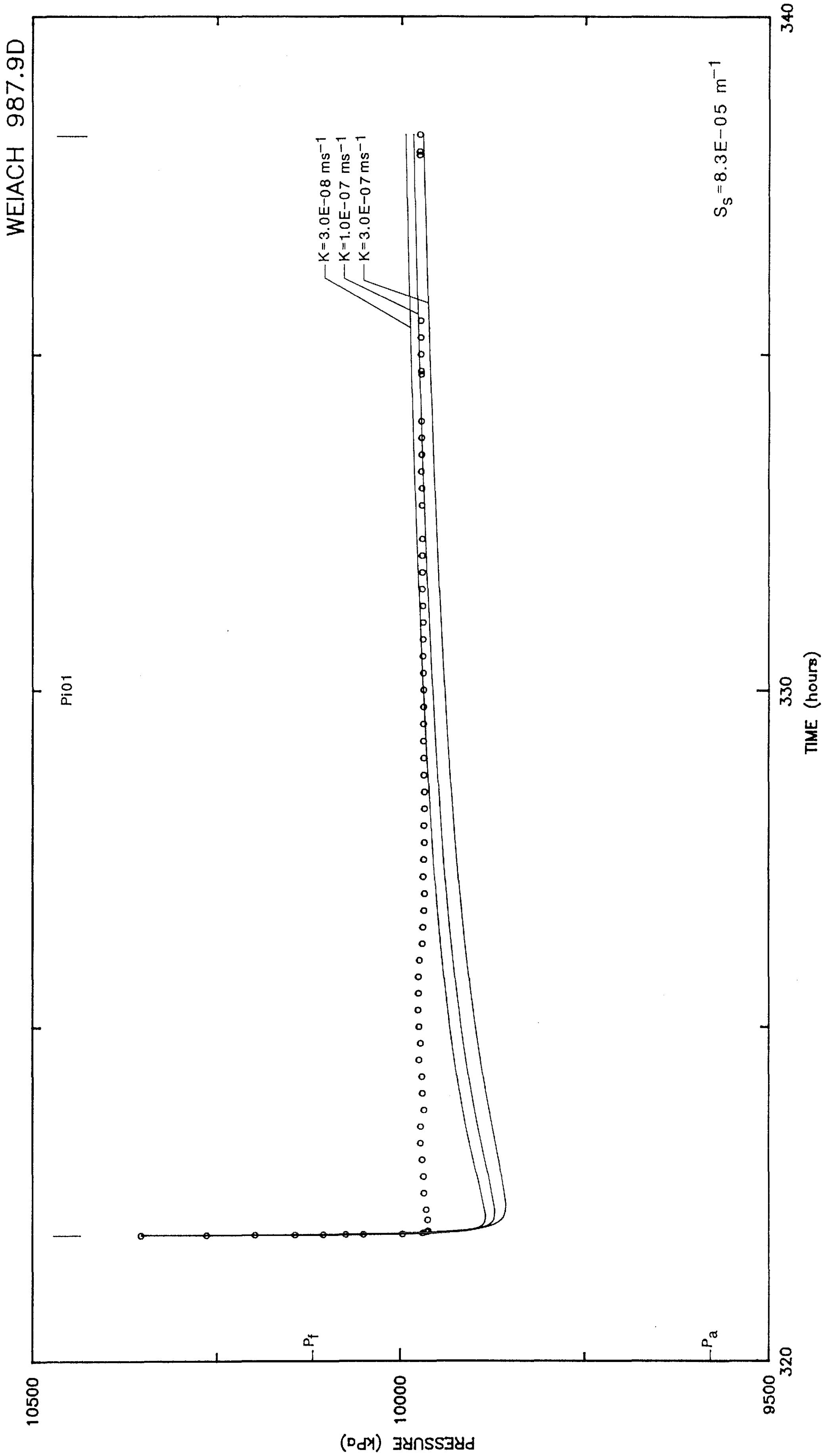


Figure 1 Measured (o) and Simulated Pressure Responses for Test Pi01

Test 1111.0D (1097.50 m to 1124.50 m) - Rotliegendes

Test 1111.0D was a double packer test of the Rotliegendes in the Weiach borehole from 1097.50 m to 1124.50 m. The measured pressure data for the testing sequence is shown in Figure 1. The tests in the testing sequence consisted of a static recovery (PSTA), a slug withdrawal test (Sw01) and a pulse withdrawal test (Pw01).

From a preliminary analysis (GARTNER LEE, 1983/84), the hydraulic conductivity was estimated at 4.1E-11 ms^{-1}. A detailed analysis of this testing sequence was not attempted because the preliminary determination of hydraulic conductivity for this testing sequence was at least two orders of magnitude lower than the hydraulic conductivity determined from tests 1116.5D and 1117.5D of the Rotliegendes. The best fit hydraulic conductivities determined from tests 1116.5D and 1117.5D were 3.0E-08 ms^{-1} and 6.0E-08 ms^{-1}, respectively. The hydraulic conductivity range estimated for this testing sequence is on the order of 1.0E-11 ms^{-1} to 1.0E-10 ms^{-1}. This range for hydraulic conductivity is based on an estimated 90 percent recovery for test Pw01 in approximately 12.5 hours to the formation pressure of 11780 kPa determined from test 1117.5D. There were not any changes to the borehole between test 1117.5D and this test that should have altered the hydraulic conductivity of the formation. Test 1117.5D was performed about 72 days after the interval was drilled, this testing sequence (1111.0D) was performed about 108 days after the interval was drilled, and test 1116.5D was performed in perforated casing about 434 days after the interval was drilled.

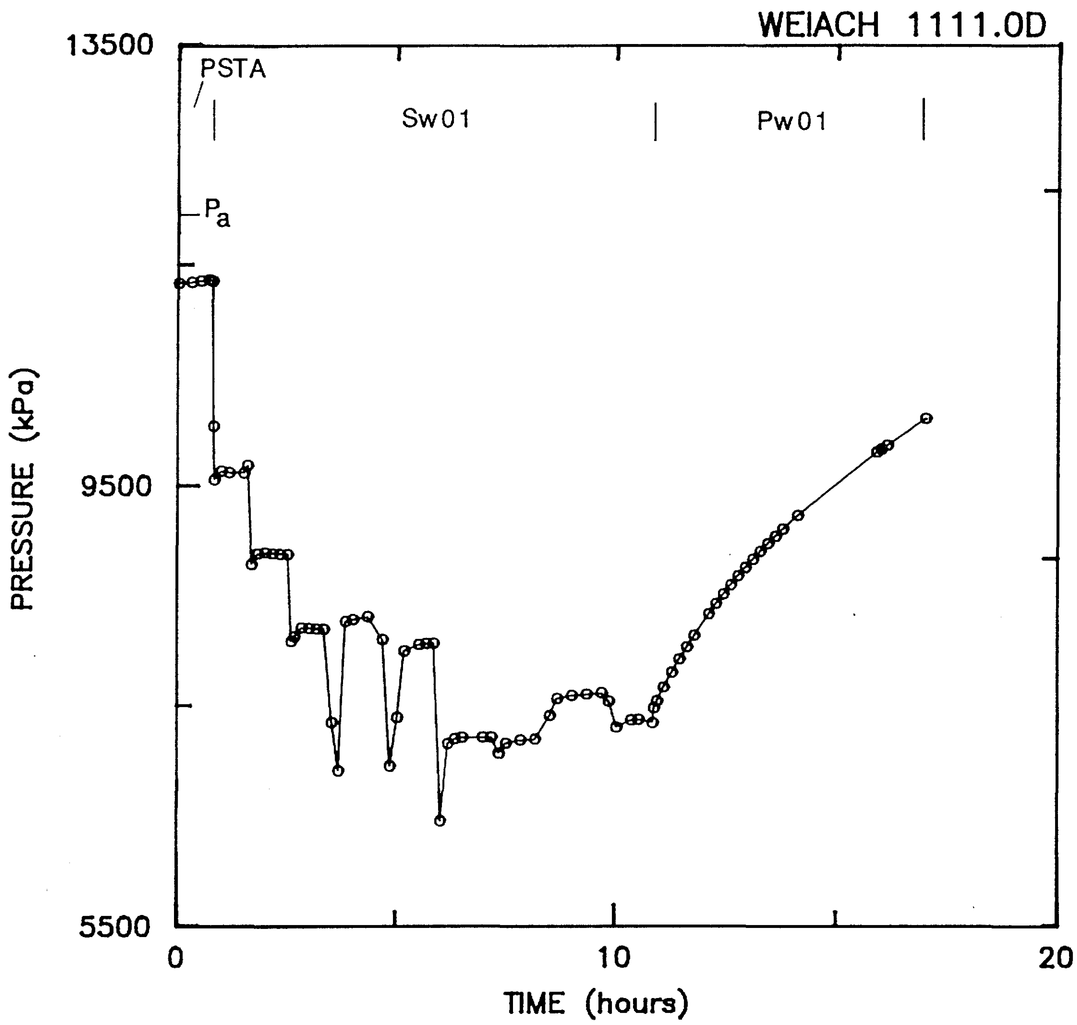


Figure 1 Measured Pressure Data for the Test Interval and Test Sequence Designations for Each Test

Test 1116.5D (1109.20 m to 1123.79 m) - Rotliegendes

Test 1116.5D was composed of two testing sequences. The second sequence of tests was not included in the simulation because it was felt that a reasonably confident estimate of K and P_f for the interval could be obtained from the first set of tests. The first sequence consisted of four hydraulic tests which were completed in the interval from 1109.20 m to 1123.79 m including a static recovery (PSTA), a drill-stem test (DST01) consisting of a slug withdrawal (Sw01) and a pulse withdrawal (Pw01), and a slug withdrawal (Sw02). During the testing sequence the temperature ranged from 57.5°C to 58.1°C. The first test was a static recovery (PSTA) which had an initial shut-in squeeze of 331 kPa followed by a recovery to 85 percent of the assumed formation pressure. The tubing was swabbed with the shut-in valve closed in preparation for DST01. The initial pressure for test Sw01 was 8378 kPa and the pressure recovered to 8535 kPa over 18 minutes. The flow rate during the flow period Sw01 was 3.1 L min^{-1} at approximately 225 m drawdown. A shut-in squeeze of about 350 kPa was recorded during Pw01. Pw01 was run for 39.4 hours and recovered to within 10 kPa of the assumed formation pressure. A swab was pulled with the shut-in valve closed for test Sw02 which had an initial pressure of 6515 kPa. The pressure recovered to 7047 kPa in 18 minutes and the flow rate during Sw02 was 6.0 L min^{-1} with a drawdown of approximately 377 m. The tubing was swabbed with the shut-in valve open to obtain formation water samples following Sw02. The upper packer failed during this swabbing period.

The testing sequence was simulated with GTFM. Horner analysis of the pressure build-up of DST01 indicated a formation pressure of 11760 kPa for the radius around the borehole currently being affected by test 1116.5D. The pressure of 11780 kPa for the test interval from test 1117.5D is the undisturbed formation pressure. The formation pressure was taken as equal to the skin pressure of 11760 kPa because of the uncertainties involved in simulating the pre-test history of the interval while the interval was behind the casing. The 5 m length of the test interval corresponds to the total length of the perforations within the packed-off zone. Figure 1 shows the measured and simulated pressure responses for the range of hydraulic conductivity 3.0E-08, 1.0E-07, and 3.0E-07 ms^{-1} at a specific storage of 8.3E-07 m^{-1}. The best fit of the measured data is for a hydraulic conductivity of 3.0E-08 ms^{-1} at a specific storage of 8.3E-07 m^{-1}. Varying the specific storage by an order of magnitude above and below the base case S_s of 8.3E-06 m^{-1} resulted in less than half an order of magnitude variation in the best estimate of hydraulic conductivity for the interval. Temperature effects were not included in the analysis due to the high hydraulic conductivity of the interval.

The simulated pressure response of PSTA was slightly higher than the measured data. The annulus pressure after perforation and prior to testing was 870 kPa lower than the formation pressure and had a small effect on PSTA. The actual annulus pressure felt by the formation may have been lower than 10891 kPa. The effect of annulus pressure on the formation was not observed in Pw01 which recovered to 99.7 percent of formation pressure.

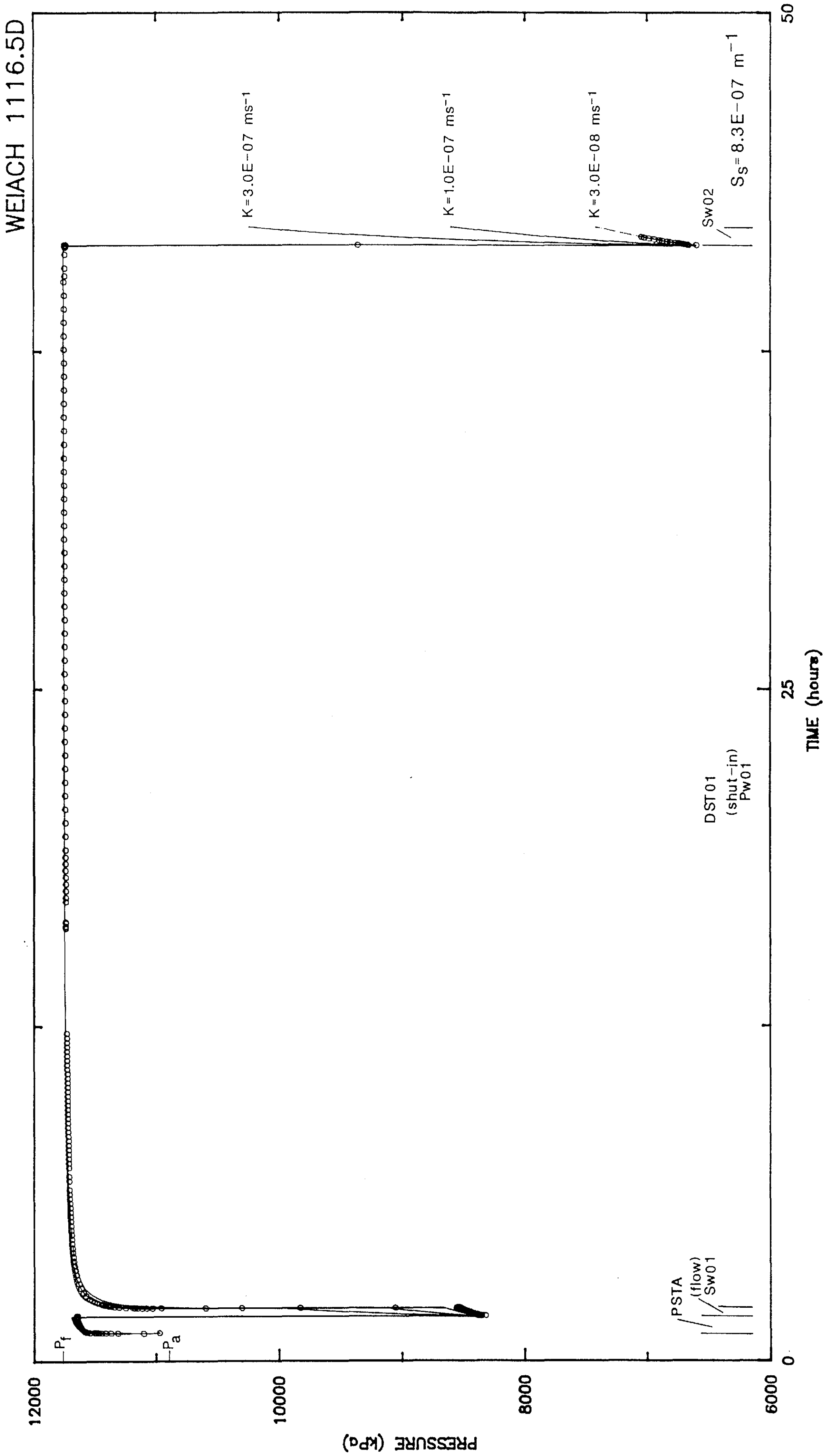


Figure 1 Measured (o) and Simulated Pressure Responses for the Testing Sequence

Test 1117.5D (1112.00 m to 1123.00 m) - Rotliegendes

Test 1117.5D was a double packer test of the interval from 1112.00 m to 1123.00 m. The testing sequence consisted of a static recovery (PSTA), two pulse withdrawals tests, Pw01 and Pw04, two drill-stem tests, DST01 (consisting of flow period Sw01 and shut-in period Pw02) and DST02 (consisting of flow period Sw02 and shut-in period Pw03), and two slug withdrawal tests, Sw03 and Sw04. The static recovery test had an initial shut-in squeeze of 240 kPa, followed by a recovery to within 6 kPa of formation pressure. Ninety percent of recovery was obtained in 18 minutes. A swab of about 100 m was pulled with the shut-in valve closed in preparation for Pw01. Pw01 had an initial shut-in squeeze of 150 kPa, and recovered to within 2 kPa of formation pressure. An average flow rate of 6.0 L min^{-1} was recorded with approximately 150 m drawdown during the flow period of DST01. The shut-in period had a shut-in squeeze of about 600 kPa and recovered to 94 percent of formation pressure in 28 minutes. DST02 had an average flow rate of 6.6 L min^{-1} at approximately 188 m drawdown. At shut-in, a squeeze pressure of 1061 kPa was observed and recovery to 99 percent of formation pressure was measured in 426 minutes. Pw04 was preceded by an extended period with the shut-in valve open. This was simulated as slug withdrawal Sw03. The average flow rate during Sw03 was about 7.1 L min^{-1} at 180 m drawdown. Pw04 had a shut-in squeeze of about 880 kPa and recovered to 99 percent of formation pressure. The first attempt of Sw04 was aborted due to tool movement. Sw04 was successfully run on the next attempt and had a flow rate of about 5.6 L min^{-1} at a drawdown of 87 m. The tubing was swabbed several times during Sw04 with the shut-in valve open in an effort to increase the interval yield. The first attempt at Sw04 and testing after swabbing began were not simulated. The measured temperature response during the testing sequence shows an increase from 49.3°C to 54.1°C.

The testing sequence was simulated using GTFM with the compliance period incorporated into the analysis. A formation pressure of 11780 kPa was determined using Horner analysis of Pw04. This formation pressure was verified by closely matching the shut-in test recovery curves using GTFM. The simulated pressure responses for the range of hydraulic conductivity 3.0E-07, 1.0E-07, and 3.0E-08 ms^{-1} at a specific storage of 8.2E-07 m^{-1} are shown in Figure 1. The best fit of the measured shut-in recovery data is for a hydraulic conductivity of 1.0E-07 ms^{-1} at a base case specific storage of 8.2E-07 m^{-1}, whereas the best-fit of the flow period data is at a hydraulic conductivity of 3.0E-08 ms^{-1}. The recommended hydraulic conductivity for the test interval is 6.0E-08 ms^{-1}. Varying the specific storage over 2 orders of magnitude results in less than half an order of magnitude variation in the best estimate of hydraulic conductivity for the interval. Temperature effects were not included in the analysis due to the high hydraulic conductivity of the interval.

The simulation of PSTA was slightly below measured pressures indicating that the annulus pressure prior to testing may have had an effect on the measured data. However, after PSTA was completed the pressure transient due to the annulus pressure had dissipated.

An equivalent freshwater head of 452.58 m ASL was calculated from the formation pressure at the center of the test interval assuming a freshwater density of 1000 kgm^{-3} from the interval center to ground surface. There is a standard deviation of 0.86 m ASL around the mean, 452.4 m ASL. The variables that predominantly cause the uncertainty in the equivalent freshwater head are the pressure at the P2 transducer and true vertical depth. Uncertainty of pressure at P2 is based on the combined accuracy and resolution specifications for a generic HTT transducer, ± 22.8 kPa. Using the endpoints as the 0.1 and 99.9 percentiles of a normal distribution is equivalent to a normal distribution having a 7.38 kPa standard deviation. Converting pressure to meters of freshwater head (7.38/g = 0.75), the transducer specifications can account for about 87 percent of the uncertainty of freshwater head. Since the distribution for true vertical depth is uniform, its standard deviation is 0.42 m. Although not as pronounced as the pressure at the P2 transducer, the effect of the uncertainty around true vertical depth is not insignificant.

