ESTIMATION OF THE RELATIVE PERMEABILITY DISTRIBUTION IN FRACTURED GRANITIC ROCKS BY MEANS OF VERTICAL FLOW MEASUREMENTS IN THE SIBLINGEN BOREHOLE, SWITZERLAND

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CONVERSION FACTORS

For readers who may prefer to use inch-pound units rather than the metric (International System) units used in this report, the following conversion factors may be used:

Multiply metric SI Units	By	To obtain inch-pound units
millimeter (mm)	0.3937	inch
millimeter per minute (mm/min)	0.3937	inch per minute
meter (m)	3.281	foot
liter per minute (L/min)	0.000589	cubic foot per second
kilopascal (kPa)	0.1450	pound per square inch

Degree Celsius (^{o}C) may be converted to degree Fahrenheit (^{o}F) by using the following equation:

$$^{o}F = 9/5(^{o}C) + 32.$$

The following terms and abbreviations also are used in this report:

minute (min)

second (s)

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ABSTRACT

The U.S. Geological Survey has developed a geophysical measurement technique for determining the vertical distribution of permeability in fractured crystalline rocks by using measurements of vertical flow during pumping or injection tests in boreholes. The technique is based on measurements made with a recently developed thermal-pulse flowmeter and requires measurements at successively larger pumping or injection rates to determine permeability values. This technique was tested in a 1,522-meter-deep borehole in granitic basement rocks located near Siblingen, Switzerland. Before injection tests were begun, flowmeter logging indicated that a naturally occurring flow of about 1.1 liters per minute entered the borehole from a fracture zone at a depth of about 700 meters, and exited the borehole through fracture zones at depths of about 930 and 1,280 meters. Measurements of the vertical-flow distribution were made during the steady injection of water at rates of 8 and 57 liters per minute. The unreliability of pressure logs intended to measure hydraulic-head differences within the borehole precluded normalization of flows using direct measurements of the hydraulic-head differences causing the flows. Flow measurements were normalized by using injection rates under the assumption that friction losses in the borehole were small. The vertical-flow profile determined from U.S. Geological Survey flowmeter measurements will be available for comparison with permeability profiles generated for the Siblingen boreholes using other, conventional measurement methods.

INTRODUCTION

Recent efforts to design radioactive-waste storage facilities in deep crystalline-rock repositories have focused attention on the possible migration of radioisotopes through permeable fractures in otherwise nearly impermeable rock. In situ properties of fractures located deep within a mass of crystalline rocks are difficult to measure by using currently (1989) available equipment and data-analysis methods based on plane fracture models (Witherspoon and others, 1981; Long and Billaux, 1987; Tsang and Tsang, 1987). Various measurement methods including remote geophysical sensing, seismic tomography, packer isolation and testing in boreholes, and solute tracing are being tested at a number of crystalline-rock research sites (Davison, 1984; Paillet, Hess, Cheng, and Hardin, 1987). These studies indicate that characterization of fracture hydrology at such sites requires investigation of fractures using a number of different methods based on measurements involving different scales of investigation that are effective for different ranges of permeability values.

The U.S. Geological Survey has been studying fracture hydrology at a number of research sites in an effort to develop geophysical logging equipment and data-analysis methods for applications including radioactive-waste disposal in deep formations, contaminant disposal in bedrock, and water-resource exploration in crystalline-rock terrain. The use of geophysical methods for rapid identification of permeable zones would assist in the otherwise expensive and time consuming process of permeability measurement using conventional packer isolation and injection (Paillet, Hsieh, and Cheng, 1987; Pickens and others, 1987). The identification of fractures that are productive during aquifer tests eliminates much trial and error in selecting intervals for packer setting. The cooperative research in fractured-rock hydrology conducted near the town of Siblingen, Switzerland with the Swiss National Cooperative for Radioactive Waste Disposal (Nationale Genossenschaft fur die Lagerung radioaktiver Abfalle, hereafter denoted by NAGRA) provides an important opportunity to evaluate recently developed geophysical methods for the qualitative and semiquantitative estimation of in situ permeability.