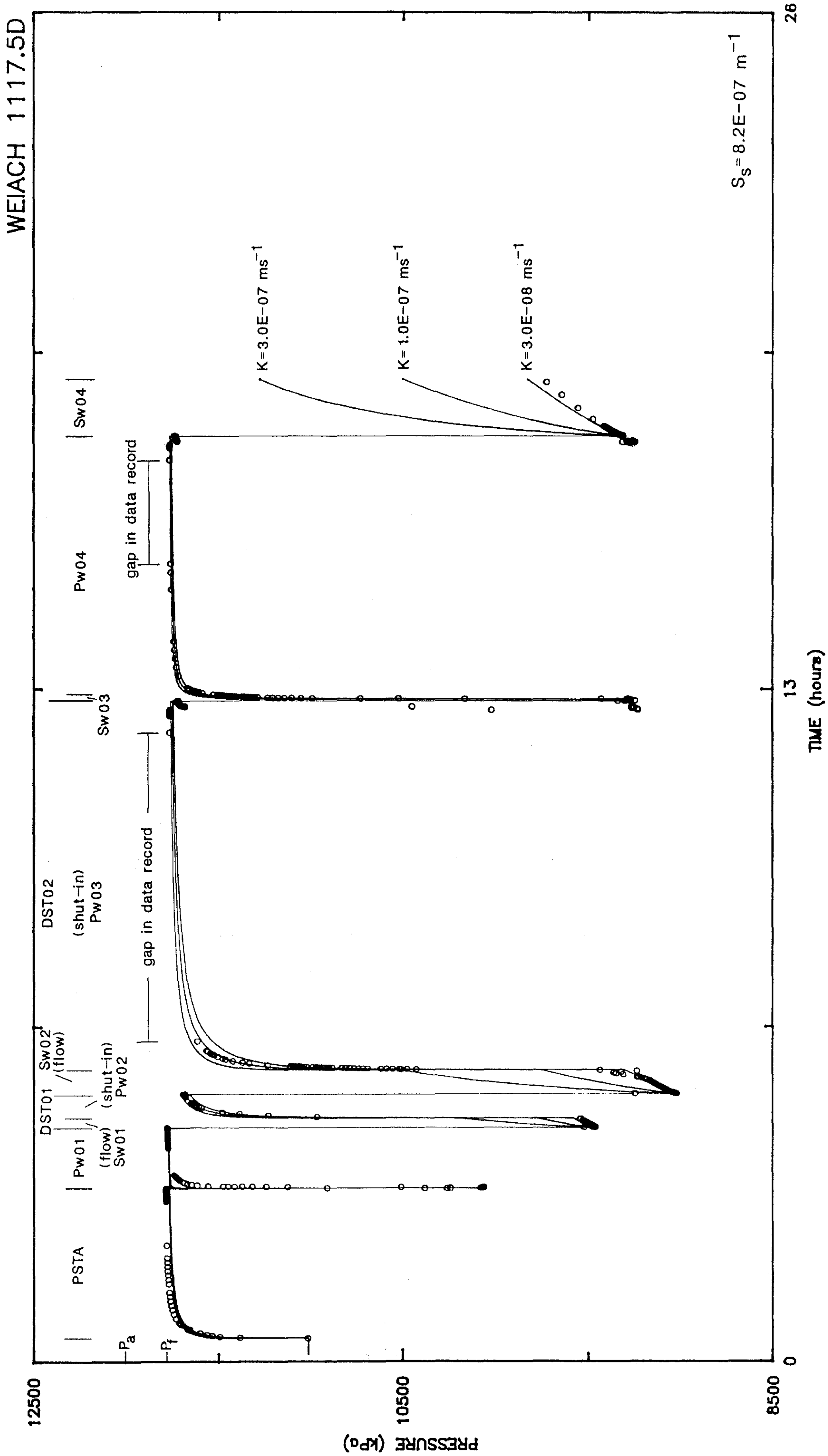


Figure 1 Measured (o) and Simulated Pressure Responses for the Testing Sequence

Test 1240.1D (1233.50 m to 1246.79 m) - Upper Rotliegendes

Double packer hydraulic testing was completed in the interval from 1233.50 m to 1246.79 m of the Weiach borehole from 29 July, 1983 to 30 July, 1983. The formation pressure was assumed at 13095 kPa based on the observed recovery of the hydraulic testing for this test interval.

The testing sequence consisted of a static recovery, two drill-stem tests and a pulse withdrawal test. An additional pulse injection test was attempted but terminated due to equipment related problems. The static recovery (PSTAT) had an initial shut-in pressure of 12363 kPa and a pressure recovery of approximately 729 kPa in 44 minutes to 13092 kPa. A DST (DST01) followed PSTAT with a flow period of about 30 minutes ($Q \approx 1$ L min^{-1}) and a build-up period of about 2.4 hours. The shut-in for the build-up period caused a pressure squeeze of 1452 kPa. The abnormal pressure response during the DST01 build-up period may have been due to partial closure of the shut-in valve. The next test, DST02, consisted of a flow period of about 32 minutes ($Q \approx 2.1$ L min^{-1}) and a build-up period of about 1.5 hours. The shut-in for the build-up period caused a pressure squeeze of 3025 kPa and the pressure recovered to 13095 kPa in about 90 minutes. The last successful test in the sequence was a pulse withdrawal (Pw01) which had a brief period (3 minutes) with the shut-in valve open prior to closing the shut-in valve for the pulse withdrawal test followed by shut-in. The shut-in for Pw01 resulted in a pressure squeeze of 2353 kPa and the pressure recovered to 13095 kPa over about 75 minutes.

Simulation of the history and testing sequence was completed using GTFM incorporating history effects. Temperature effects were not included in the simulations because the temperature measured at T2 changed less than 0.4°C while the shut-in valve was closed and the estimated K was greater than 1.0E-09 ms^{-1}. The pressure squeeze effects reported in the observed pressure data were included at approximately 50 percent of their value because the corresponding simulated response for the 100 percent value did not replicate the observed response. Also, the shut-in period for DST01 was not matched in the simulations because it is probable that the shut-in valve was only partially closed during this test. The recovery of DST02 and Pw01 to virtually the same pressure indicates that the system was not underpressured during DST01 as the observed data indicate. Simulations conducted for hydraulic conductivities of 1.0E-06, 3.0E-07, and 1.0E-07 ms^{-1}, and for a specific storage of 6.4E-07 m^{-1} at the assumed formation pressure are shown in Figure 1. The best-fit estimates of hydraulic conductivity are based on the PSTAT test and the flow period of DST01. It was determined that the pressure response for DST02 and Pw01 was not attainable due to the uncertainty associated with the pressure squeeze of the shut-in. From the fit of PSTAT the most reasonable hydraulic conductivity for the test zone is 3.0E-07 ms^{-1} at a specific storage of 6.4E-07 m^{-1}. However, the testing sequence is unresponsive as indicated by the lack of flow during flow periods and the immediate recovery of the build-up to virtually the same pressure (≃13095 kPa) independent of the underpressure history. The formation may have drilling fluid in it which restricts the hydraulic response and causes the squeeze pressures to drive the response. The effect of varying specific storage over about one and one-half orders of magnitude results in less than half an order of magnitude uncertainty in the final estimate of K for the test zone.

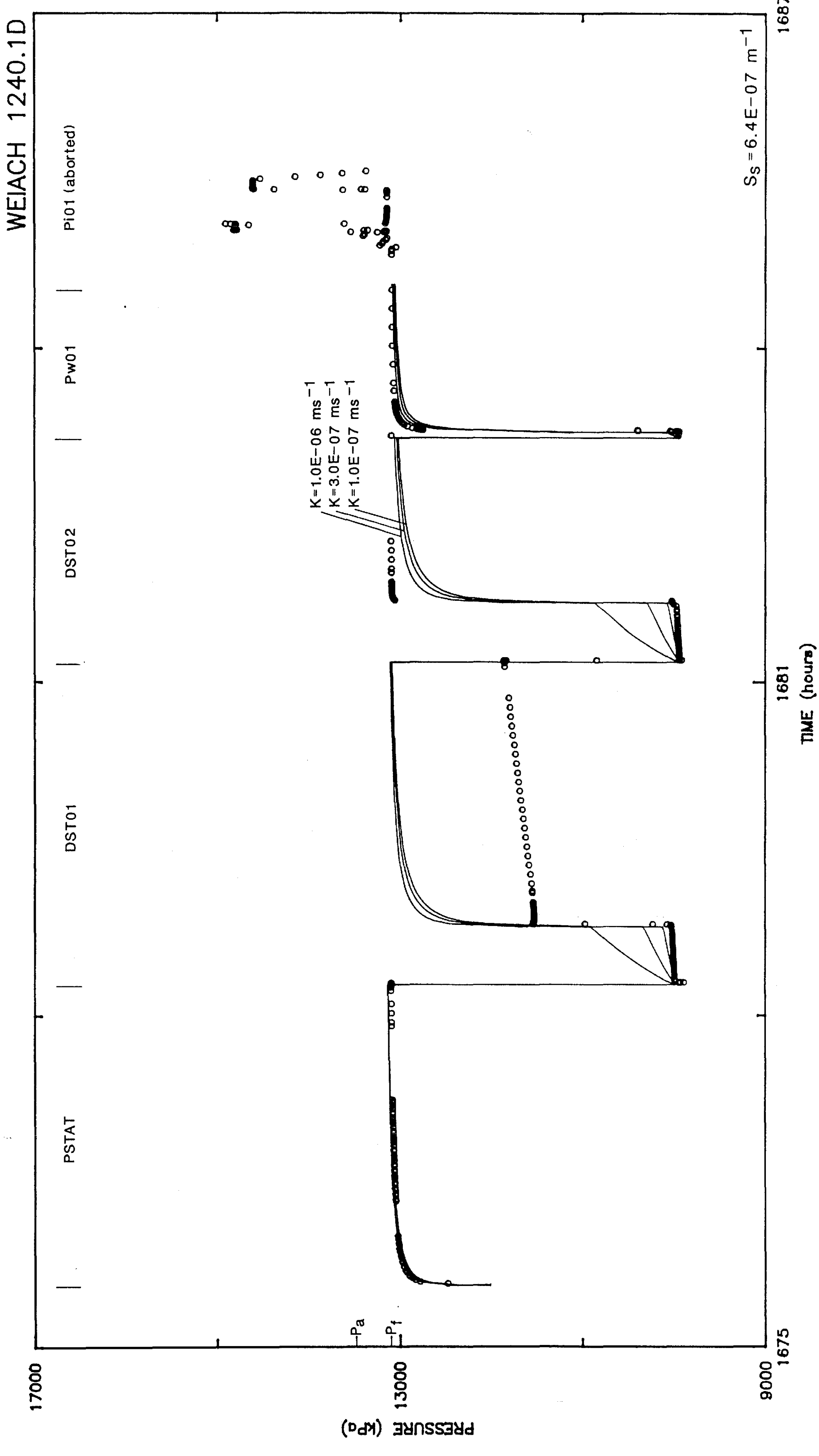


Figure 1 Measured (o) and Simulated Pressure Responses for the Testing Sequence

Test 1303.3D (1296.70 m to 1309.99 m) - Lower Rotliegendes

Test 1303.3D was a double packer test of the Weiach borehole from 1296.70 m to 1309.99 m. The measured pressure data for the temperature sequence is shown in Figure 1. During the testing sequence, the temperature ranged from 57.4°C to 59.2°C. The tests in the testing sequence consisted of a static recovery (PSTA), two drill-stem tests (DST01 and DST02), and a slug withdrawal test (SW01). The slug withdrawal test was preceded by surging of the formation, consisting of running the swab bar up and down the hole with the shut-in tool open.

From a preliminary analysis (GARTNER LEE, 1985a), the hydraulic conductivity was estimated at 6.0E-14 ms^{-1} for the formation and 1.0E-10 ms^{-1} for the borehole surrounding (skin zone). A detailed analysis of this testing sequence was not attempted because it was suspected that the formation was probably clogged with drilling mud adjacent to the test tool. The squeeze pressures associated with the shut-in periods of the drill-stem tests and the static recovery indicated that the formation was of very low hydraulic conductivity causing the measured pressure responses to be that of the fluid in the packed-off interval undergoing compression. The flow periods of the drill-stem tests had no measurable flow and the measured pressure responses actually dropped during the tests. After the second drill-stem test, the interval was surged with a swab tool in an attempt to get fluid to flow from the formation. The final flow period demonstrated a 15 kPa recovery over a period of an hour with an average flow rate of 0.24 L min^{-1}. This flow rate and pressure recovery indicate a hydraulic conductivity on the order of 1.0E-11 ms^{-1} to 1.0E-10 ms^{-1}. This range for hydraulic conductivity is similar to the hydraulic conductivities for surrounding test intervals.

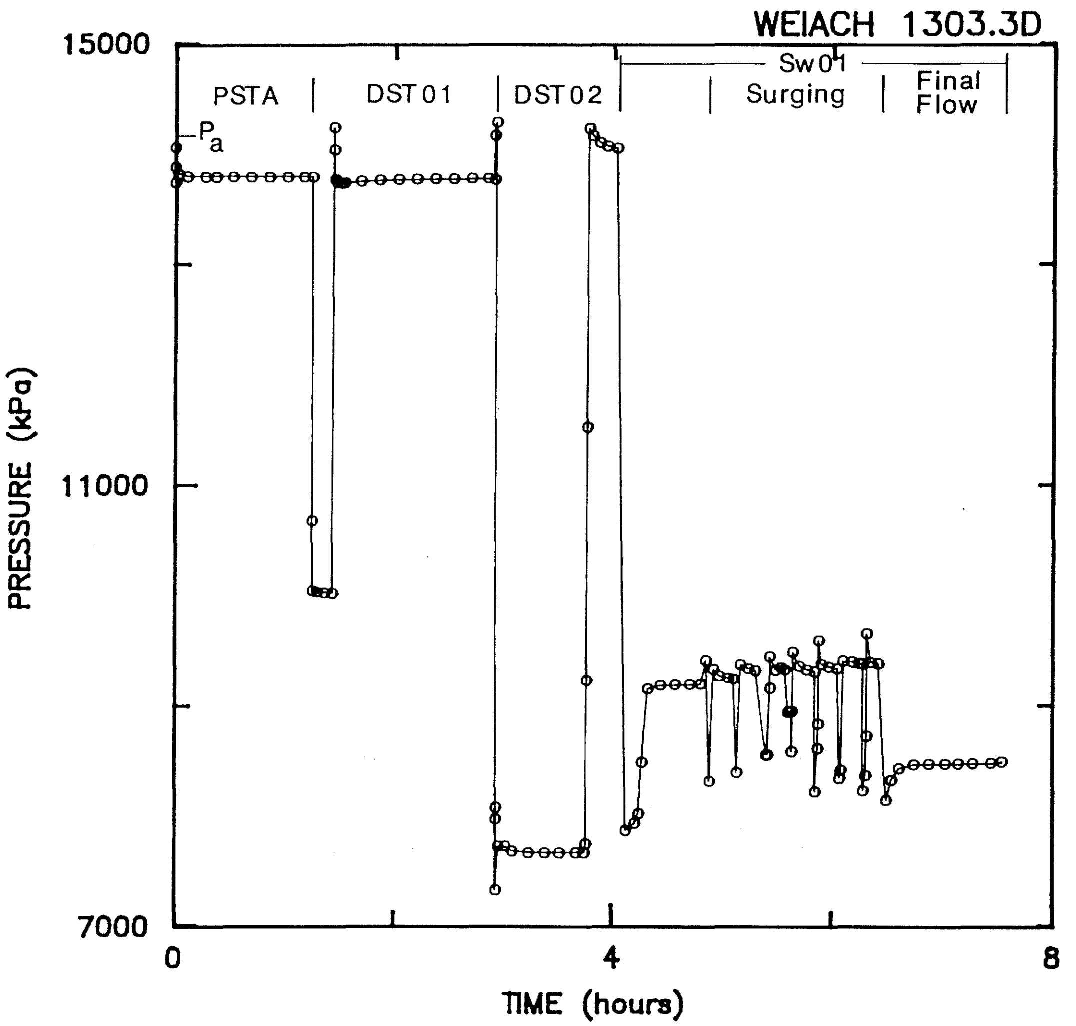


Figure 1 Measured Pressure Data for the Test Interval and Test Sequence Designations for Each Test

Test 1369.4D (1359.30 m to 1379.50 m) - Upper Carboniferous

Double packer hydraulic testing was completed in the interval from 1359.30 m to 1379.50 m of the Weiach borehole on 09 August, 1983. The formation pressure was assumed to be 14800 kPa based on extrapolation of the pressure recovery of the first drill-stem test.

The testing sequence consisted of two drill-stem tests separated by a swabbing period. The initial drill-stem test (DST01) flow period had an initial pressure of 11463 kPa. Flow of 0.25 L min^{-1} was observed for about 40 minutes with a 200 m drawdown. The shut-in valve was then closed with an estimated squeeze of 500 kPa for the build-up period. DST01 build-up had a pressure recovery to 14535 kPa over approximately four hours. A 40 minute period of swabbing with the shut-in valve open followed. The second drill-stem test (DST02) flow period had an initial pressure of 8270 kPa and a flow rate of 0.50 L min^{-1} with a 550 m drawdown. The build-up period of DST02 had an initial pressure of 8380 kPa. The pressure increased over the approximately four hour build-up period to 13888 kPa.

Simulation of the history and testing sequence was completed using GTFM incorporating history effects. Temperature effects were not included in the simulations because the T2 temperature increased only 0.5°C during the testing period.

The simulated responses for the range of hydraulic conductivity 1.0E-09, 3.0E-10, and 1.0E-10 ms^{-1} and for a specific storage (S_s) of 2.6E-06 m^{-1} at the assumed formation pressure are shown in Figure 1. A hydraulic conductivity of 3.0E-10 ms^{-1} provided the most reasonable fit for the range of specific storages used in this analysis. Varying S_s over two orders of magnitude results in half an order of magnitude change in the best-fit K.

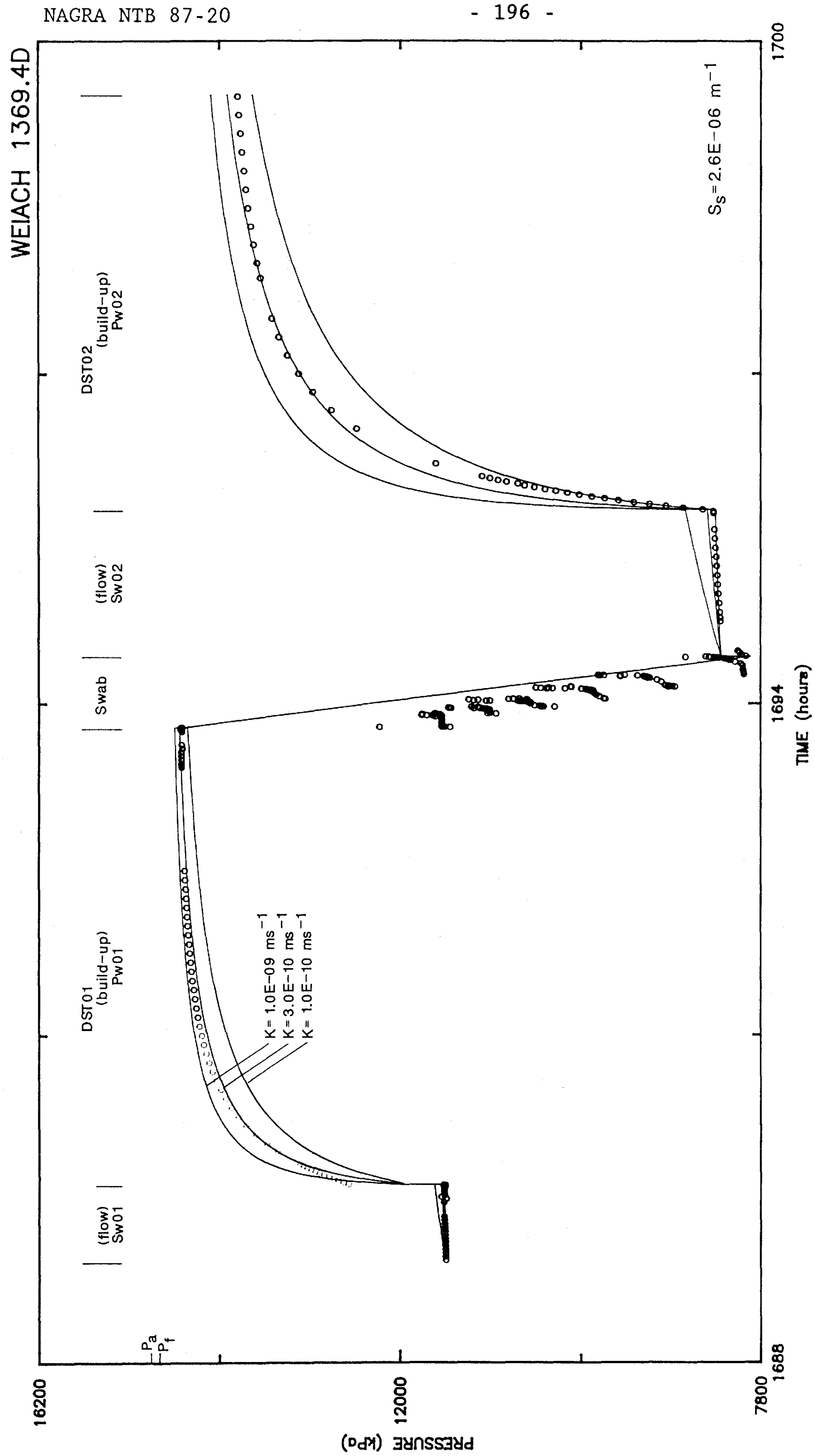


Figure 1 Measured (o) and Simulated Pressure Responses for the Testing Sequence

Test 1411.1D (1401.0 m to 1421.15 m) - Upper Carboniferous

Between depths of 1401.0 m and 1421.15 m in the Weiach borehole, a sequence of hydraulic tests were conducted for the purpose of determining formation hydraulic conductivity, hydraulic head, yield and the potential for sampling.

The testing sequence consists of a compliance monitoring period after setting the packers, a pulse withdrawal test (Pw01) showing the recovery of the test interval pressure to a near stable value, two slug withdrawal tests (Sw01 and Sw02), and a final pulse withdrawal test (Pw02). A period of swabbing separated the slug withdrawal tests.

The formation pressure used in the simulation of testing in this interval was 14517 kPa, based on an assumption of a static fluid level at the top of the borehole and a depth integrated density of the fluid column of 1049 kgm^{-3}. The density was obtained from PEARSON and LOLCAMA (1987) and corrected for temperature. Since the overpressure transient around the borehole is likely to influence the recovery pressure of Pw01, and the period of underpressure prior to Pw02 is likely to affect the recovery pressure for this test, a calibrated formation pressure is not possible. For this same reason, that is the existence of a pressure transient, a Horner analysis of the Sw02 and Pw02 sequence would likely provide an inaccurate estimate of P_f.

The temperature of the fluid near the test interval (at T2) increased from 63.5°C to 64.1°C across the testing period. This change is significant at the low hydraulic conductivity expected for the interval. To model the effects of thermal expansion of the borehole fluid on the testing response, thermal effects were considered in the simulations.

Estimates of hydraulic conductivity and specific storage for the interval were obtained using GTFM. A suite of hydraulic conductivity was run over the range 3.0E-10, 1.0E-10, and 3.0E-11 ms^{-1}. Specific storage was varied from 1.0E-05 to 9.3E-05 m^{-1} for each hydraulic conductivity. From the simulated pressure response of tests Pw01 and Pw02, the most reasonable hydraulic conductivity of the test zone is 1.0E-10 ms^{-1} at a specific storage of 1.0E-05 m^{-1} as shown in Figure 1. The poor fit of the late time data of both of these tests may result from either an underestimate of the pressure transient around the test zone, or an estimated formation pressure below the undisturbed value. From the available data, the estimates of pressure history and formation pressure used in these simulations are still considered reasonable. The uncertainty in hydraulic conductivity from the specific storage sensitivity study is about half an order of magnitude for a range in S_s of two orders of magnitude.

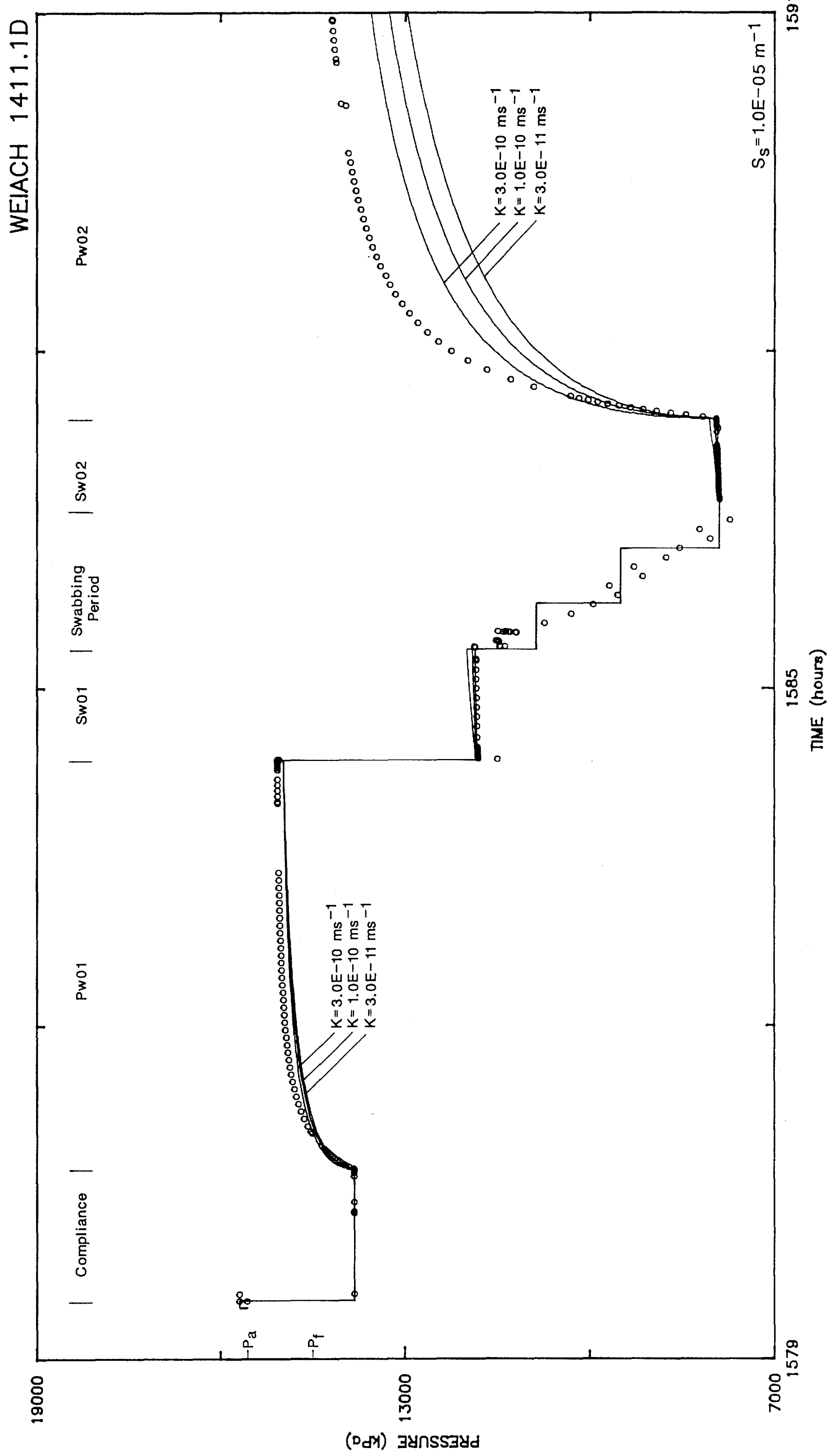


Figure 1 Measured (o) and Simulated Pressure Responses for the Testing Sequence

Test 1456.9D (1446.81 m to 1466.96 m) - Upper Carboniferous

The testing sequence for 1456.9D consisted of two pulse withdrawal tests separated by two slug withdrawal tests. The first pulse withdrawal test (Pw01) consisted of a shut-in at a pressure of 14312 kPa. Pressure build-up was monitored for 4.5 hours to about 15605 kPa. The borehole was swabbed to 225 m with the shut-in tool closed. The shut-in tool was then opened to begin the first slug withdrawal test (Sw01) at 12394 kPa. After a flow period (estimated flow of 0.01 L min^{-1}) of about one hour, additional swabbing to a depth of 600 m took place. The second swabbing event was undertaken in an attempt to surge the formation to remove possible mud cake from the borehole wall. The second slug withdrawal test (Sw02) started at a pressure of 8365 kPa. A small pressure increase of about 140 kPa occurred at the beginning of the flow period increasing the interval pressure from 8192 kPa to 8365 kPa. The flow during Sw02 was estimated at 0.25 L min^{-1} and occurred for over an hour for a recovery to 8408 kPa. Test Pw02 began when the test interval was shut-in with a squeeze of 90 kPa to a pressure of 8517 kPa. The pressure build-up was monitored for 5 hours at which time the testing sequence was terminated at a pressure of 14452 kPa.

Simulation of the history and testing sequence was completed using GTFM to incorporate the pressure history. Temperature effects are not included in the simulations because the effects of the temperature change of 0.3°C during testing were considered negligible. Simulations were completed for hydraulic conductivities of 1.0E-10, 3.0E-11, and 1.0E-11 ms^{-1} and for S_s of 2.2E-05, 2.8E-06, and 9.0E-07 m^{-1} at the assumed formation pressure. The best-fit simulation of the test data and the measured pressure responses are shown in Figure 1. This simulation corresponds to a formation hydraulic conductivity of about 6.0E-11 ms^{-1} at a specific storage of 2.8E-06 m^{-1}.

The uncertainty in hydraulic conductivity, as the result of varying specific storage over close to two orders of magnitude for the formation, is about half an order of magnitude.

The formation pressure for this zone in the Carboniferous had to be assumed in order to complete the simulations since there was no calibrated formation pressures near this test interval available for reference. A formation pressure at P2 was therefore chosen as 15600 kPa. This pressure may be somewhat high as can be seen from Figure 1, where the simulations overfit the late time data of test Pw02. It seems reasonable that at the relatively high specific storage chosen, the overpressure transient which would have developed in the formation from the interval being exposed to borehole pressures would have dissipated in close vicinity of the borehole. Since the pressure recovery during Pw02 is not affected by the overpressure transient, the simulated formation pressure response is likely seeing a higher formation pressure than the measured response.

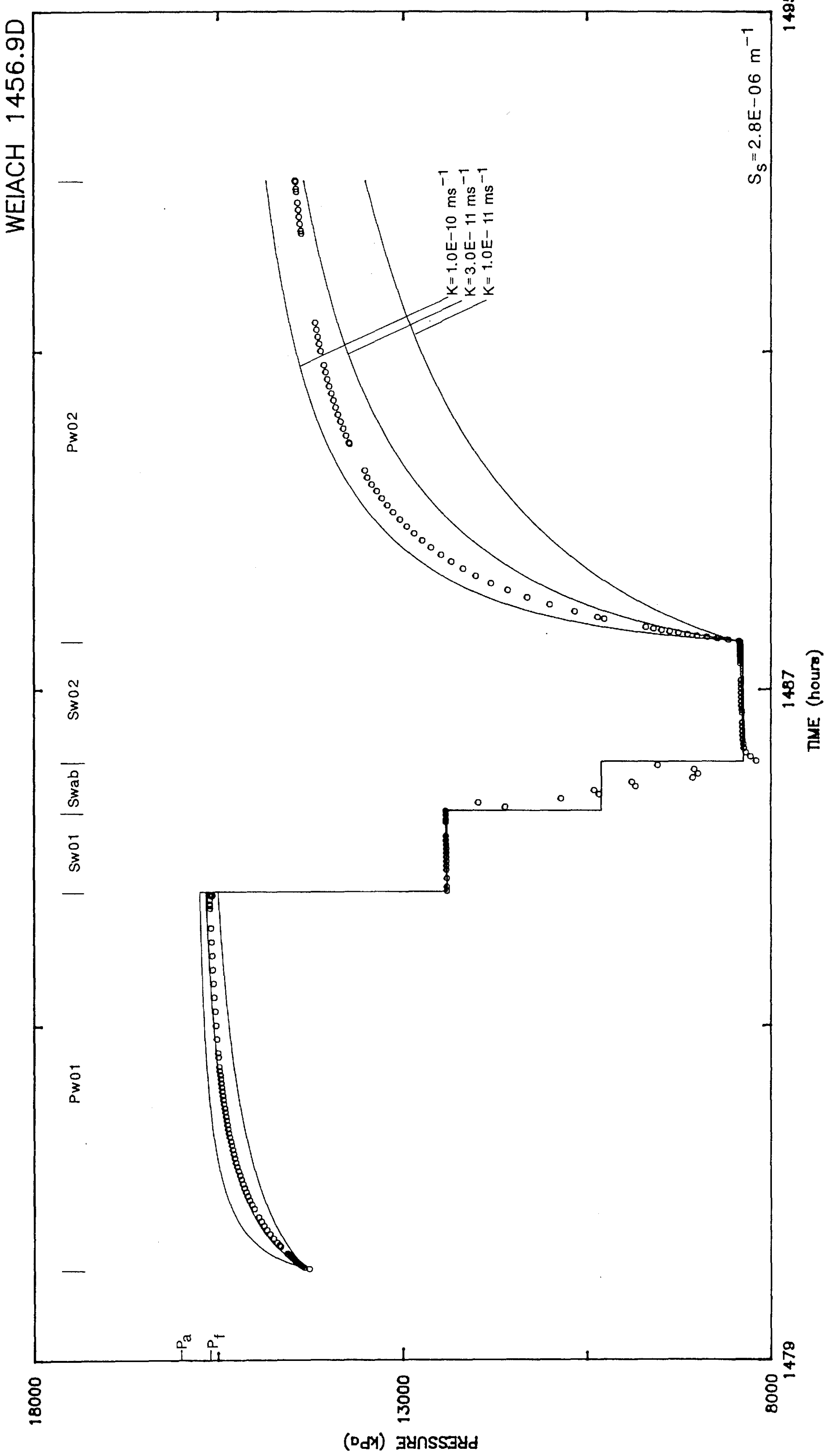


Figure 1 Measured (o) and Simulated Pressure Responses for the Testing Sequence

Test 1603.1D (1593.00 m to 1613.15 m) - Upper Carboniferous

Double packer hydraulic testing was completed in the interval from 1593.00 m to 1613.15 m of the Weiach borehole from 07 August to 08 August, 1983. The formation pressure was assumed to be 18000 kPa based on an extrapolation of the shut-in recovery of the second drill-stem test. This extrapolated formation pressure may be lower than the undisturbed formation pressure due to underpressure events prior to the second drill-stem test.

The testing sequence consisted of a static recovery test (PSTA), a drill-stem test (DST01), a failed slug test, a slug withdrawal test (Sw01), a swab event, and a second drill-stem test (DST02). The initial static recovery test (PSTA) starting pressure was 15667 kPa. The measured response recovered for approximately 3 hours to a pressure of 17032 kPa. DST01 followed after swabbing with the shut-in valve closed to 200 m below full tubing level. After opening the shut-in valve, flow of 0.08 L min^{-1} was observed for about 16 minutes with 200 m drawdown. The shut-in valve was then closed for a build-up period of one hour. A 600 m swab did not develop the expected P2 pressure response during the failed slug test. A 2.5 hour period of inspection, swabbing and application of overpressure (3000 kPa) to the full tubing followed, with the shut-in valve open. The P2 transducer started responding to test interval pressure at 17:27 on 07 August, 1983. An overpressure of 3000 kPa was applied for a second time with the shut-in valve closed and then bled off to assure that P2 was responding properly. Swabbing to approximately 215 m was conducted with the shut-in tool open. A slug withdrawal (Sw01) was conducted with a starting pressure of about 13531 kPa and virtually no flow after the first 6 minutes of the test. While swabbing from 500 m for Sw02 the shut-in closed resulting in a pressure increase of about 5000 kPa. Test Sw02 was abandoned as swabbing continued to 550 m in preparation for DST02. The DST02 flow period had an initial pressure of 10244 kPa. During the 1.5 hour flow period, an average flow rate of 0.14 L min^{-1} was measured. The shut-in valve was closed for the DST02 build-up period with a pressure squeeze of about 52 kPa. DST02 had a pressure recovery to 75 percent of the assumed formation pressure over about 6 hours.

The testing sequence was interrupted by closure problems with the shut-in tool in the failed slug test. Also, the tool came out of the J slot later in Sw02. In addition, it is speculated that there were problems with blockage in the P2 port as the tool was lowered into the hole and perhaps again at the end of DST01. The pressure at P2 did not drop to the expected level of swabbing during the aborted slug test following DST01. Another possibility was that the shut-in value was not opened and therefore the underpressure in the tubing was not transmitted to the test zone. The tool and P2 observation problems created significant uncertainty in the K in the early tests so that only DST02 was evaluated for a K.

Simulation of the history and testing sequence was completed using GTFM to incorporate the history and thermal effects. Because of the uncertainty associated with prior pressure measurements only test DST02 was simulated with GTFM. The pressure response preceding DST02 was built into the simulations as history to develop a sufficient pressure disturbance around the borehole for accurate simulations. An average pressure response was used to represent the two 3000 kPa overpressure periods and swabbing for test Sw01. Test Sw02 was also built into the simulation with an average pressure response. Thermal effects were included in the simulations because of the T2 temperature decrease of approximately 3°C during the DST02 testing period. Figure 1 shows the simulated pressure responses for the range of hydraulic conductivity 1.0E-10, 3.0E-11, and 1.0E-11 ms^{-1} at a specific storage of 2.6E-06 m^{-1} at the assumed formation pressure. The most reasonable hydraulic conductivity for the test zone is 3.0E-11 ms^{-1} for the range of specific storages used in this analysis when considering the fit on the early portion of DST02. The effect of varying S_s over this range results in virtually no change in the best fit K as would be expected. From previous experience, at this hydraulic conductivity, the effect of S_s variation on the best-fit K only becomes significant (i.e., changes K by greater than half an order of magnitude) when S_s is varied by two or more orders of magnitude.

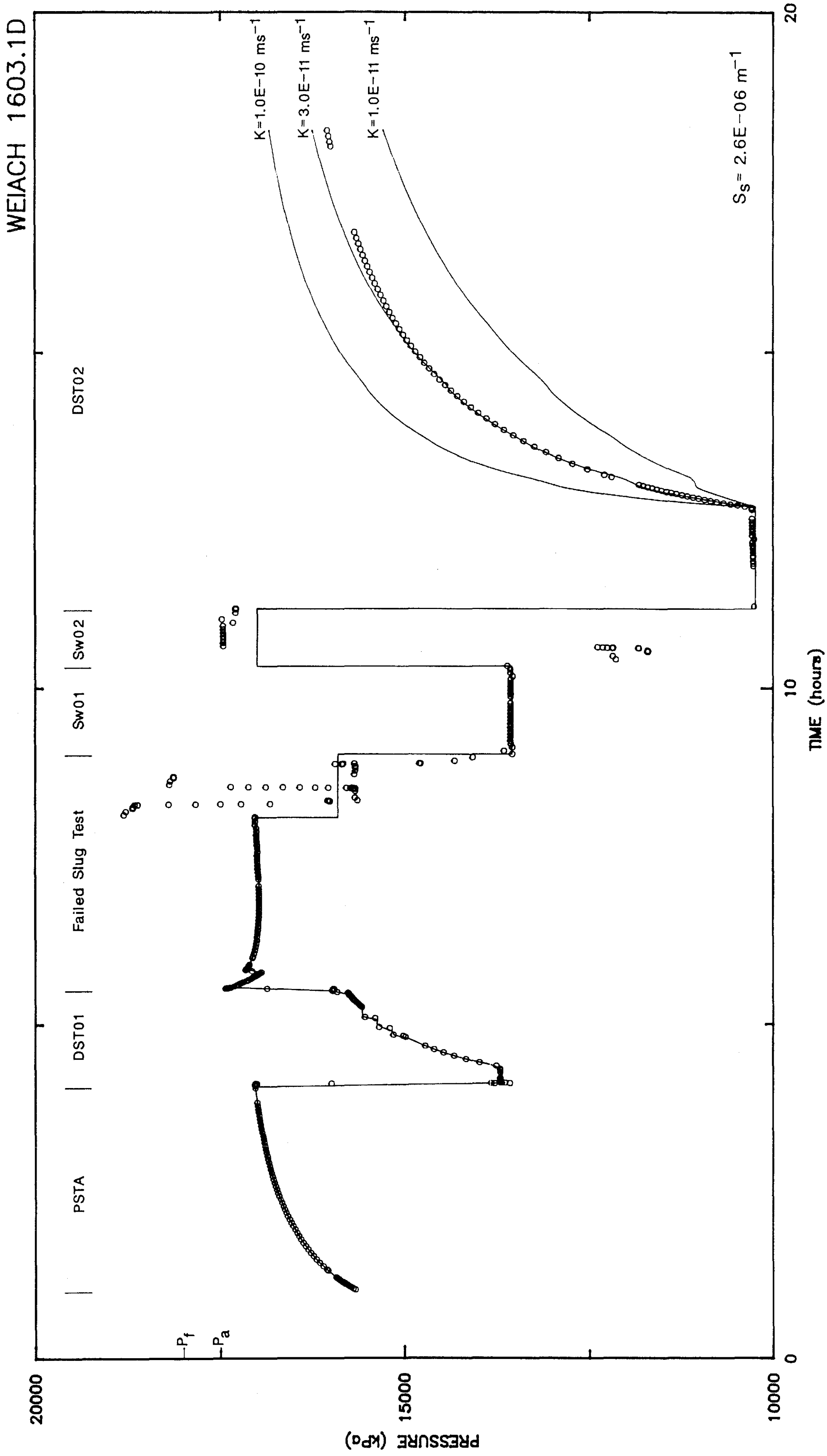


Figure 1 Measured (o) and Simulated Pressure Responses for the Testing Sequence

Test 1880.8S (1876.44 m to 1885.10 m) - Carboniferous

Test 1880.8S was a single packer test of the Weiach borehole from 1876.44 m to 1885.10 m. The measured pressure data for the testing sequence is shown in Figure 1. Two pulse withdrawal tests (Pw01 and Pw02) and a slug withdrawal test (Sw01) were performed on the test interval. From a preliminary analysis (GARTNER LEE, 1983/84), the hydraulic conductivity was estimated at 4.4E-11 ms^{-1}.