Purpose and Scope

This report describes a technique for estimating the in situ vertical distribution of fracture permeability that appears to have important applications in radioactive-waste-disposal research. This technique uses high-resolution, vertical-flow profiling during pumping or injection to characterize the vertical distribution of permeability along the borehole. In several previous studies (Paillet, Hess, Cheng and Hardin, 1987; Paillet, Hsieh and Cheng, 1987; Morin and others, 1988; Paillet, 1988) this technique has provided information that qualitatively agree with results from other permeability measurements, including packer tests and cross-hole pumping. The Siblingen-borehole experiment provides an opportunity to evaluate the results of permeability profiling using a high-resolution flowmeter with the results of other permeability measurements. The vertical-flow profile given for the Siblingen borehole in this report is presented in a form suitable for comparison with the results of these other measurements after they have been made, or when the results of experiments already performed at the site of the Siblingen borehole have been interpreted and published.

Description of the Study Site

The Siblingen borehole is located in north-central Switzerland where fewer than 400 m of sedimentary rocks cover the granitic basement (fig. 1). The study site is north of a trough of sediments, which are 250 to 300 million years old, where basement rocks are below the depth of a potential radioactive-waste respository. The land-surface elevation at the Siblingen borehole is 574 m above sea level. Drilling of the Siblingen borehole was begun on September 2, 1988. Drilling was stopped at a depth of 1,522 m on April 2, 1989. The borehole was completed with telescoping steel casing to a depth of 490.5 m; the 96-mm-diameter borehole (entirely in granite) is uncased from that depth to the total depth.

Equipment Used for this Study

The vertical-flow profiles generated during this study were obtained by using a recently designed thermal-pulse flowmeter (Hess, 1982, 1986, in press). Dudgeon and others (1975) reported the development of a heat-pulse flowmeter for boreholes that used a low-energy thermal pulse in a tag-trace travel-time method. The flowmeter sensor was only 41 mm in diameter, had