The testing sequence was not simulated due to probable tool related problems. Non-characteristic pressure responses were observed at P1 and P2 during individual tests in the testing sequence. These pressure changes occurred without any actions taken at the surface to modify the test tool's configuration. The abrupt pressure changes in P1 and P2 could have been due to packer slippage down the borehole, or perhaps clogged apertures in the test tool. Due to the problems with the measured data, the formation's pressure and hydraulic conductivity were not determined. However, based on an approximation of the early pressure responses during the pulse withdrawal tests, the hydraulic conductivity of the interval is probably on the order of 1.0E-10 ms^{-1}. This value for hydraulic conductivity is comparable to hydraulic conductivities for surrounding test intervals.

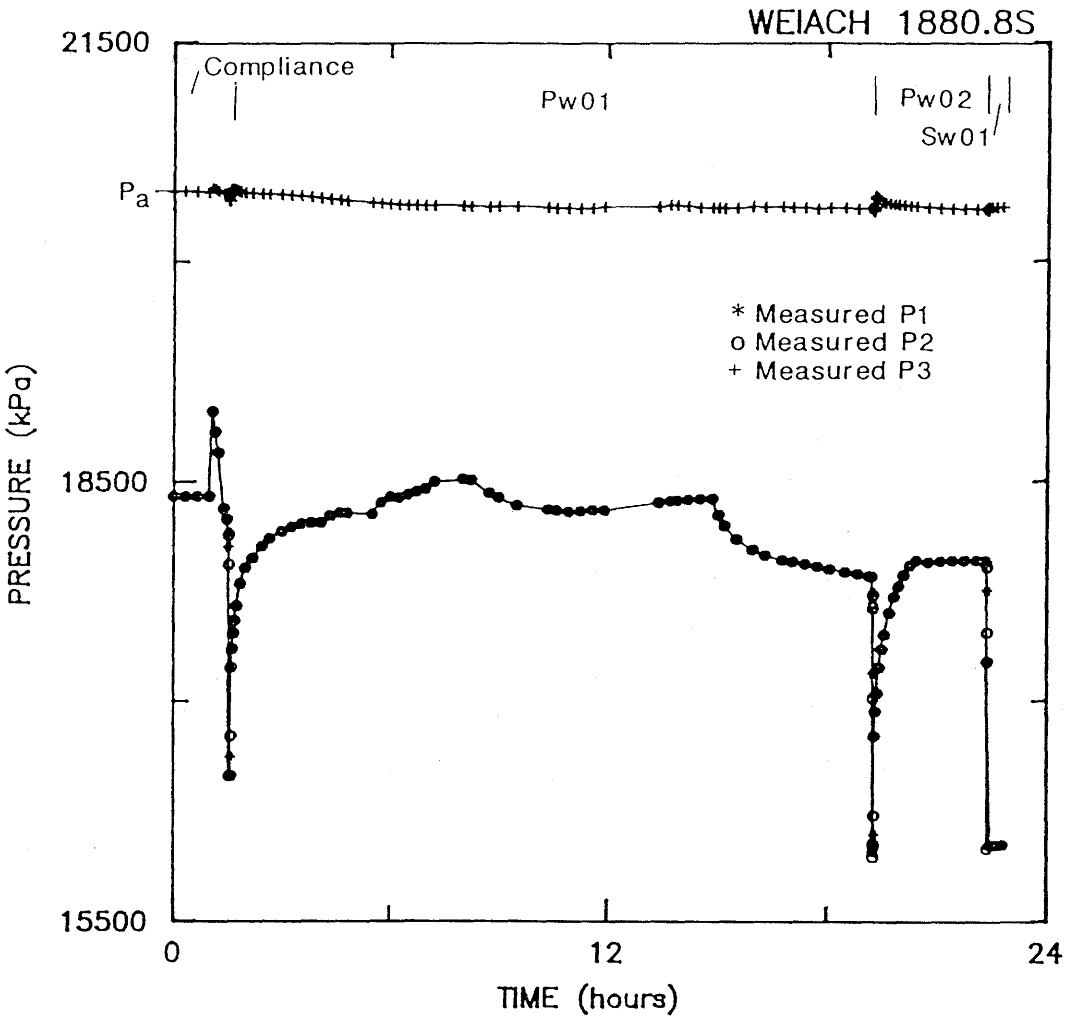


Figure 1 Measured Pressure Data for the Test Interval and Test Sequence Designations for Each Test

Test 1965.1D (1960.00 m to 1970.24 m) - Lower Carboniferous

Double packer hydraulic testing was completed in the interval from 1960.00 m to 1970.24 m of the Weiach borehole on 06 September, 1983. The formation pressure was assumed to be 17000 kPa based on the pressure required to dissipate the history overpressure transient from the history period and match the hydraulic test recovery pressures.

The testing sequence consisted of three drill-stem tests. The P1 port was apparently blocked during testing. The first drill-stem test (DST01) consisted of a flow period of about 13 minutes followed by a build-up period of about 38 minutes. The shut-in for the build-up period occurred at 17911 kPa and a squeeze of 39 kPa resulted in an initial pressure of 17950 kPa for the shut-in recovery period. The build-up P2 pressure reached about 18995 kPa prior to the beginning of DST02. DST02 consisted of a flow period interrupted by a 10 minute swabbing period with the shut-in valve open. The initial portion of the flow period experienced an increase of about 4 kPa over about 65 minutes. The swabbing period reduced the pressure to 17253 kPa. The second portion of the flow period lasted about 45 minutes and resulted in about a 4 kPa increase to 17258 kPa in P2 pressure. DST03 consisted of a flow period of about 62 minutes with an increase of about 6 kPa. On shut-in for the build-up period, a pressure squeeze of about 30 kPa occurred. The pressure then rose during the build-up by about 2900 kPa to a pressure of 17984 kPa. The build-up period lasted about 280 minutes. Test DST03 consisted of a flow period which started at 15274 kPa with the opening of the shut-in valve and a build-up period with a starting pressure of 15317 kPa following a squeeze of 33 kPa. Pressure recovery over about 4.2 hours was to 18176 kPa with the pressure still increasing. In general, the flow periods produced very little flow (<.02 L min^{-1}) over the duration of the period. Due to the 1.5°C temperature change during the testing sequence thermal effects were included in the simulation.

Simulation of the history and testing sequence was completed using GTFM to incorporate history and temperature effects. Simulations were completed for hydraulic conductivities of 3.0E-11, 1.0E-11, 3.0E-12, and 1.0E-12 ms^{-1} and for specific storage values of 2.0E-05, 2.6E-06, and 8.4E-07 m^{-1} at the assumed formation pressure. The most reasonable simulation results shown in Figure 1 indicate that the best-fit hydraulic conductivity for the test zone is 1.0E-12 ms^{-1} at a S_s of 2.6E-06 m^{-1}. The effect of varying S_s over this range results in a change of about one order of magnitude in the K.

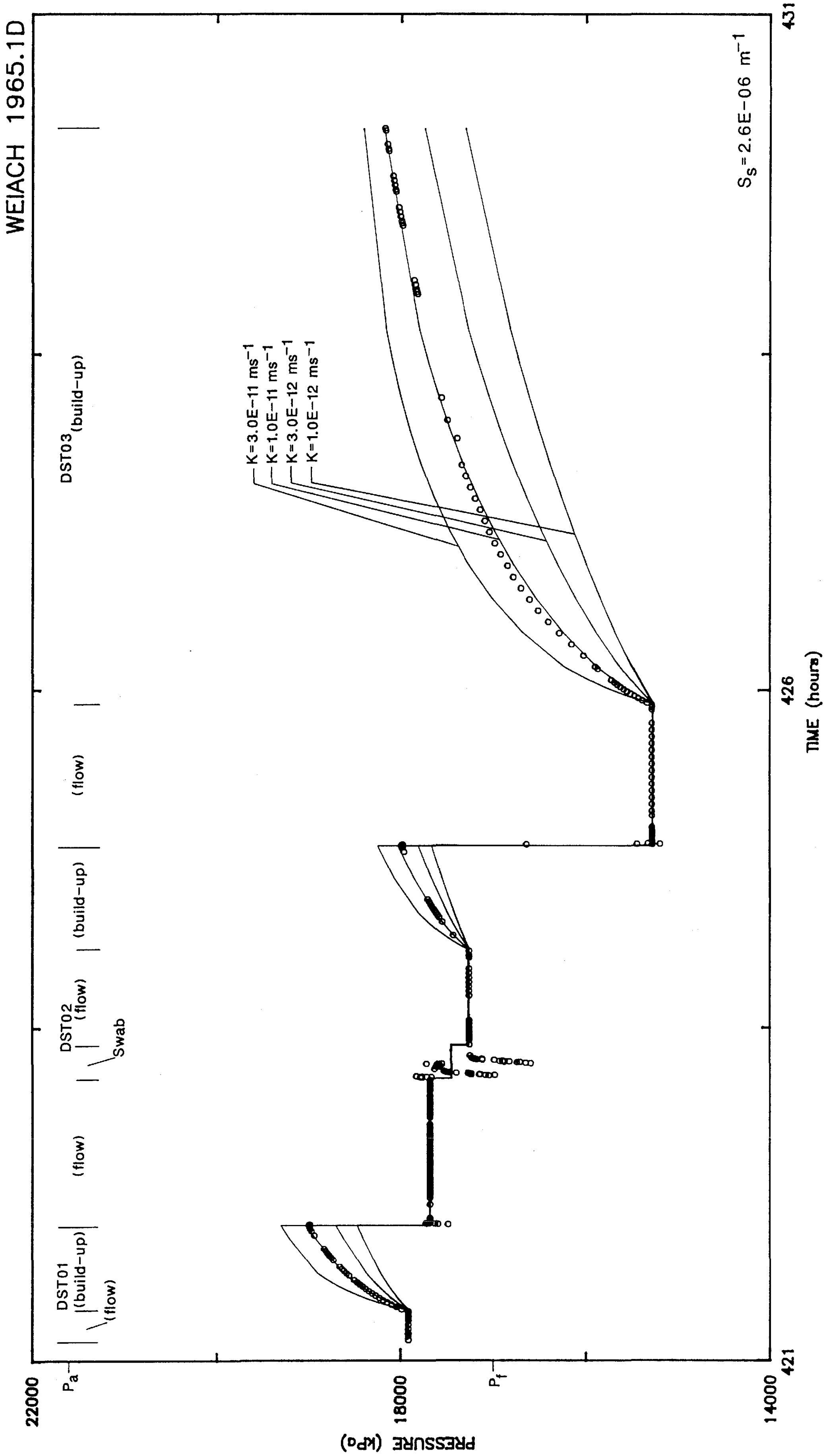


Figure 1 Measured (o) and Simulated Pressure Responses for the Testing Sequence

Test 2018.5D (2015.61 m to 2021.28 m) - Carboniferous/Crystalline

Test 2018.5D was a double packer test of the Weiach borehole from 2015.61 m to 2021.28 m. The test interval was at the bottom of the Karbon Formation and the top of the crystalline rock with the interface at about 2020.20 m. The interval was tested over about 14 hours on 09 September, 1983. Two pulse withdrawal tests (PSTA and Pw01) and a slug withdrawal test were completed in the testing sequence.

The shut-in valve was closed following compliance causing an initial squeeze of about 19 kPa in test PSTA. The measured pressure reached 20144 kPa over a period of 37 minutes. A swab from about 50 m was pulled with the shut-in valve closed prior to test Pw01. The shut-in valve was opened for about 4 minutes before shutting in for test Pw01. This was simulated as a history period with an average pressure of 19196 kPa. A shut-in squeeze of about 24 kPa preceded test Pw01 which had a measured pressure increase to 22116 kPa over a period of 11.7 hours. A swab from about 255 m was pulled with the shut-in valve closed prior to test Sw01. Test Sw01 had an initial pressure of 17178 kPa. No measurable flow or pressure recovery was recorded during the test. The temperature increased from about 82.4°C to 88.1°C during the testing sequence. Due to the 5.7°C temperature change and the apparent low K of the test zone as indicated by the shut-in recovery rates, thermal effects were included in the simulation.

The testing sequence was simulated with GTFM incorporating history and thermal effects. An assumed formation pressure of 20058 kPa was derived by interpolating the Long Term Monitoring formation pressures for Zones 6 and 7 in the crystalline rock to the center of this interval and correcting the pressure to the P2 transducer depth. Figure 1 shows the measured pressure responses and the simulated pressure responses for the range of hydraulic conductivity 1.0E-12, 3.0E-12, 1.0E-11 and 3.0E-11 ms^{-1} at a specific storage of 8.3E-06 m^{-1}.

All of the simulated pressure responses fit the measured data for the slug withdrawal test (Sw01). The simulated responses for the lower hydraulic conductivities during the pulse tests were higher than the measured pressure response. For the higher hydraulic conductivity values, the simulated responses were higher than the measured data in the early portions of the pulse tests and showed lower final pressures than the measured data. During the pulse tests, the simulated pressure responses for the higher hydraulic conductivities were more affected by the overpressure during the pre-test history and the formation pressure, whereas the lower hydraulic conductivities were more affected by the temperature change during the tests. Simulations were run to determine the sensitivity to the pre-test history and thermal effects. These sensitivities indicated that the testing sequence was responding to the thermal effects but that the interval may not have been affected by the pre-test history. The most reasonable fit of the measured pressure data for a hydraulic conductivity of 1.0E-12 ms^{-1} at a base case specific storage of 8.3E-06 m^{-1} was determined based on the sensitivity runs. The effect of the pre-test history caused the best-fit simulated response to increase to a higher pressure than the measured data. The simulations without a pre-test history also indicated that the assumed formation pressure should be considered a maximum value for this test interval. Varying the specific storage by an order of magnitude higher and lower than the base case specific storage results in about an order of magnitude change in hydraulic conductivity.

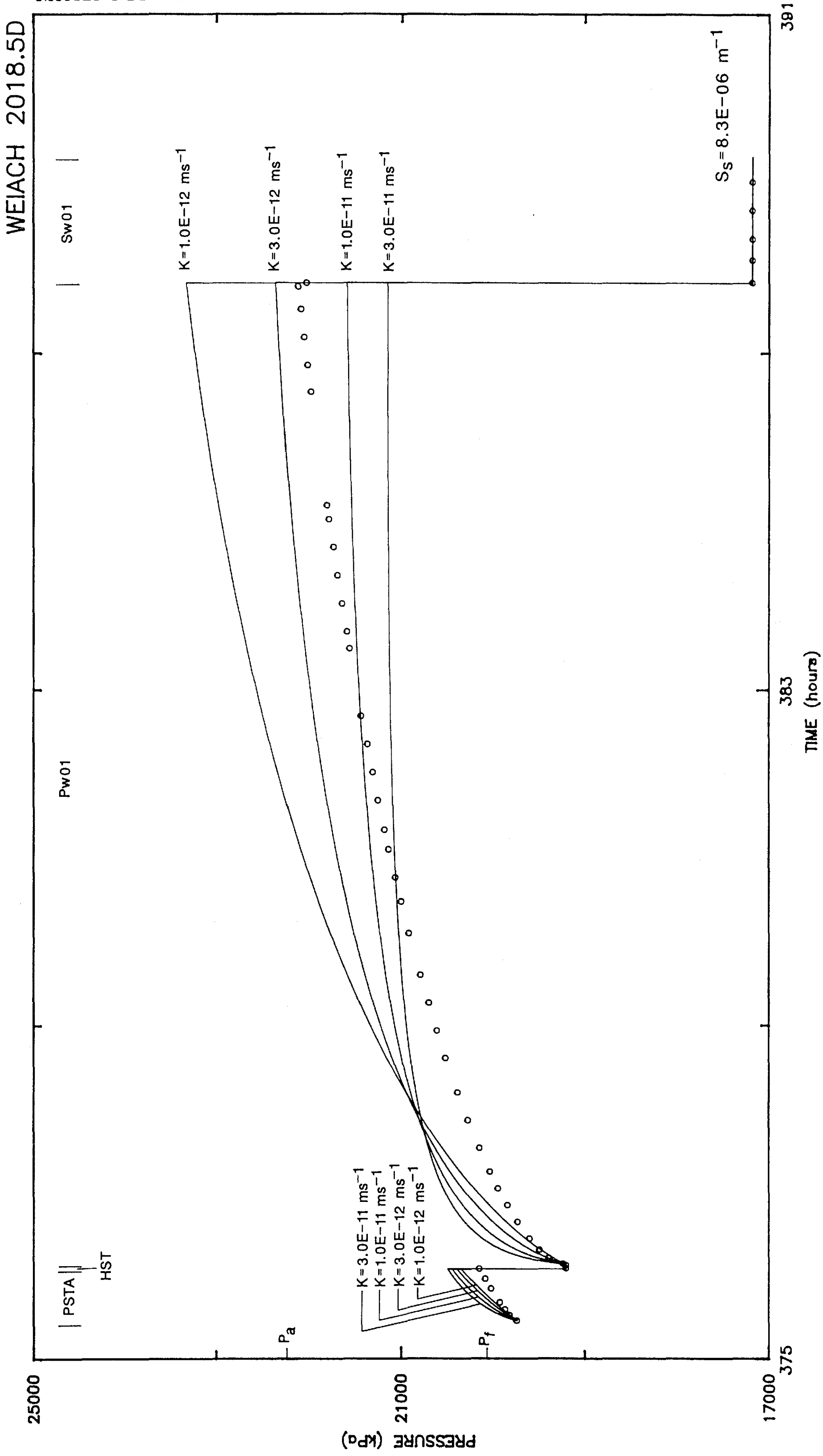


Figure 1 Measured (o) and Simulated Pressure Responses for the Testing Sequence

Test 2063.3S (2059.61 m to 2067.00 m) - Crystalline

Test 2063.3S was a single packer test with the bottom of the packer set at 2059.61 m and the bottom of the borehole at 2067.00 m. The testing sequence consisted of a static recovery (PSTA), a drill-stem test, DST01 (consisting of a flow period Sw01 and shut-in period Pw01), three flow tests, Sw02, Sw03 and Sw04, and two pulse withdrawal tests, Pw03 and Pw04. The static recovery test had an initial shut-in squeeze of about 180 kPa, followed by recovery to within 24 percent of annulus pressure. A swab of about 100 m was pulled with the shut-in valve closed in preparation for the DST01. No fluid recovery was observed during the flow period of the drill-stem test. At shut-in, a squeeze of about 525 kPa was measured. Tests Sw02 and Sw03 were preceded by swabbing with the shut-in valve open. The average flow rate during Sw02 was 0.17 L min^{-1} in the tubing string. An average flow rate of 0.18 L min^{-1} was recorded during Sw03. Test Pw03 was attempted twice causing a short pulse in between Sw03 and Pw03. This was simulated as a pulse withdrawal following Sw03, then a slug withdrawal (Sw04) and then the final pulse withdrawal (Pw03). A shut-in squeeze of about 100 kPa preceded both pulse withdrawal tests (Pw02 and Pw03). Due to the temperature increase from 91.4°C to 98.0°C during the testing sequence, thermal effects were included in the simulation.

The testing sequence was simulated using GTFM such that the history pressures and thermal effects could be incorporated into the analysis. Figure 1 shows the measured and simulated pressure responses for the range of hydraulic conductivity 1.0E-09, 3.0E-10, and 1.0E-10 ms^{-1} at a specific storage of 2.1E-07 m^{-1}. An assumed formation pressure of 19300 kPa was derived by matching the measured pressure response for tests PSTA and DST01 shut-in. This formation pressure is not considered a calibrated value since these shut-in tests were responding to a pressure transient around the borehole resulting from history effects. The most reasonable fit of the measured data of tests PSTA and DST01 is for a hydraulic conductivity of about 6.0E-10 ms^{-1} at a base case specific storage of 2.1E-07 m^{-1}. Varying the specific storage over two orders of magnitude for the crystalline rock results in about half an order of magnitude variation in the best estimate of hydraulic conductivity for the interval.

The final test in the sequence, Pw03, could not be simulated at a hydraulic conductivity of 6.0E-10 ms^{-1}. The effects of overpressure during the history period followed by swabbing the interval would cause pressure interference. The swabbing periods may have freed the filter cake on the borehole wall which might have resulted in clogging the apertures of the test tool resulting in a slower pressure recovery during the shut-in monitoring.

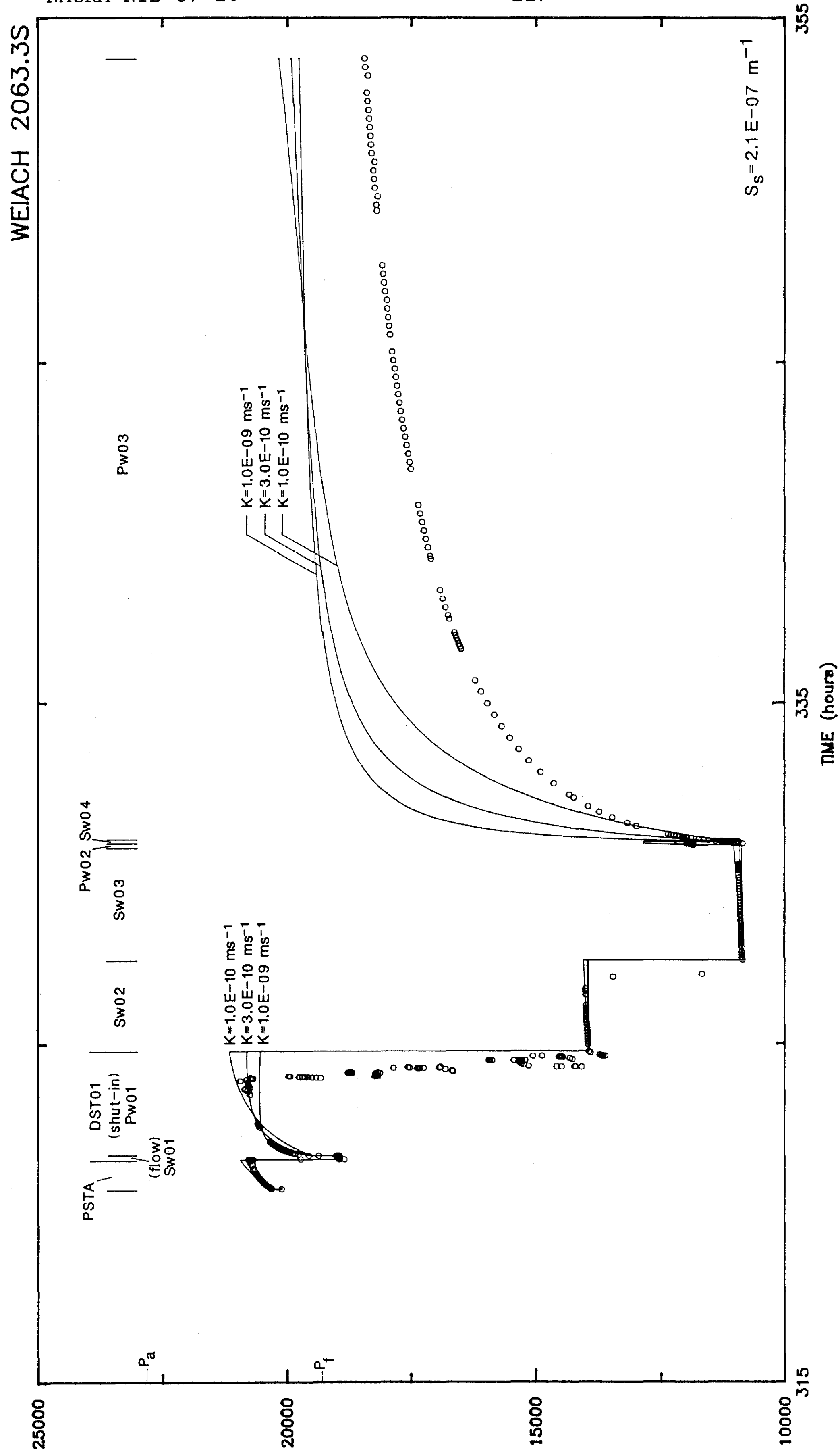


Figure 1 Measured (o) and Simulated Pressure Responses for the Testing Sequence

Test 2077.4D (2072.86 m to 2082.00 m) - Crystalline

Test 2077.4D was a double packer test of the interval 2072.86 m to 2082.00 m in the Weiach borehole. The testing sequence consisted of a pulse injection test (Pi01), a slug withdrawal (Sw01), and a pulse withdrawal (Pw01). At the end of the compliance period, the pressure was increased to 677 kPa above the compliance pressure during Pi01. The measured pressure during Pi01 dropped to annulus pressure in 11 minutes. The pressure then increased by approximately 30 kPa during swabbing, with the shut-in valve closed for the drill-stem test. The drill-stem test run after Pi01 was not included in the simulation due to the lack of measured data. Sw01 had no measurable flow at about 200 m drawdown and the pressure recovery was 1 kPa. The initial shut-in squeeze for Pw01 was about 165 kPa. Pw01 recovered to 99 percent of the assumed formation pressure before dropping to annulus pressure. The upper packer failed during the drill-stem test attempted following Pw01. Thermal effects are neglibible in formations of hydraulic conductivity greater than 1.0E-10 ms^{-1}, therefore, thermal effects were not included in the simulations.

The testing sequence was simulated using GTFM with the interval history incorporated in the simulation. An assumed formation pressure of 20520 kPa, determined by Horner analysis of Pw01 was used in the simulation. Figure 1 shows the measured and simulated pressure responses over the range of hydraulic conductivities 1.0E-10, 3.0E-10, and 1.0E-09 ms^{-1} for a specific storage of 2.1E-07 m^{-1}. The best fit of the measured data was a hydraulic conductivity of 3.0E-10 ms^{-1} at a specific storage of 2.1E-07 m^{-1}. Varying the specific storage over two orders of magnitude caused a change of less than half an order of magnitude in the best fit hydraulic conductivity.

The diagnostic Horner analysis of test Pw01 indicated enhanced recovery in the early time of the shut-in and reduced response during the end of the shut-in. This indicates that the packer could be leaking causing the early and late-time measured responses to be influenced by annulus pressure. The formation pressure determined by

Horner analysis was taken from data during the middle of test Pw01 but could not be reported with confidence because the pressure recovery could have been influenced by the ruptured upper packer element. For the same reason, a calibration of the simulated pressure curves to Pw01 shut-in was not attempted. Due to the possible packer leakage, the hydraulic conductivity of 3.0E-10 ms^{-1} should be considered a maximum value for the test interval.

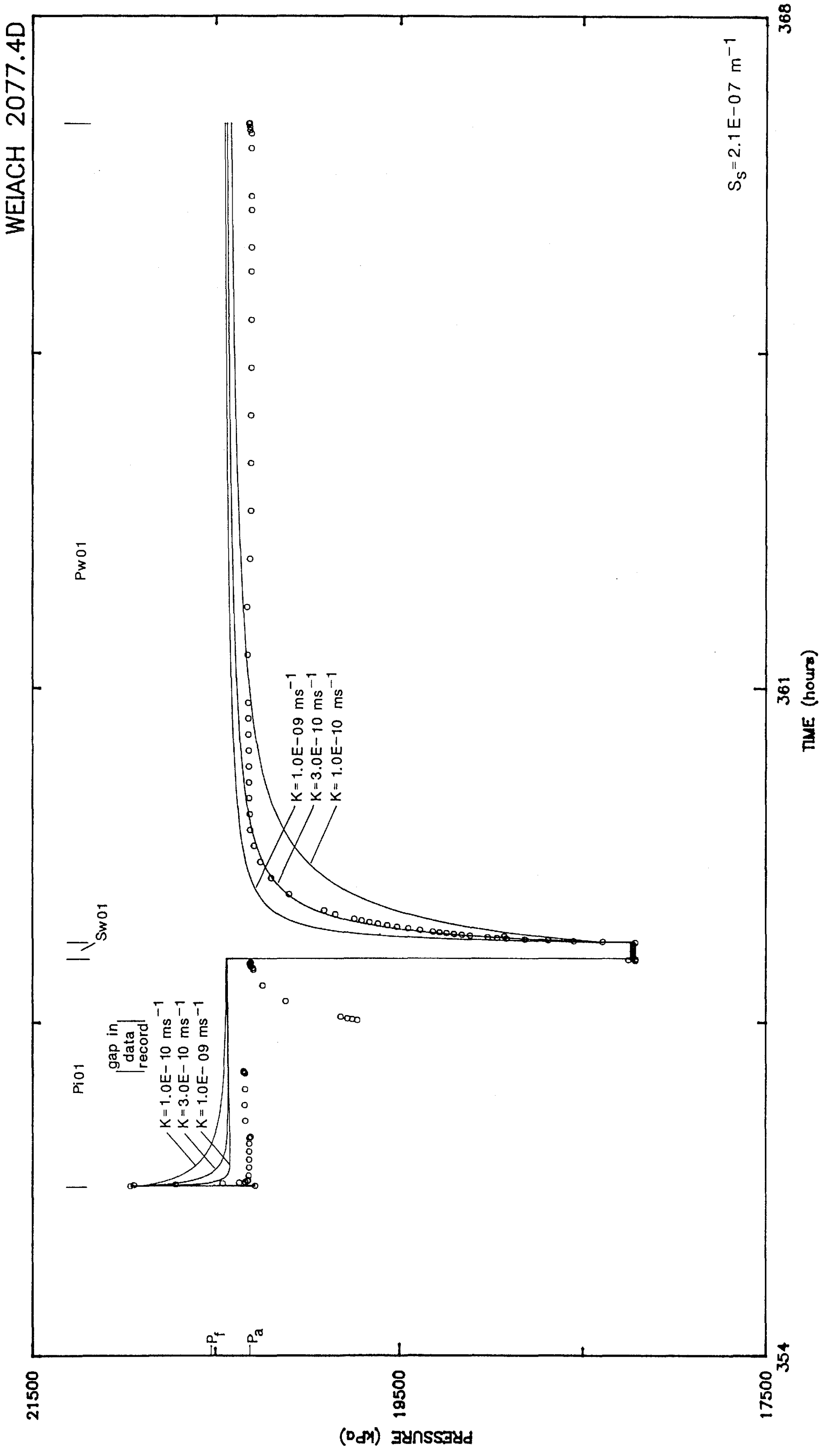


Figure 1 Measured (o) and Simulated Pressure Responses for the Testing Sequence

Test 2218.1D (2211.60 m to 2224.63 m) - Crystalline

Test 2218.1D was a double packer test of the crystalline formation in the Weiach borehole from 2211.60 m to 2224.63 m. The testing sequence was performed over a 17 day period from 11 April, 1984 to 28 April, 1984. A pulse injection test (Pi01), three pulse withdrawal tests (Pw01, Pw02, and Pw03), and three slug withdrawal tests (Sw01, Sw02, and Sw03) were completed in the testing sequence.

A compliance period was not performed after packer inflation. Because of this, the first test in the sequence (Pi01) is a pulse injection test resulting from the initial shut-in following packer inflation. The pressure was about 21071 kPa at the start of test Pi01. The measured pressure dropped to approximately 17662 kPa before recovering to about 18729 kPa. The tubing was swabbed to about 550 m with the shut-in valve closed. A slug withdrawal test (Sw01) resulted when the shut-in valve was opened. The measured pressure was about 16110 kPa at the start of test Sw01 and recovered to 16139 kPa over 1 hour. The shut-in valve was closed and test Pw01 had a shut-in squeeze of about 75 kPa. The measured pressure recovered to about 65 percent of the assumed formation pressure over 14.8 hours. The tubing was swabbed from 750 m with the shut-in valve closed in preparation for test Pw02. Test Pw02 had an initial pressure of about 15528 kPa and recovered to 67 percent of the assumed formation pressure over 86 minutes. Test Pw03 had an initial pressure of about 15648 kPa and recovered to about 65 percent of formation pressure over 93 minutes. 450 L of water were added to the tubing string prior to slug withdrawal test Sw02 causing the initial pressure for test Sw01 to about 1430 kPa higher than the initial pressure of test Pw03. Test Sw02 had an initial pressure of about 17075 kPa and the measured pressure increased by about 293 kPa over 21 hours. The average flow rate over the first hour was about 0.15 L min^{-1} and the average flow rate after 3 hours was about 0.08 L min^{-1}. A 550 m swab was pulled with the shut-in valve open for test Sw03. The flow rate during the events after test Sw03 varied from about 0.06 L min^{-1} to 0.04 L min^{-1}. The initial pressure for test Sw03 was about 16408 kPa and recovered to 17489 kPa over

77 hours. The flow rate during Sw03 started at about 0.09 L min^{-1} and decreased to about 0.06 L min^{-1}. Several bailer runs and two swabbing events were performed with the shut-in valve open following test Sw03. The measured pressure response at P1 shows some slight communication (several kPa pressure disturbance) with the P2 zone during the swabbing periods throughout the testing sequence. However, the pressure record for the P1 and P2 zones, which showed a differential of over 3000 kPa during most of the pulse tests during the testing sequence, did not indicate significant communication between these zones. The observed pressure response of transducer P1 to a pressure of 20515 kPa during the testing period most likely results from the recovery of the P1 zone to formation pressure from a low pressure disturbance and not P1-P2 communication. Due to the small temperature change during the testing sequence (less than 0.2°C), thermal effects were not included in the simulation.

The testing sequence was simulated with GTFM incorporating the pre-test history. The simulations were run through the third slug withdrawal. An assumed formation pressure of 21883 kPa was derived by interpolating the Long Term Monitoring formation pressures for Zones 6 and 7 in the crystalline rock to the center of this test interval and correcting the pressure to the P2 transducer depth. Figure 1 shows the measured and simulated pressure responses for the range of hydraulic conductivity 1.0E-11, 3.0E-11, 1.0E-10 and 3.0E-10 ms^{-1} at a specific storage of 2.1E-06 m^{-1}. The best fit of the measured pressure responses during the pulse tests varied from a hydraulic conductivity of slightly less than 1.0E-10 ms^{-1} to slightly less than 3.0E-10 ms^{-1} at a specific storage of 2.1E-06 m^{-1}. The best fit during the slug withdrawal tests was consistent at about 2.0E-10 ms^{-1} at this same S_s. Because of relatively consistent range for hydraulic conductivity, the most reasonable fit of the measured data is for a hydraulic conductivity of 2.0E-10 ms^{-1} at a specific storage of 2.1E-06 m^{-1}. Varying the specific storage by one order of magnitude above and below the base case specific storage of 2.1E-07 m^{-1} affected the best-fit hydraulic conductivity by less than a half an order of magnitude.

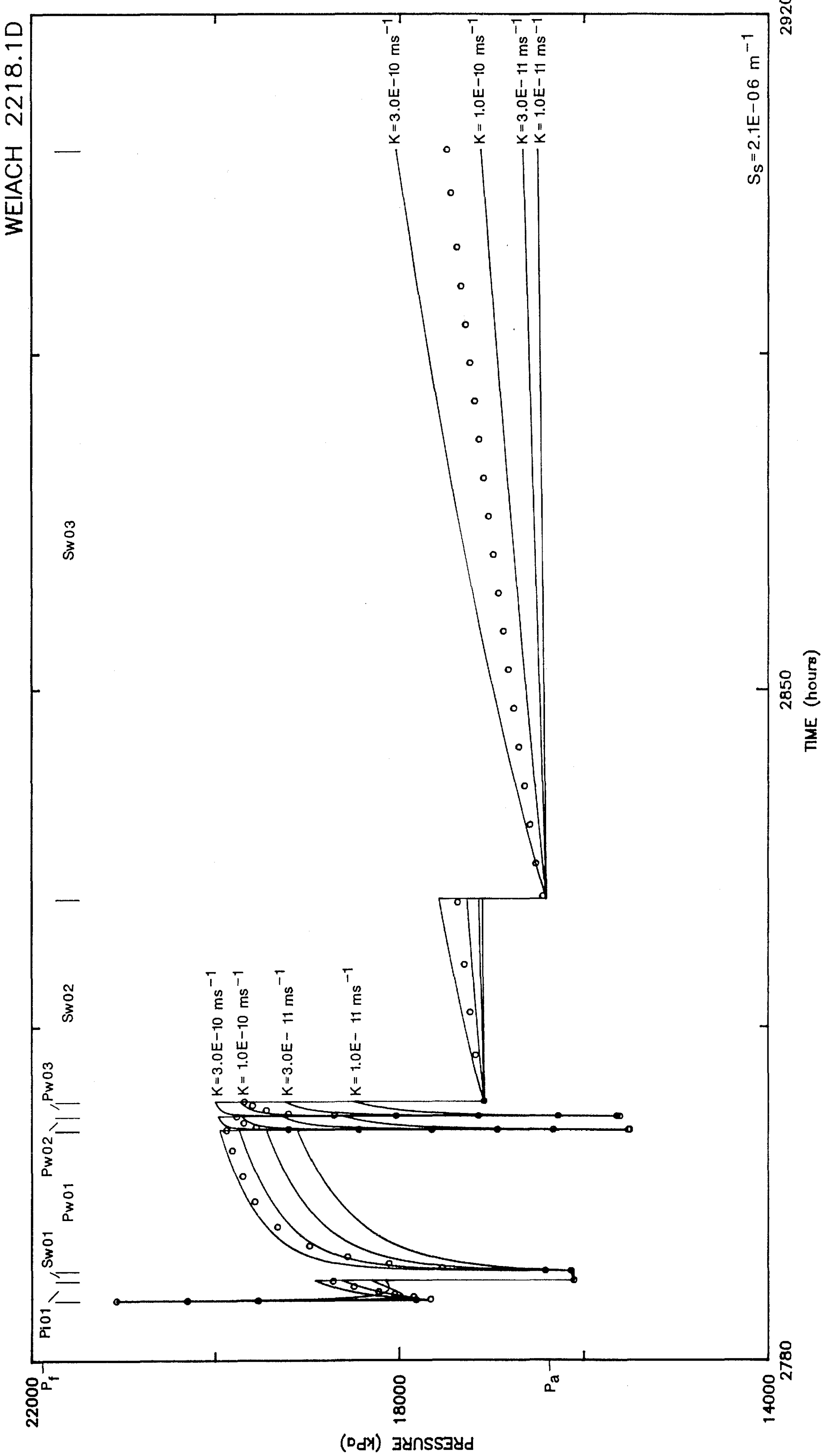


Figure 1 Measured (o) and Simulated Pressure Responses for the Testing Sequence

Test 2266.8D (2260.31 m to 2273.34 m) - Crystalline

Test 2266.8D was a single packer test of the crystalline formation in the Weiach borehole from 2260.31 m to 2273.34 m. Two pulse injection tests (Pi01 and Pi02) and a slug withdrawal test (Sw01) were completed in the testing sequence. The pressure was increased to about 23609 kPa with the shut-in valve open prior to test Pi01. The measured pressure dropped to approximately 19319 kPa before recovering to about 19964 kPa. The shut-in valve was opened and the interval was pressured up to about 23919 kPa prior to starting test Pi02. The measured pressure dropped to 20433 kPa before recovering to 20467 kPa. The tubing was swabbed from 600 m with the shut-in valve closed prior to test Sw01. Test Sw01 had an initial pressure of about 16720 kPa and recovered to a pressure of 17675 kPa over a period of about 90.6 hours. The initial flow rate during Sw01 was about 0.68 L min^{-1} and decreased to about 0.05 L min^{-1} during the test. During the pulse tests and early slug test recovery at P2, the P1 zone pressure was recovering at close to the same rate as the P2 zone pressure. The tubing was then swabbed from 550 m with the shut-in valve open. The measured pressure response at P1 began to decrease and the P2 pressure data showed an enhanced recovery indicating that the lower packer had failed or that the tested interval was in communication with the P1 zone through the formation. The P1 and P3 pressure data show the crystalline formation above and below the test interval recovering throughout the testing sequence from the underpressure in the borehole from the 630 m swab of the annulus during the pre-test history. Similarly, the P2 readings during the pulse injection tests dropped responding to the underpressure before beginning a recovery towards the formation pressure. The P1 pressure transducer indicated some communication across or around the lower packer at the beginning of the slug withdrawal test and possibly from the start of the test. The degree of communication increased through the first part of test Sw01 until the swab with the open shut-in valve. Due to the small temperature change during the pulse testing sequence (approximately 0.1°C), thermal effects were not included in the simulation.