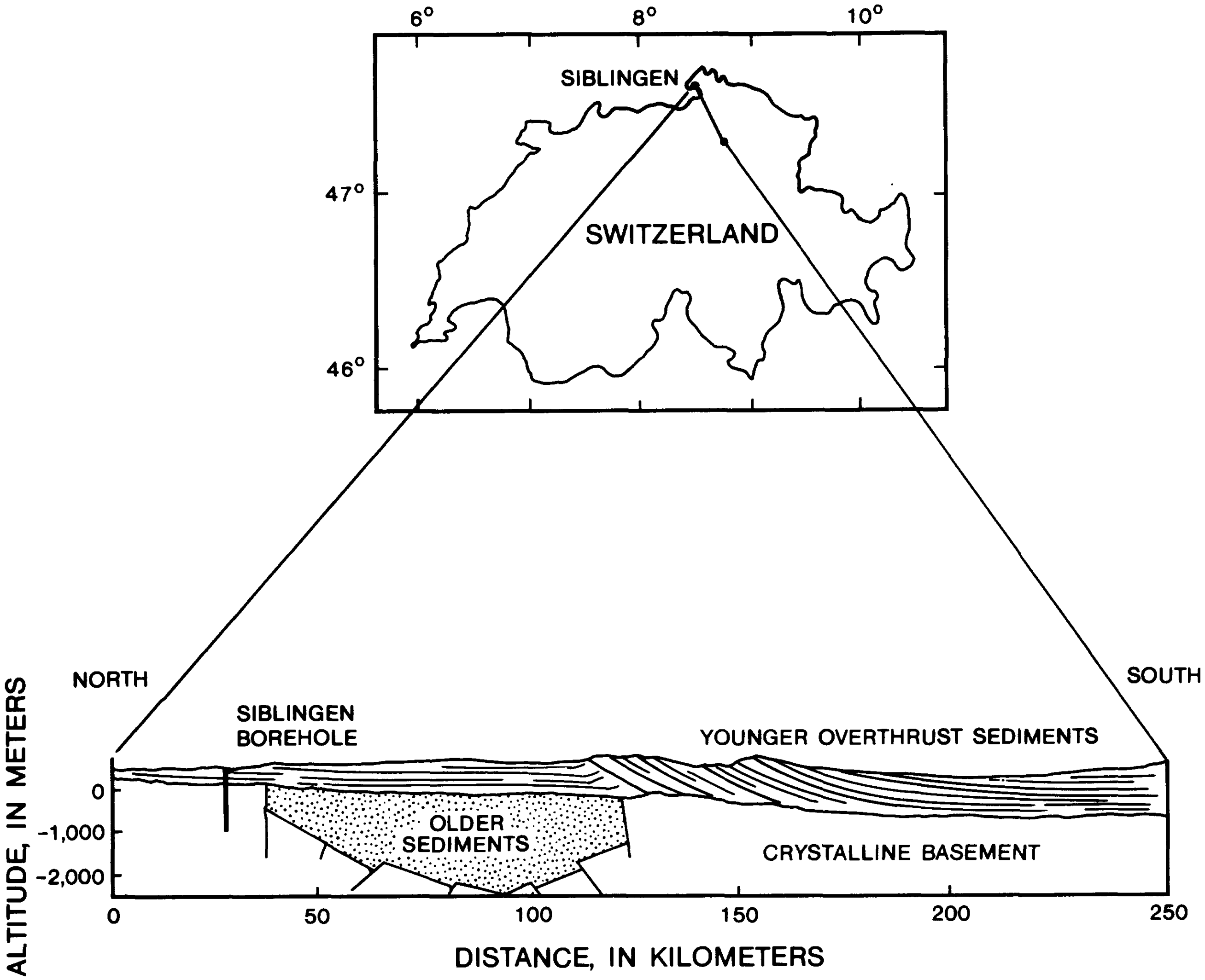

Figure 1. Map showing location of the Siblingen borehole in north-central Switzerland.

slow-flow sensitivity, and could be used in small-diameter boreholes. The U.S. Geological Survey evaluated a commercial version of the Dudgeon style heat-pulse flowmeter and determined that the thermal technique is viable even though the instrument lacked several important features. The urgent need for a slow-velocity flowmeter prompted the Geological Survey to develop an improved version of the Dudgeon-style, heat-pulse flowmeter that would operate reliably when connected to a conventional four-conductor logging cable that is at least 5,000 m long. The thermal-pulse flowmeter of the Geological Survey (figs. 2 and 3) has interchangeable 41- and 64-mm-diameter flow sensors, and has excellent slow-flow sensitivity in boreholes with diameters that range from 50 to 125 mm. The vertical velocity of water in a borehole is determined by correlating the inverse of the thermal-pulse arrival time with the known water velocity in laboratory calibration columns of various diameters. Examples of calibration curves are given in figure 4.

To decrease the measurement uncertainties caused by thermal convection currents within the borehole fluid and to increase flow sensitivity in larger diameter holes, the Geological Survey developed a logging-line powered, inflatable/deflatable, flow-concentrating packer. The thermal flowmeter and packer have been integrated into a single probe that can be operated on logging cables that have four or more conductors (fig. 5). The packer system requires one conductor (plus the cable armor) and can be used with other borehole probes that could benefit from a wireline-powered packer, such as spinner flowmeters and pressure transducers. The thermal-pulse flowmeter and flow-concentrating packer system has been used to measure natural and artificially induced flow distributions in boreholes that range from 75 to 250 mm in diameter, at temperatures from 6 to 60 ^{o}C, and in a variety of rock types including granite, basalt, sandstone, shale, limestone, and dolomite. Calibration of flowmeter measurements obtained with an inflated packer are made using inverse-pulse travel times except that the calibrated measurements are given in volume discharge--liters per minute--instead of velocity (fig. 4).

Examples of flowmeter interpretation for measurements made in the Siblingen borehole are shown in figure 6. In the first example, each of a set of three repeated thermal-response pulses arrive in about 1.9 s after the flowmeter was triggered. Pulse deflection to the left indicates downflow. The inverse of the 1.9-s pulse arrival time (0.53 s^{-1}) corresponds to a borehole downflow of 2.7 L/min in figure 4. In a 96-mm-diameter borehole, this discharge corresponds to an average downward velocity of about 340 mm/min. In the second example, there is no thermal-response pulse arrival after the flowmeter was triggered. In this instance, flowmeter response indicates that if any flow occurs, it is less than 0.05 L/min up or down. The examples given in figure 6 apply to the large-diameter (64 mm) sensor with packer inflated. When measurements are made with the packer deflated, response needs to be calibrated for the specific borehole radius. The calibration curve for the small-diameter (41 mm) sensor with inflated packer is shown in figure 4b. The small-diameter sensor with inflated packer has about three times the sensitivity to flow because the flow is concentrated to pass through a smaller velocity-measuring cross section.