The testing sequence was simulated with GTFM incorporating the pre-test history. The test sequence was simulated to the time at which the P1 pressure data dropped due to the swab with the shut-in valve open. Simulation of this sequence of test responses should provide a reasonable estimate of formation hydraulic properties. An assumed formation pressure of 22339 kPa was derived by interpolating the Long Term Monitoring formation pressures for Zones 6 and 7 in the crystalline rock to the center of this test interval and correcting the pressure to the P2 transducer depth. As with other tests in the crystalline, this assumes a hydrostatic gradient across the crystalline. Figure 1 shows the measured and simulated pressure responses for the range of hydraulic conductivity 3.0E-11, 1.0E-10 and 3.0E-10 ms^{-1} at a specific storage of 2.1E-07 m^{-1}. A hydraulic conductivity of 1.0E-10 ms^{-1} provided a reasonable fit for the range of specific storages used in this analysis. Therefore, using a reasonable rock compressibility of 2.2E-10 Pa^{-1} for the crystalline formation the best-fit of the measured data for test Sw01 is for a hydraulic conductivity of 1.0E-10 ms^{-1} at a base case specific storage of 2.1E-07 m^{-1}. Varying the specific storage by one order of magnitude above and below the base case specific storage of 2.1E-07 m^{-1} affected the best-fit hydraulic conductivity by less than a half an order of magnitude.

The simulated results of the pulse injection tests were about 1000 kPa to 2000 kPa higher than the measured pressure data. This is probably due to some communication between the P1 and P2 zones. The large pressure differential across the zones appears to have caused the measured pressure in the test interval to be reduced. The pressure in the P1 zone results from the underpressure transient. The P2 zone pressure disturbance due to history has been dissipated somewhat by the overpressure of the pulse injection event. Because of this, the best fit for this testing sequence was based on the results of the simulation of the slug withdrawal test and the best fit hydraulic conductivity of 1.0E-10 ms^{-1} should be considered a maximum value for the test interval.

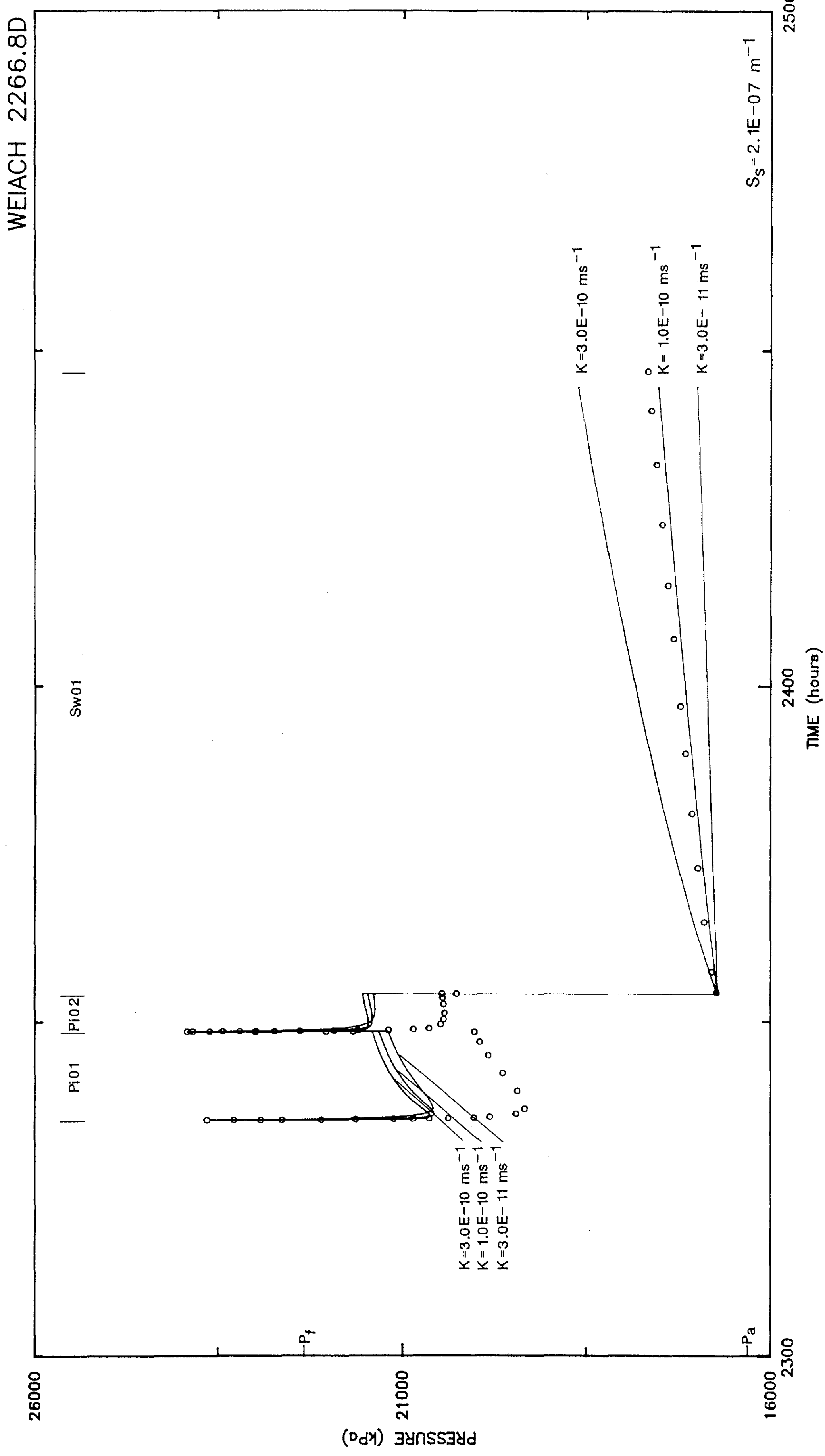


Figure 1 Measured (o) and Simulated Pressure Responses for the Testing Sequence

Test 2272.7S (2063.26 m to 2482.20 m) - Crystalline

Test 2272.7S was a single packer test of the crystalline formation in the Weiach borehole from 2063.26 m to 2482.20 m. A pulse injection (Pi01), a pulse withdrawal (Pw01), and a slug withdrawal (Sw01) were completed in the testing sequence. The pressure was increased to about 21552 kPa with the shut-in valve open prior to shutting in the interval for test Pi01. The measured pressure recovered to 91 percent of annulus pressure over 14.8 hours. A swab of about 150 m was pulled with the shut-in valve closed prior to test Pw01. At the start of test Pw01 the shut-in valve was open for about 2 minutes. This was included as a history period (HST) with an average pressure of 18961 kPa. The measured pressure during test Pw01 recovered to 59 percent of annulus pressure over 2.7 hours. Test Sw01 had an initial pressure of 18980 kPa and had a 38 kPa recovery over a period of 38 minutes. Due to the temperature change of less than 1°C during the testing sequence, thermal effects were not included in the simulation.

The testing sequence was simulated with GTFM incorporating the pre-test history. The interval length of 417.20 m corresponds to the uncased portion of the interval. About 1.74 m of the interval below the single packer was in cased hole. An assumed formation pressure of 20491 kPa was derived by interpolating the Long Term Monitoring formation pressures for Zones 6 and 7 in the crystalline rock to the center of this test interval and then correcting the pressure to the P2 transducer depth. Figure 1 shows the measured and simulated pressure responses for the range of hydraulic conductivity 3.0E-12, 1.0E-11, 3.0E-11 and 1.0E-10 ms^{-1} at a specific storage of 2.1E-06 m^{-1}.

A sensitivity to the pre-test history and formation pressure were performed to yield the best estimate of the hydraulic conductivity and specific storage of the test interval. The simulated responses were sensitive to changes in the fluid level. Pulling the tubing out of the hole within a few days of the testing sequence had up to a 200 kPa effect on the final simulated pressure during test Pi01 depending on the length of time that the tubing was out of the borehole without fluid replacement. As shown in Figure 1, the simulations using the best estimates of pre-test history and formation pressure indicate that either the formation is responding to less of an underpressure during the history and/or the formation pressure used in the simulation could be low. Simulations were run with either a shortened length of underpressure during the 462 m swab in the pre-test history or an increased formation pressure. The results of these simulations indicate that the best fit for hydraulic conductivity is 1.0E-11 ms^{-1} at a specific storage of 2.1E-06 m^{-1}. Varying the specific storage by one order of magnitude above and below the base case specific storage of 2.1E-07 m^{-1} affected the best-fit hydraulic conductivity by about half an order of magnitude.

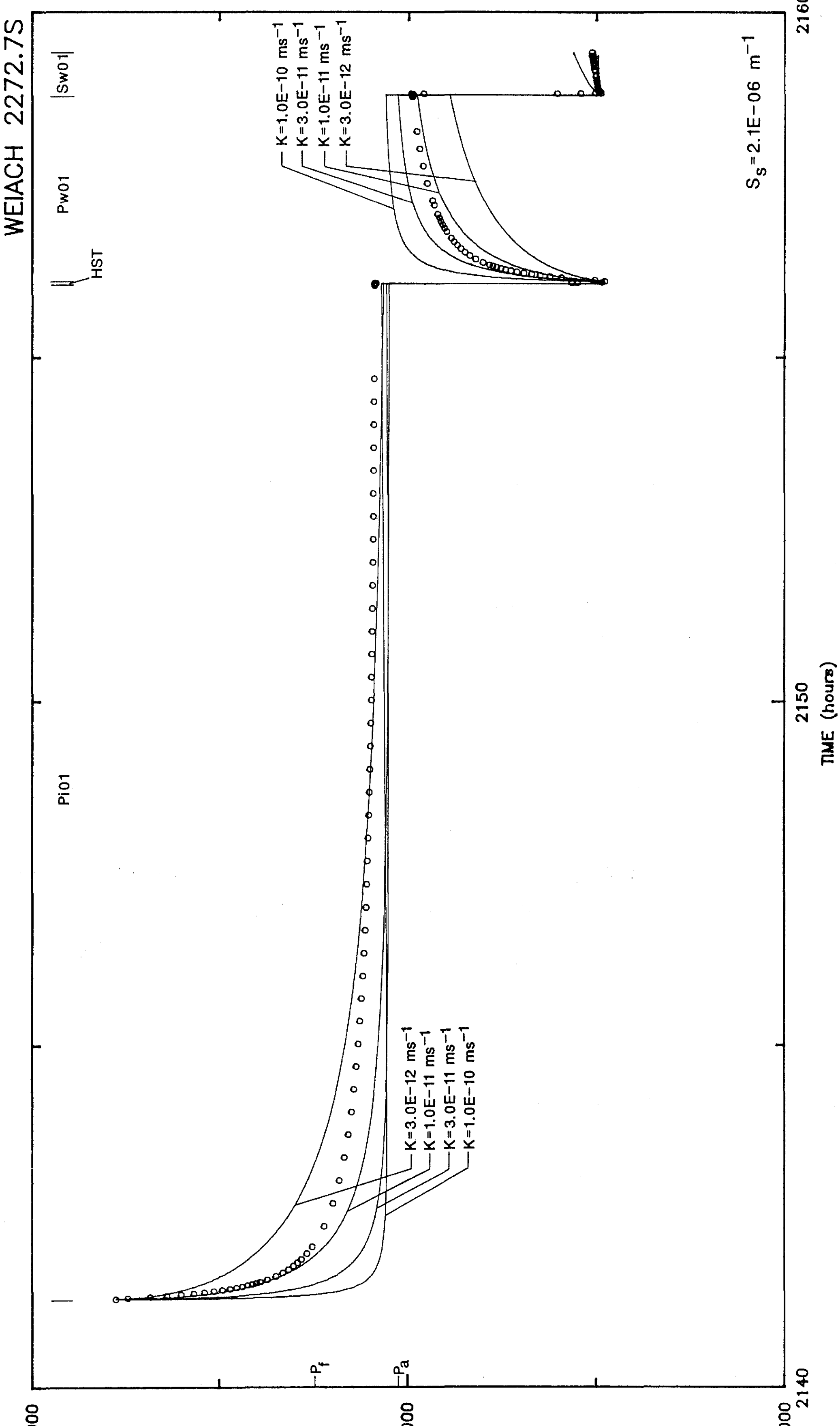


Figure 1 Measured (o) and Simulated Pressure Responses for the Testing Sequence

Test 2282.0S (2081.80 m to 2482.20 m) - Crystalline

Test 2282.0S was a single packer test of the crystalline formation in the Weiach borehole from 2081.80 m to 2482.20 m. A pulse injection (Pi01), a pulse withdrawal (Pw01), and a slug withdrawal (Sw01) were completed in the testing sequence. The pressure was increased to about 21880 kPa with the shut-in valve open prior to shutting in the interval for test Pi01. The measured pressure recovered to within 5 kPa of annulus pressure over 15.2 hours. A swab of about 150 m was pulled with the shut-in valve closed prior to test Pw01. The measured pressure during test Pw01 recovered to 92 percent of annulus pressure over 2 hours. Test Sw01 had an initial pressure of 19058 kPa and had a 46 kPa recovery over a period of 55 minutes. Due to the temperature change of less than 0.5°C during the testing sequence, thermal effects were not included in the simulation.

The testing sequence was simulated with GTFM incorporating the pre-test history. An assumed formation pressure of 20667 kPa was derived by interpolating the Long Term Monitoring formations pressures for Zones 6 and 7 in the crystalline rock to the center of this test interval and then correcting the pressure to the P2 transducer depth. Figure 1 shows the measured and simulated pressure responses for the range of hydraulic conductivity 3.0E-12, 1.0E-11, 3.0E-11 and 1.0E-10 ms^{-1} at a specific storage of 2.1E-06 m^{-1}.

A sensitivity to the pre-test history and formation pressure were performed to yield the best estimate of the hydraulic conductivity and specific storage of the test interval. The simulated responses were sensitive to changes in the fluid level. Pulling the tubing out of the hole within a few days of the testing sequence had up to a 200 kPa effect on the final simulated pressure of test Pi01 depending on the length of time that the tubing was out of the borehole without fluid replacement. The results of these simulations indicate that the best fit for hydraulic conductivity is 1.0E-11 ms^{-1} at a specific storage of 2.1E-06 m^{-1}. Varying the specific storage by one order of magnitude above and below the base case specific storage of

2.1E-07 m^{-1} affected the best-fit hydraulic conductivity by about half an order of magnitude.

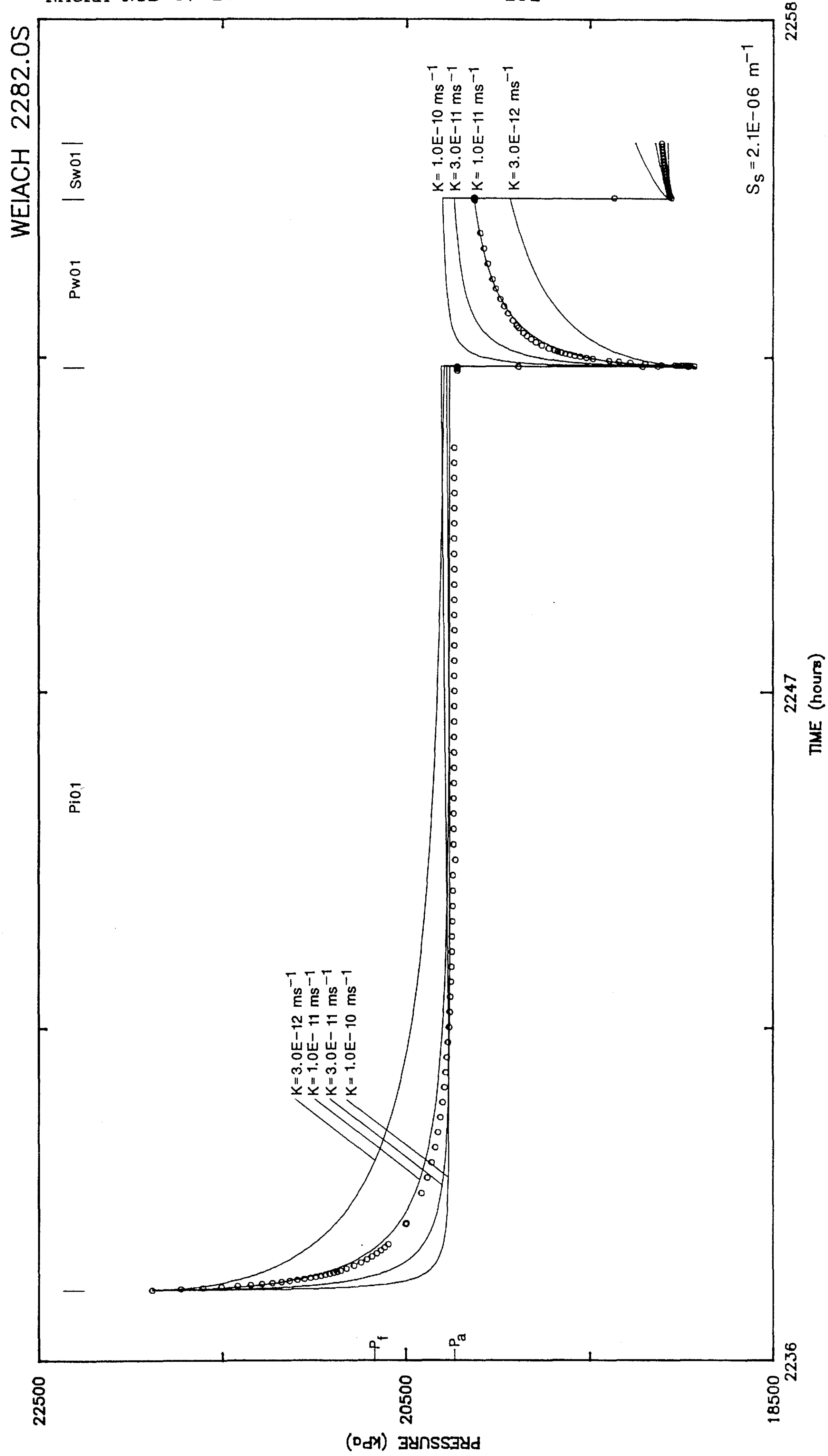


Figure 1 Measured (o) and Simulated Pressure Responses for the Testing Sequence

Test 2306.8S (2131.34 m to 2482.20 m) - Crystalline

Test 2306.8S was a single packer test of the crystalline formation in the Weiach borehole from 2131.34 m to 2482.20 m. A pulse injection (Pi01), a pulse withdrawal (Pw01), and a slug withdrawal (Sw01) were completed in the testing sequence. The pressure was increased to about 22130 kPa with the shut-in valve open prior to test Pi01. The measured pressure recovered to 82 percent of annulus pressure over 2.9 hours. A swab of about 180 m was pulled with the shut-in valve closed prior to shutting in the interval for test Pw01. At the start of test Pw01 the shut-in valve was open for about 4 minutes. This was included as a history period (HST) with an average pressure of 19194 kPa. The measured pressure during test Pw01 recovered to 93 percent of the assumed formation pressure over 15 hours. Test Sw01 had an initial pressure of 19227 kPa and had a 38 kPa recovery over a period of 33 minutes. Due to the temperature change of less than 0.5°C during the testing sequence, thermal effects were not included in the simulation.

The testing sequence was simulated with GTFM incorporating the pre-test history. An assumed formation pressure of 21133 kPa was derived by interpolating the Long Term Monitoring formations pressures for Zones 6 and 7 in the crystalline rock to the center of this test interval and then correcting the pressure to the P2 transducer depth. Figure 1 shows the measured and simulated simulated pressure responses for the range of hydraulic conductivity 3.0E-12, 1.0E-11, 3.0E-11 and 1.0E-10 ms^{-1} at a specific storage of 2.1E-06 m^{-1}.

A sensitivity to the pre-test history and formation pressure were performed to yield the best estimate of the hydraulic conductivity and specific storage of the test interval. The results of these simulations indicate that the best fit for hydraulic conductivity is 1.0E-11 ms^{-1} at a specific storage of 2.1E-06 m^{-1}. Varying the specific storage by one order of magnitude above and below the base case specific storage of 2.1E-07 m^{-1} affected the best-fit hydraulic conductivity by about half an order of magnitude.

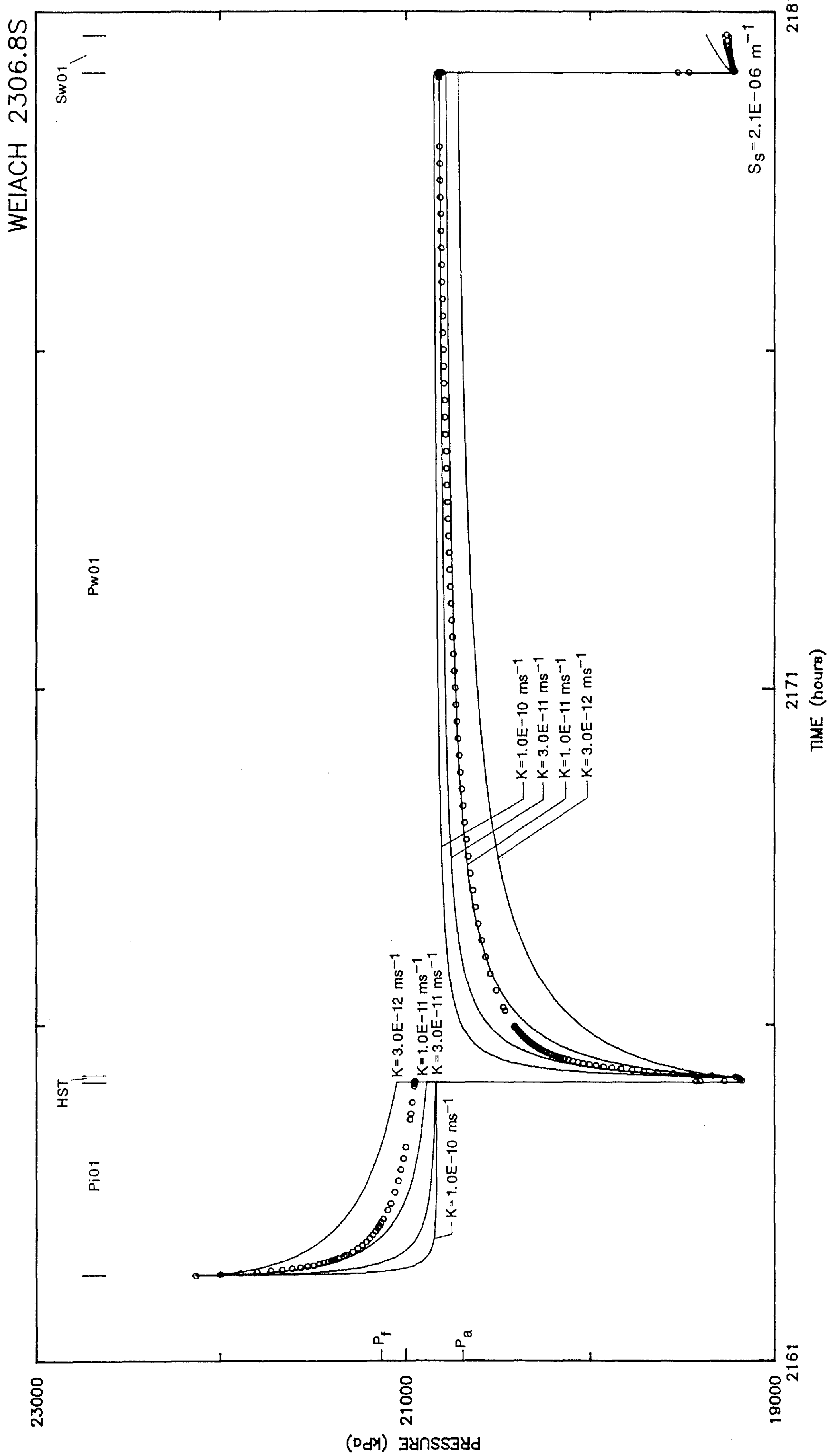


Figure 1 Measured (o) and Simulated Pressure Responses for the Testing Sequence

Test 2350.5S (2218.84 m to 2482.20 m) - Crystalline

Test 2350.5S was a single packer test of the crystalline formation in the Weiach borehole from 2218.84 m to 2482.20 m. A pulse injection (Pi01), a pulse withdrawal (Pw01), and a slug withdrawal (Sw01) were completed in the testing sequence. The pressure was increased to about 23151 kPa with the shut-in valve open prior to shutting in the interval for test Pi01. The measured pressure recovered to 92 percent of annulus pressure over 16.5 hours. A swab of about 150 m was pulled with the shut-in valve closed prior to test Pw01. At the start of test Pw01 the shut-in valve was open for about 2 minutes. This was included as a history period (HST) with an average pressure of 20440 kPa. The measured pressure during test Pw01 recovered to 95 percent of annulus pressure over 2 hours. Test Sw01 had an initial pressure of 20454 kPa. The average flow rate for test Sw01 was about 0.22 L min^{-1} and had a 31 kPa recovery over a period of 50 minutes. Due to the temperature change of less than 0.3°C during the testing sequence, thermal effects were not included in the simulation.

The testing sequence was simulated with GTFM incorporating the pre-test history. An assumed formation pressure of 21946 kPa was derived by interpolating the Long Term Monitoring formation pressures for Zones 6 and 7 in the crystalline rock to the center of this test interval and then correcting the pressure to the P2 transducer depth. Figure 1 shows the measured and simulated pressure responses for the range of hydraulic conductivity 3.0E-12, 1.0E-11, 3.0E-11 and 1.0E-10 ms^{-1} at a specific storage of 2.1E-06 m^{-1}.

A sensitivity to the pre-test history and formation pressure were performed to yield the best estimate of the hydraulic conductivity and specific storage of the test interval. The simulated responses were sensitive to changes in the fluid level. Pulling the tubing out of the hole within a few days of the testing sequence had up to a 200 kPa effect on the final simulated pressure during test Pi01 depending on the length of time that the tubing was out of the borehole without fluid replacement. As shown in Figure 1, the simulations using the best estimates of pre-test history and formation pressure indicate that either the formation is responding to less of an underpressure during the history and/or the formation pressure used in the simulation could be low. Simulations were run with either a shortened length of underpressure during the 462 m swab in the pre-test history or an increased formation pressure. The results of these simulations indicate that the best fit for hydraulic conductivity is 1.0E-11 ms^{-1} at a specific storage of 2.1E-06 m^{-1}. Varying the specific storage by one order of magnitude above and below the base case specific storage of 2.1E-07 m^{-1} affected the best-fit hydraulic conductivity by about half an order of magnitude.

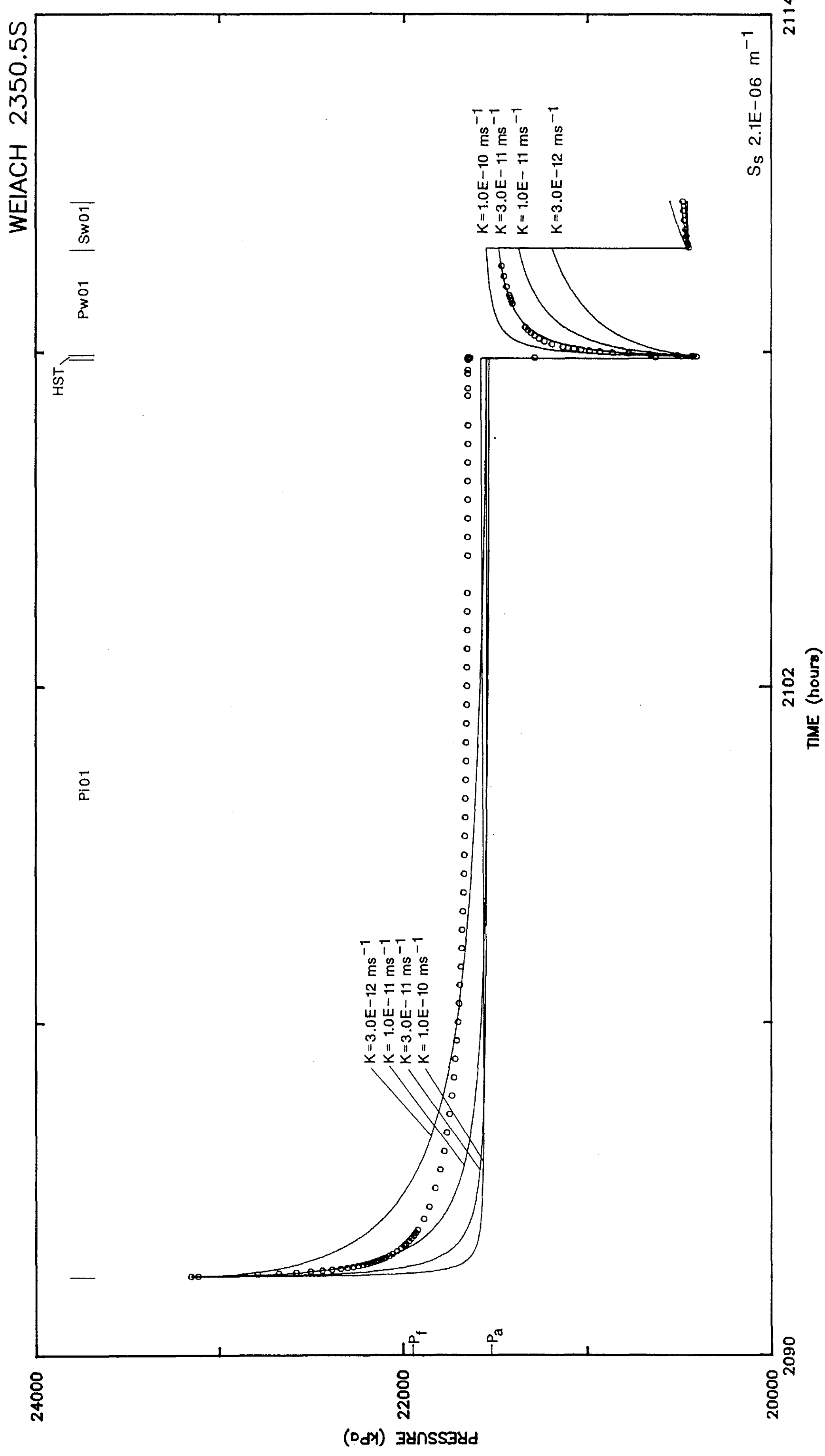


Figure 1 Measured (o) and Simulated Pressure Responses for the Testing Sequence

Test 2410.7H (2398.23 m to 2423.26 m) - Crystalline

H-log hydraulic testing was completed in the interval from 2398.23 m to 2423.26 m of the Weiach borehole from 06 March, 1984 to 07 March, 1984. The formation pressure was based on the long-term monitoring pressure and was assumed to be 23833 kPa. P_f was determined based on an integrated density of 954.7 kgm^{-3} and a hydrostatic gradient across the crystalline formation.

The testing sequence consisted of a pulse injection test followed by a slug withdrawal test. The pulse injection test (Pi01) consisted of a pulse of 1538 kPa above annulus pressure. Recovery was monitored over 12 hours to a pressure slightly below annulus (23156 kPa). This was followed by the slug withdrawal test (Sw01) which consisted of an underpressure of 2027 kPa below annulus pressure, with a flow period of about 25 minutes at a rate of 0.06 L min^{-1}. The pressure recovery during test Sw01 was about 5 kPa over about 25 minutes. During Sw01 and Pi01, hydraulic communication was evident between P1 and P2. The P1 pressure increased by 93 kPa in response to the overpressuring of P2 during Pi01. The P1 pressure also dropped by about 1600 kPa during Sw01 in response to the underpressuring of the P2 zone. Thus, the hydraulic conductivity values reported for this test are maximum values for the test interval. The test was terminated early on 07 March, 1984 due to the hydraulic communication problem.

Simulation of the history and testing sequence was completed using GTFM to include history effects on the test zone. Temperature effects were not included in the simulations because the temperature measured at T2 (the operational P2 temperature) was stable during testing. Simulations were completed for hydraulic conductivities of 1.0E-12, 3.0E-12, 1.0E-11, and 3.0E-11 ms^{-1}, and for specific storage values of 1.9E-05, 1.9E-06, and 2.1E-07 m^{-1} at the assumed formation pressure. The measured pressure responses and the simulation results are shown in Figure 1 for a best-fit S_s of 3.0E-06 m^{-1}. The best-fit hydraulic conductivity for the test interval is about 9.0E-12 ms^{-1}. The effect of varying S_s over about two orders of magnitude results in close to an order of magnitude uncertainty in the final estimate of K for the test zone. The K is a maximum for the test interval due to the hydraulic communication problems which would result in a larger section of the formation responding to the pressure events. This propagates a more rapid pressure recovery in the test zone which is simulated at a K which is an over-estimate for that zone.

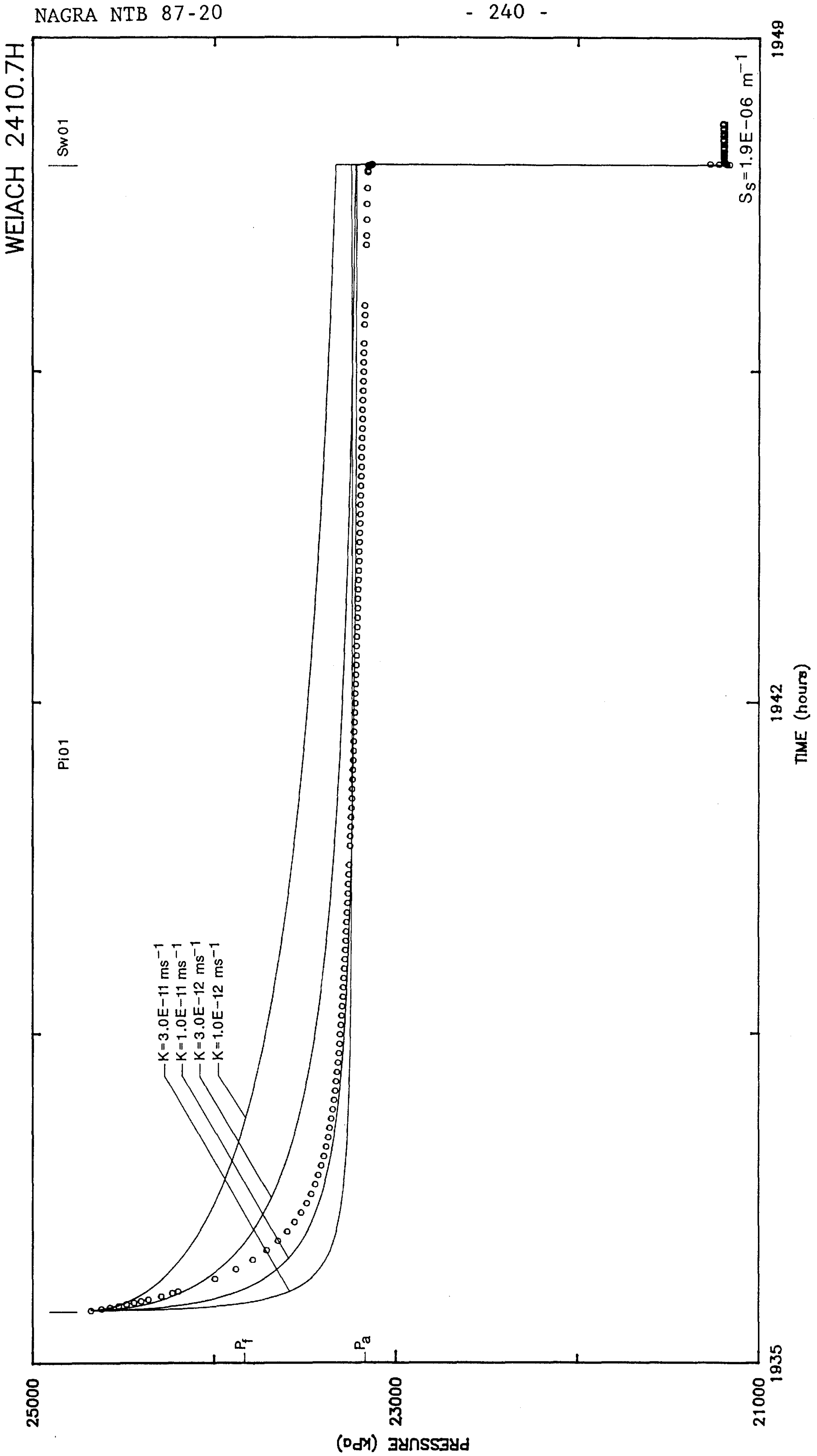


Figure 1 Measured (o) and Simulated Pressure Responses for the Testing Sequence

Test 2435.8H (2423.26 m to 2448.30 m) - Crystalline

H-log hydraulic testing was completed in the interval from 2423.26 m to 2448.30 m of the Weiach borehole on 06 March, 1984. The testing sequence consisted of a pulse injection test and a slug withdrawal test. The pulse injection test (Pi01) consisted of a pulse of 1434 kPa above the annulus pressure of 23420 kPa. The pressure decayed a total of 1391 kPa or 97 percent of total recovery after 5.75 hours. The slug withdrawal test (Sw01) consisted of a 1937 kPa underpressure below annulus pressure. GLAG noted that hydraulic communication developed between the test interval and the zone below the bottom packer shortly after the start of the slug withdrawal test. This occurrence caused GLAG to terminate the test. The observed pressure data also indicates hydraulic communication may be occurring during the latter portion of Pi01. Because of this possible communication between P1 and P2, the interpreted K is likely a maximum value.

Simulation of the history and testing sequence was completed using GTFM to include history effects. Temperature effects were not included in the simulations because there was not a significant change in the temperature during the testing sequence. Simulations were completed for hydraulic conductivities of 3.0E-12, 1.0E-11, 3.0E-11 and 1.0E-10 ms^{-1} and for specific storage (S_s) values of 1.9E-06, 2.1E-07, and 4.1E-08 m^{-1} at the assumed formation pressure.

The formation pressure was assumed at 24066 kPa based on the long-term monitoring pressure of 23269 kPa at 2350.4 m and a hydrostatic gradient across the crystalline.

The measured pressure responses and the best-fit set of simulations of the measured data are shown in Figure 1 for the test sequence. The specific storage of 2.1E-07 m^{-1} is taken from the sensitivity study results and appears to be most representative of the test interval. The hydraulic conductivity of the rock at this depth in the Weiach borehole is about 2.5E-11 ms^{-1}. The effect of varying S_s over about two orders of magnitude results in close to half an order of magnitude uncertainty in the final estimate of K for the test zone.