Interpretation of the flowmeter measurements to determine hydraulic conductivity requires knowledge of the hydraulic-head difference causing the flow into or out of individual fracture zones during pumping or injection

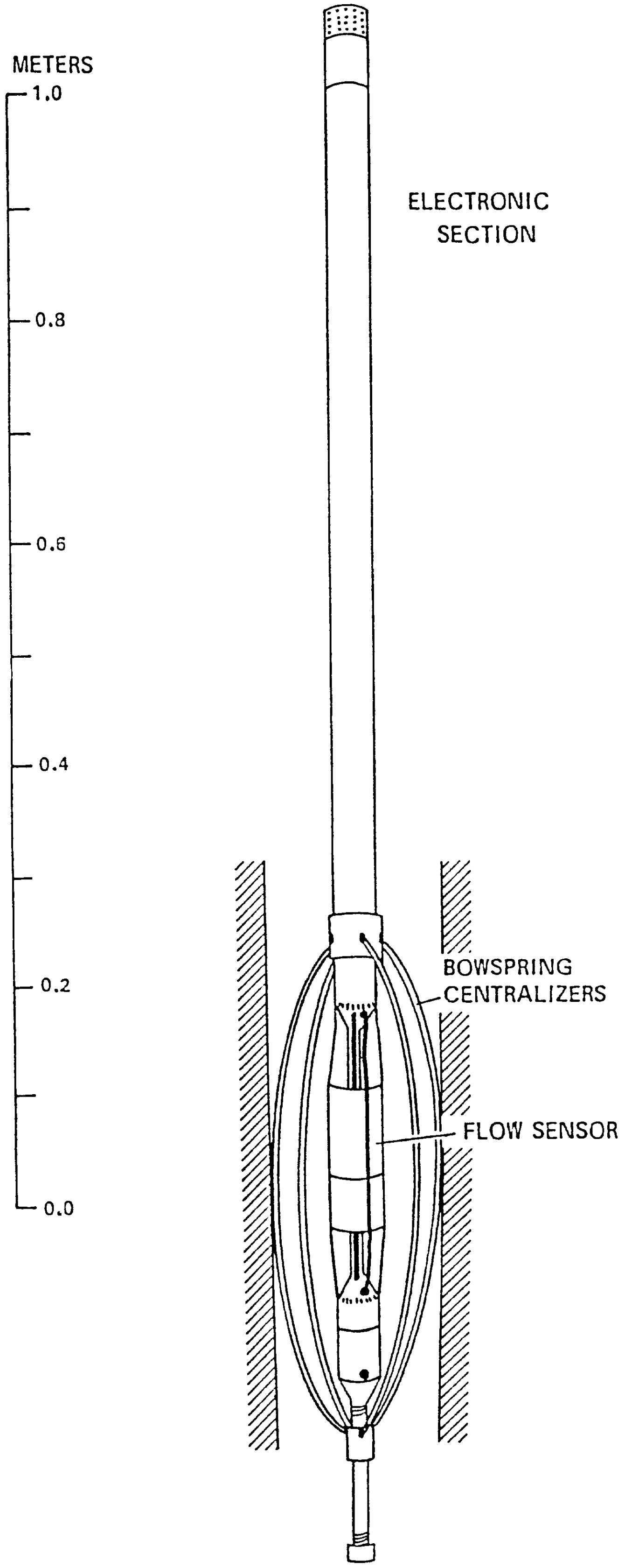

Figure 2. Sketch of U.S. Geological Survey thermal-pulse flowmeter.