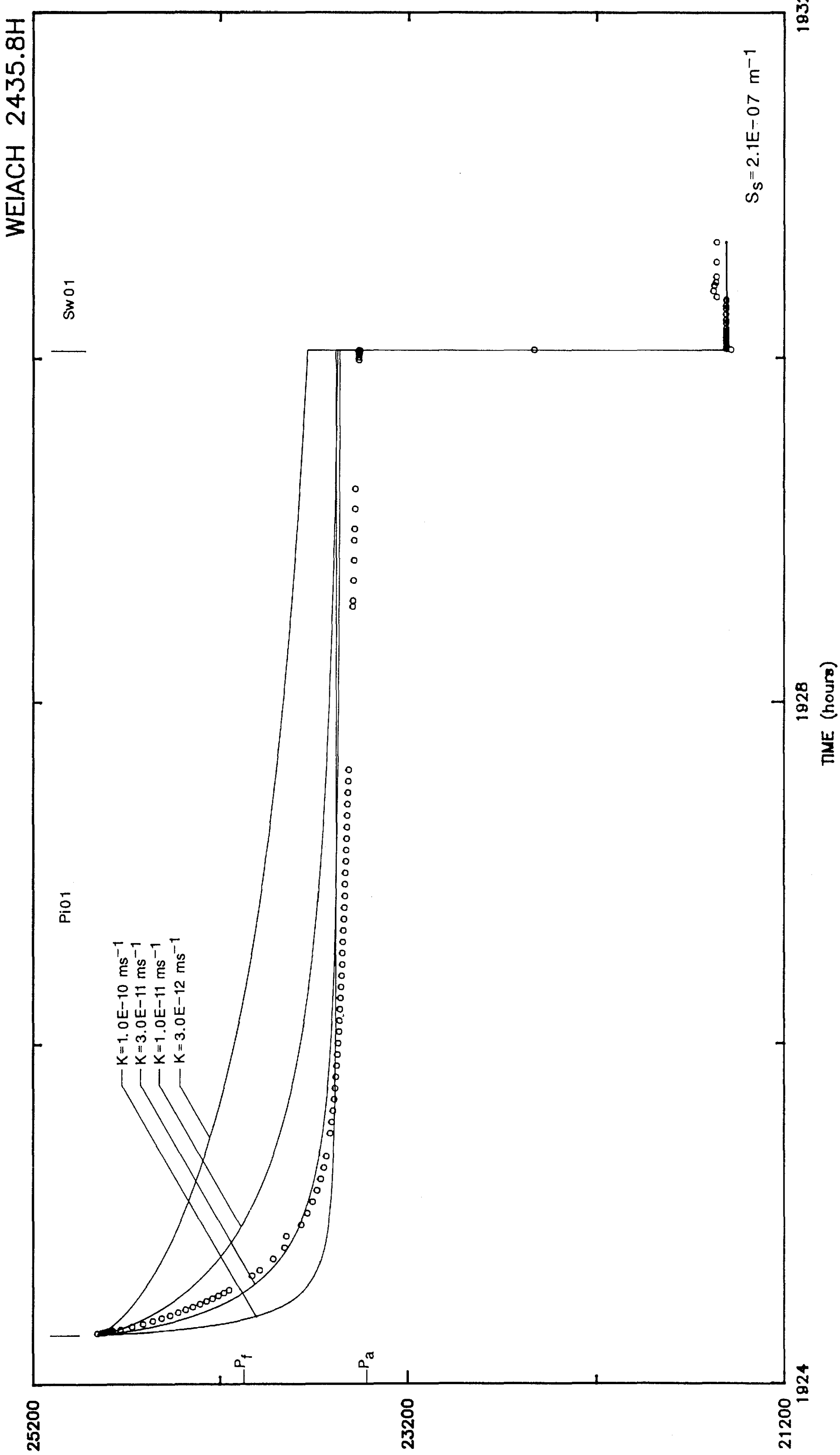


Figure 1 Measured (o) and Simulated Pressure Responses for the Testing Sequence

Test 2458.2H (2445.71 m to 2470.74 m) - Crystalline

H-log hydraulic testing was completed in the interval from 2445.71 m to 2470.74 m of the Weiach borehole on 10 February, 1983. The formation pressure was calibrated at 23930 kPa based on the extrapolated recovery pressure of test Pi01. This H-log testing sequence consisted of a single pulse injection test followed by a slug withdrawal test. The pulse injection test (Pi01) consisted of a pulse of 1367 kPa over P2 pressure. Recovery was monitored for approximately four hours. Pressure decayed 80 percent of the initial pulse in the four hours. Then, the slug withdrawal test (Sw01) underpressured the test interval by 2477 kPa. Recovery on Sw01 was only 31 kPa during the 84 minute flow period. The testing was terminated at 18:00 on 10 February, 1984 because all three transducers had failed by that time. (P1 pressure transducer failed early in the test; P2 and P3 failed after 7 hours of testing).

Simulation of the history and testing sequence was completed using GTFM. Temperature effects were not included in the simulations because there was not a significant change in the test interval temperature during the testing period. Simulations were completed for hydraulic conductivities of 1.0E-11, 3.0E-11, and 1.0E-10 ms^{-1} and for specific storage (S_s) values of 1.9E-06, 2.1E-07, and 4.1E-08 m^{-1} at the assumed formation pressure. Some of the simulation results for the most reasonable formation specific storage and the measured pressure responses are shown in Figure 1. The best-fit simulation corresponds to a K of about 3.0E-11 ms^{-1} at the specific storage of 2.1E-07 m^{-1}.

The effect of varying specific storage over about two orders of magnitude (1.9E-06 to 4.1E-08 m^{-1}) should result in close to half an order of magnitude uncertainty in the final estimate of K for the test zone.

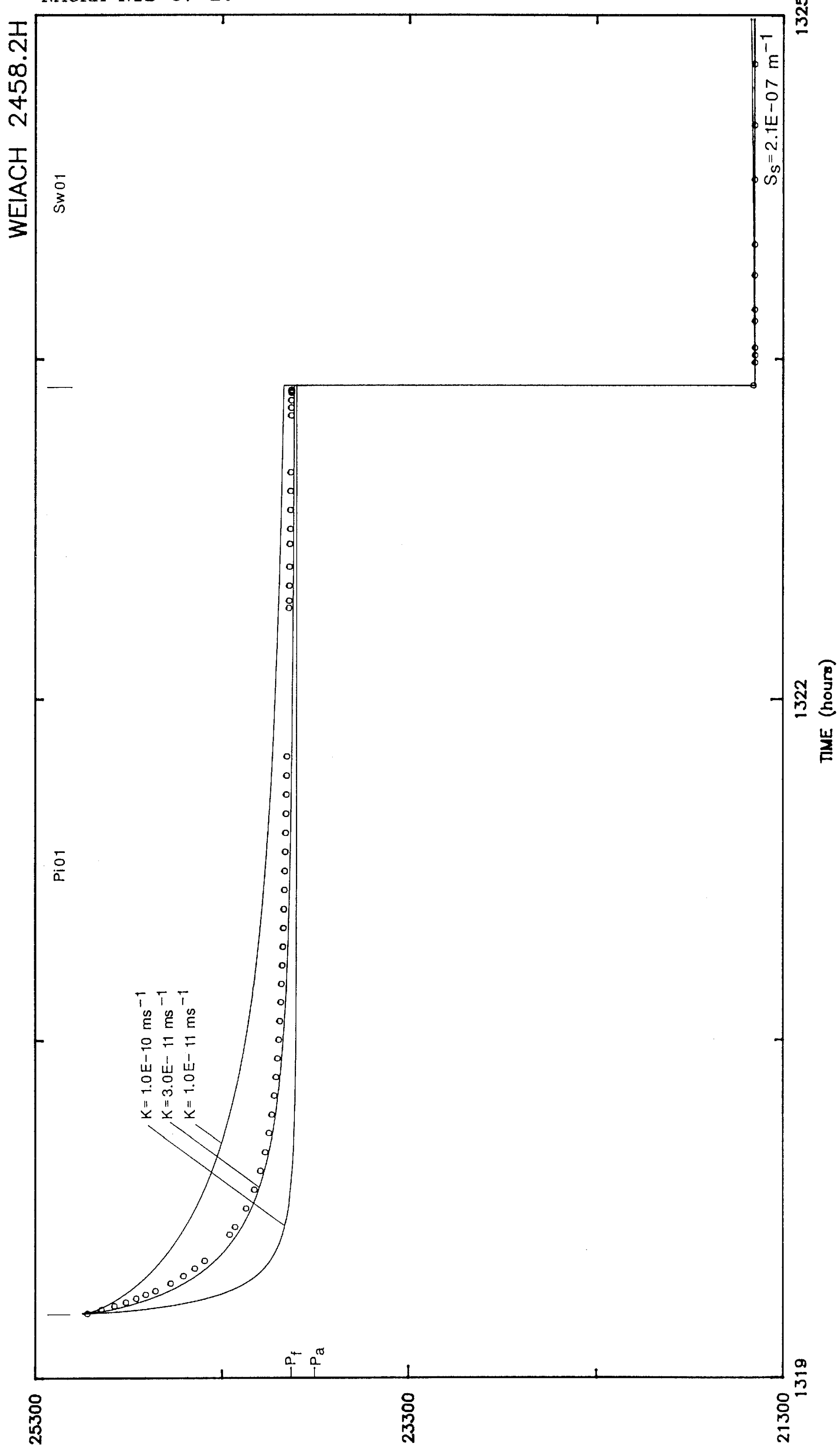


Figure 1 Measured (o) and Simulated Pressure Responses for the Testing Sequence

Test 2468.6SI (2454.95 m to 2482.20 m) - Crystalline

Single packer hydraulic testing was completed in the interval from 2454.95 m to 2482.20 m of the Weiach borehole from 15 November, 1983 to 04 December, 1983. The formation pressure was estimated at 24273 kPa based on observed pressure recovery data for the borehole during the annulus shut-in period from December 1983 through February 1984. A calibrated formation pressure was not determined due to hydraulic communication of the test zone with the annulus.

The testing sequence consisted of two pulse injection tests (Pi01 and Pi02) and a slug withdrawal test (Sw01). During the testing, only the test interval pressure and temperature were recorded without malfunction. Thus, no trustworthy annulus pressure measurement (P3) was available. The first pulse injection test (Pi01) consisted of a pulse of 564 kPa above assumed annulus pressure (23900 kPa). Recovery was monitored for over 13 hours. With the shut-in tool closed, the tubing string was swabbed down about 100 m in preparation for a slug withdrawal test. The slug withdrawal test (Sw01) consisted of a 991 kPa underpressure from assumed annulus pressure and a 23 kPa recovery during a flow period of 10 hours. The tubing was filled with the shut-in valve open to bring the interval pressure back to pre-slug withdrawal pressure. Completing the sequence was another pulse injection (Pi02) test where the pulse was 864 kPa above assumed annulus pressure. The recovery was monitored for 17 days. Midway through the recovery, the annulus was capped and the P2 pressure began to rise. The cap was adjusted to stop leakage at the end of November 1983. The testing was terminated on 04 December, 1983 because of equipment overheating and transducer malfunction, as reported by Gartner Lee AG.

Temperature effects introduce uncertainty in this test due to both the range and absolute value of the test interval temperature. The temperature increases by nearly 5.0°C over the test period. Also, the recorded temperature (109-113.8°C) is above the temperature specifications (105°C) of the transducer. Transducer malfunction was reported by GLAG as cause to abandon testing in this interval.

The P2 pressure reading during the last few days of the test period has a marked increase over the recovery pressures for tests Pi01, Sw01, and Pi02. This pressure increase may be partially explained by the capping of the annulus of the borehole which was in hydraulic communication with the test zone. The reason for the pressure increase above assumed formation pressure is uncertain. The slight pressure decrease after the annulus was capped was due to the adjustment in the cap to stop leakage, whereby some flow was released.

Simulation of the history and testing sequence was completed using GTFM to provide an estimate of K. Keeping in mind that communication between the test zone and annulus may be impacting test zone pressure recovery, all interpreted K's are treated as maximum values. Also, as the result of communication, the reference pressures to which the test zone is recovering may be that of the full annulus (Pa). Temperature effects were included in the simulations because the temperature change of ± 4.8°C is significant at low permeability. Simulations were completed for the hydraulic conductivities of 3.0E-12, 1.0E-11, and 3.0E-11 ms^{-1} and for a specific storage of 4.1E-08, 2.1E-07, and 1.9E-06 m^{-1} at the assumed formation pressure discussed above. The best-fit K is difficult to determine from these analyses. The measured and simulated pressure responses are shown in Figure 1 for the best-fit value of specific storage. From the fit of the pulse tests, the most reasonable hydraulic conductivity of the test zone is probably 3.0E-11 ms^{-1} for the specific storage of 4.1E-08 m^{-1}.

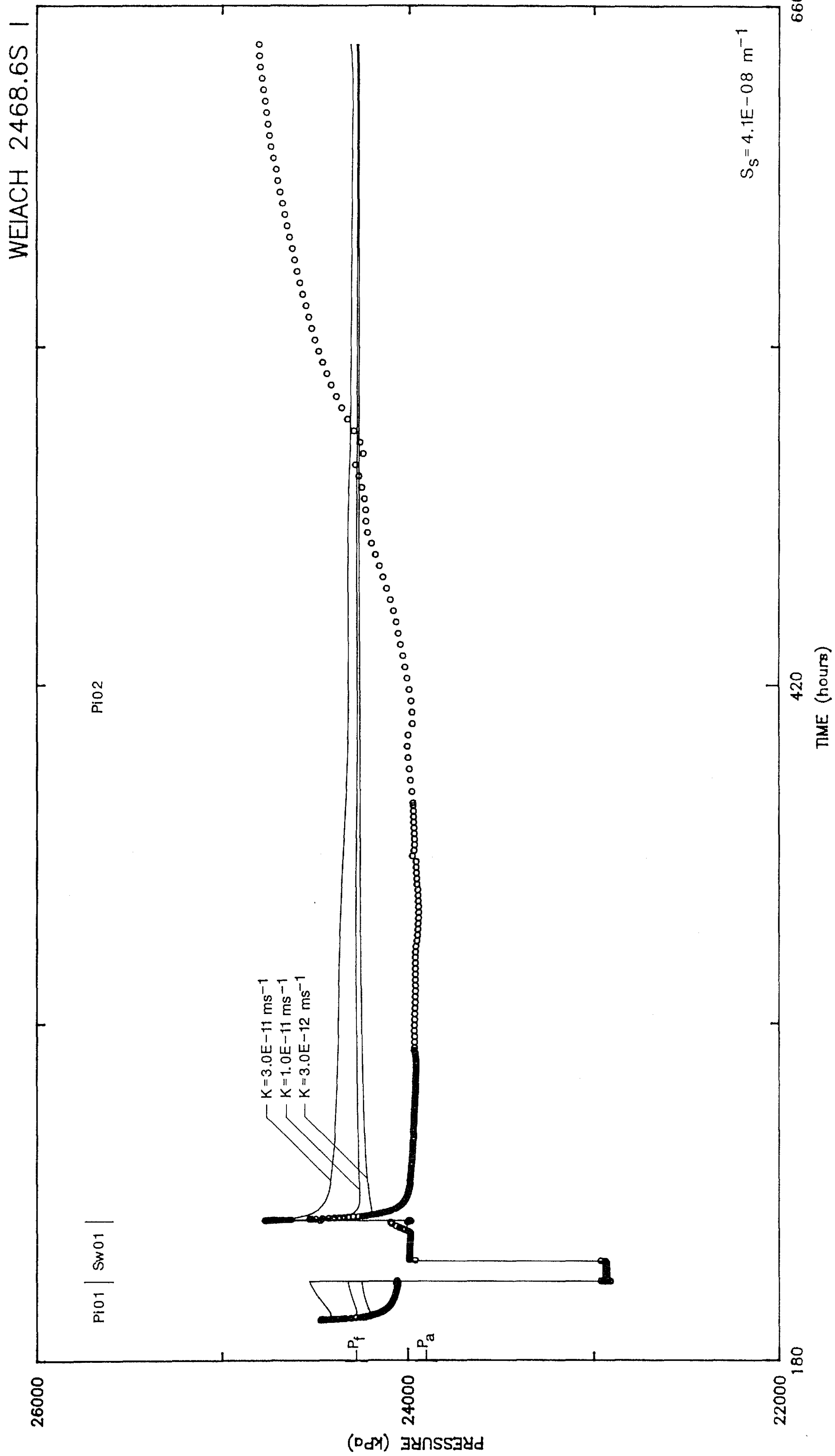


Figure 1 Measured (o) and Simulated Pressure Responses for the Testing Sequence

Test 2468.6SII (2454.95 m to 2482.20 m) - Crystalline

Single packer hydraulic testing was completed in the interval from 2454.95 m to 2482.20 m of the Weiach borehole from 03 February, 1984 to 04 February, 1984.

The testing sequence consisted of two pulse injection tests. GLAG noted that hydraulic communication appears to have occurred between the test interval and the borehole annulus through the rock formation for the current test sequence. The first pulse injection test (Pi03) consisted of a pulse of 1347 kPa above annulus pressure. Recovery was monitored over 30 hours. During shut-in of Pi03, 1.6 m of water was added to the annulus as a test of communication between the annulus and the packed off zone. The P2 pressure measurement increased gradually after the addition of water to the annulus. The second pulse injection (Pi04) consisted of a pulse of 2287 kPa above annulus pressure. Recovery was monitored over 60 hours. During shut-in of Pi04, 4.0 m of water was removed from the annulus as a further test of fluid communication between the annulus and the packed off zone. GLAG confirmed the presence of hydraulic communication and terminated the test on 07 February, 1984.

Simulation of the history and testing sequence was completed using GTFM. Because of the hydraulic communication of the test interval with the annulus, the formation pressure was assumed. Temperature effects were not included in the simulations because there was not a significant change in the temperature. Simulations were completed for hydraulic conductivities of 3.0E-12, 1.0E-11, and 3.0E-11 ms^{-1} and for a range of S_s of 1.9E-06, 2.1E-07,and 4.1E-08 m^{-1} at an assumed formation pressure.

The assumed formation pressure was 23800 kPa, as determined from the observed pressure recovery data. It should be noted that hydraulic communication between P2 and P3 would have affected the stable pressure recovery, resulting in an underestimate of formation pressure. For comparison, the P_f determined from the long term monitoring tests, extrapolated to this zone, was 24300 kPa.

Figure 1 shows the measured pressure responses and the GTFM simulations for the hydraulic conductivities above and a specific storage that best represents the formation. The simulations best fit the measured data for a K of between 1.0E-12 and 6.0E-12 ms^{-1}, considering the communication between P2 and P3 in the interpretation. The most suitable specific storage, based on a sensitivity study over about 2 orders of magnitude, is 2.1E-07 m^{-1}.

The effect of varying specific storage over about two orders of magnitude (1.9E-06 to 4.1E-08 m^{-1}) results in close to half an order of magnitude uncertainty in the final estimate of K for the test zone. Additional uncertainty exists in this test because of the communication of fluid around the packer and because the fluid density, fluid thermal expansion coefficient, and the formation fluid compressibility must be extrapolated from the available charts.

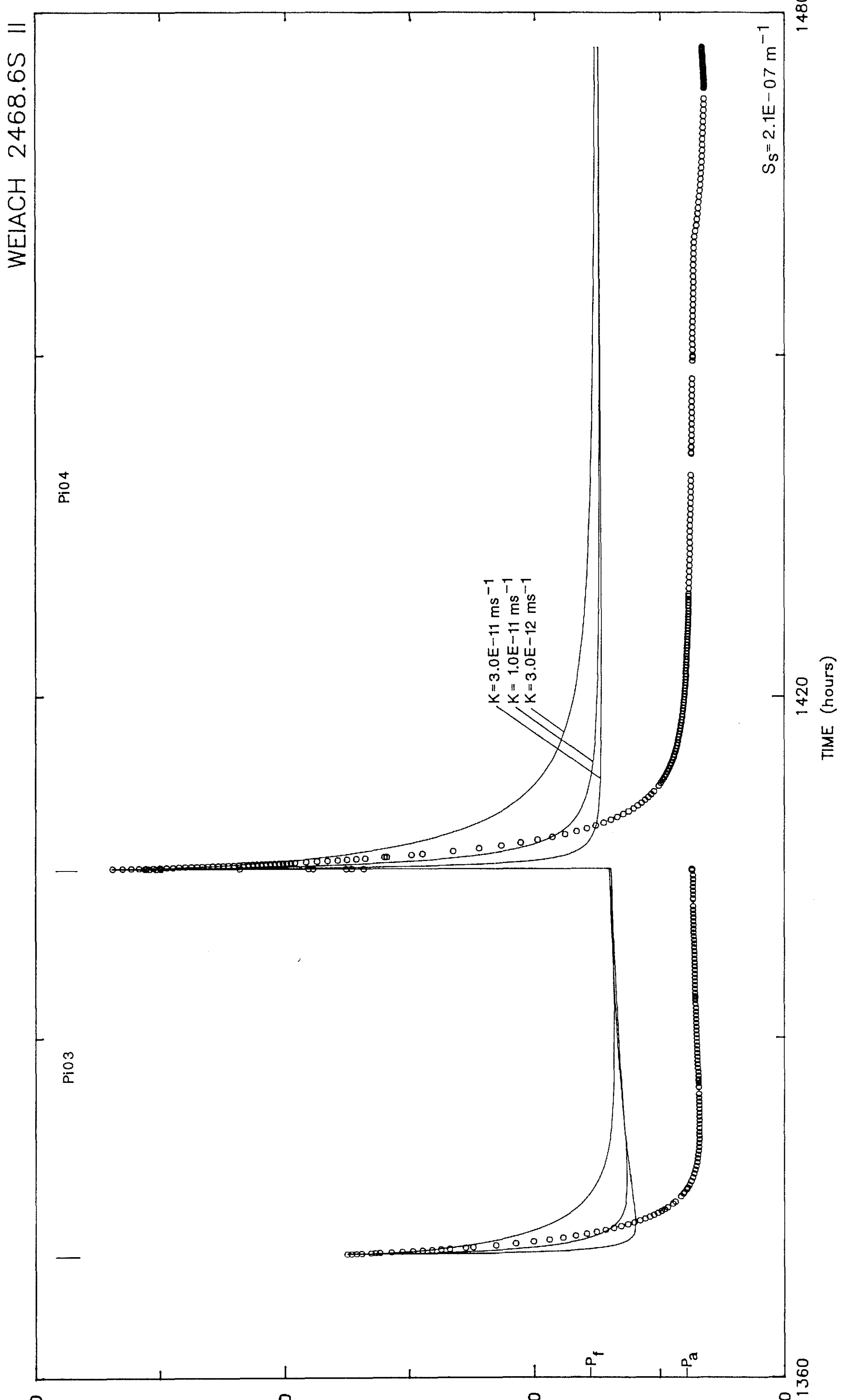


Figure 1 Measured (o) and Simulated Pressure Responses for the Testing Sequence