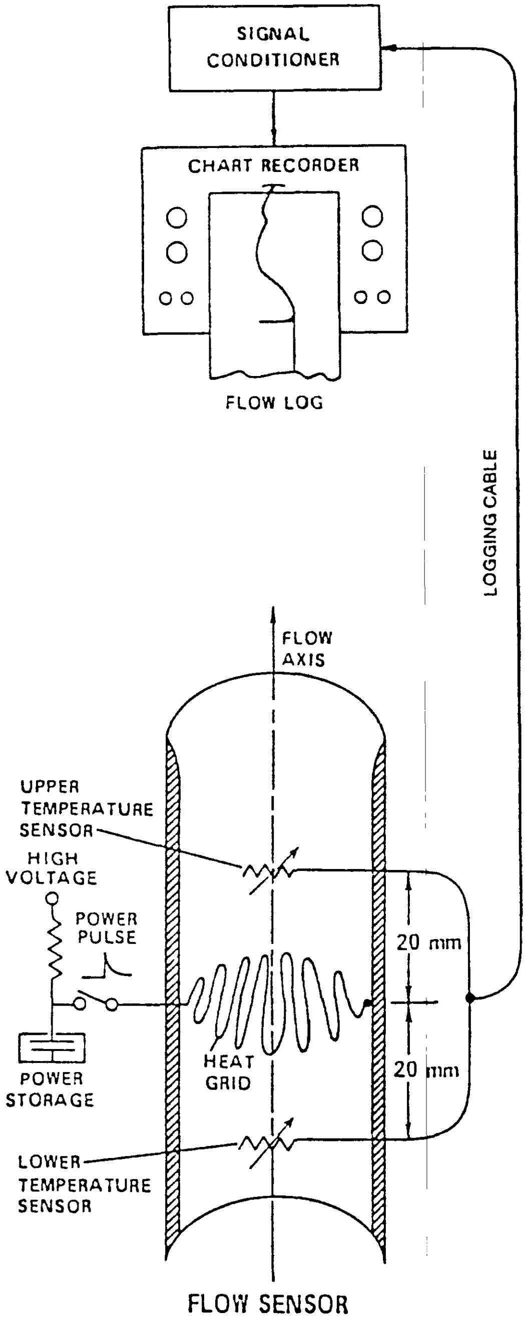

Figure 3. Sketch of heat grid and thermistor arrangement in the thermal-pulse flowmeter.

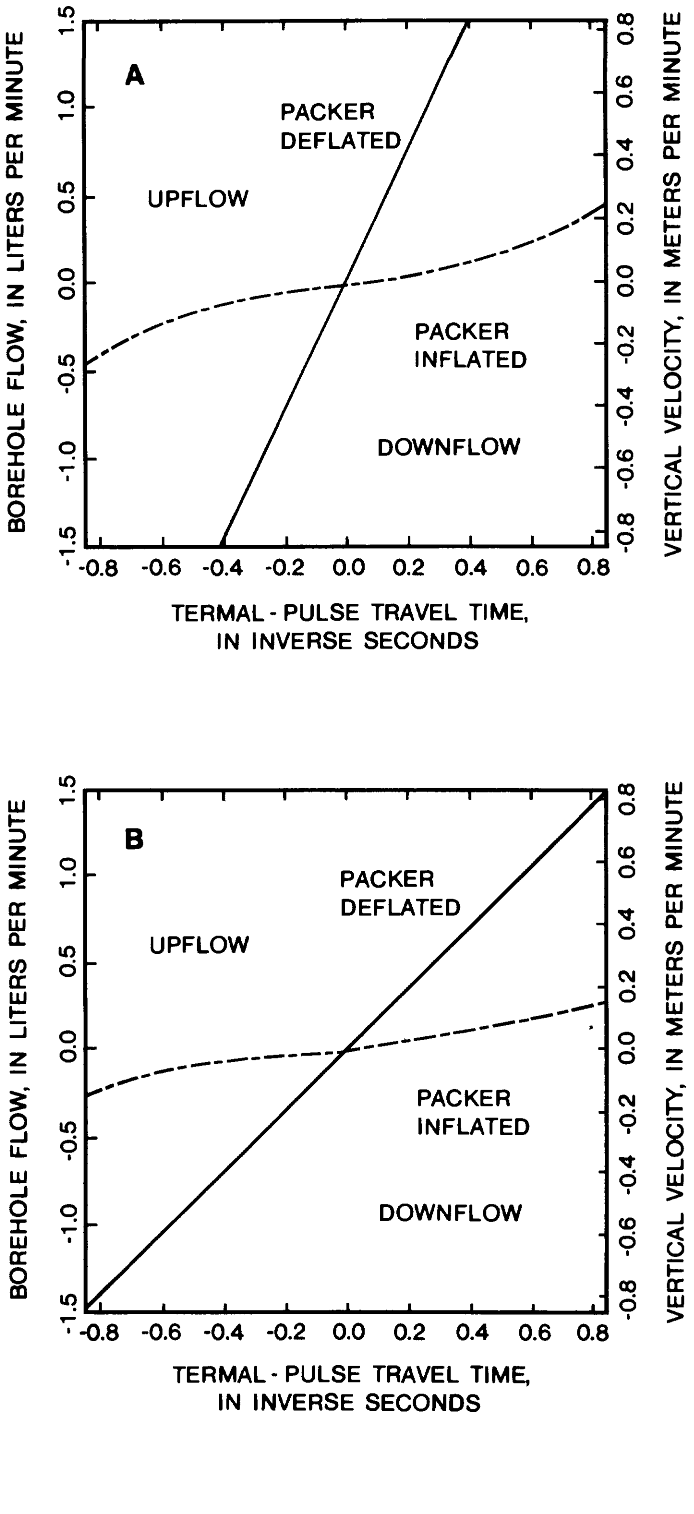

Figure 4. Graphs showing calibration curves for large- and small-diameter flowmeter sensors in a 100-millimeter-diameter borehole with an inflated or deflated packer.

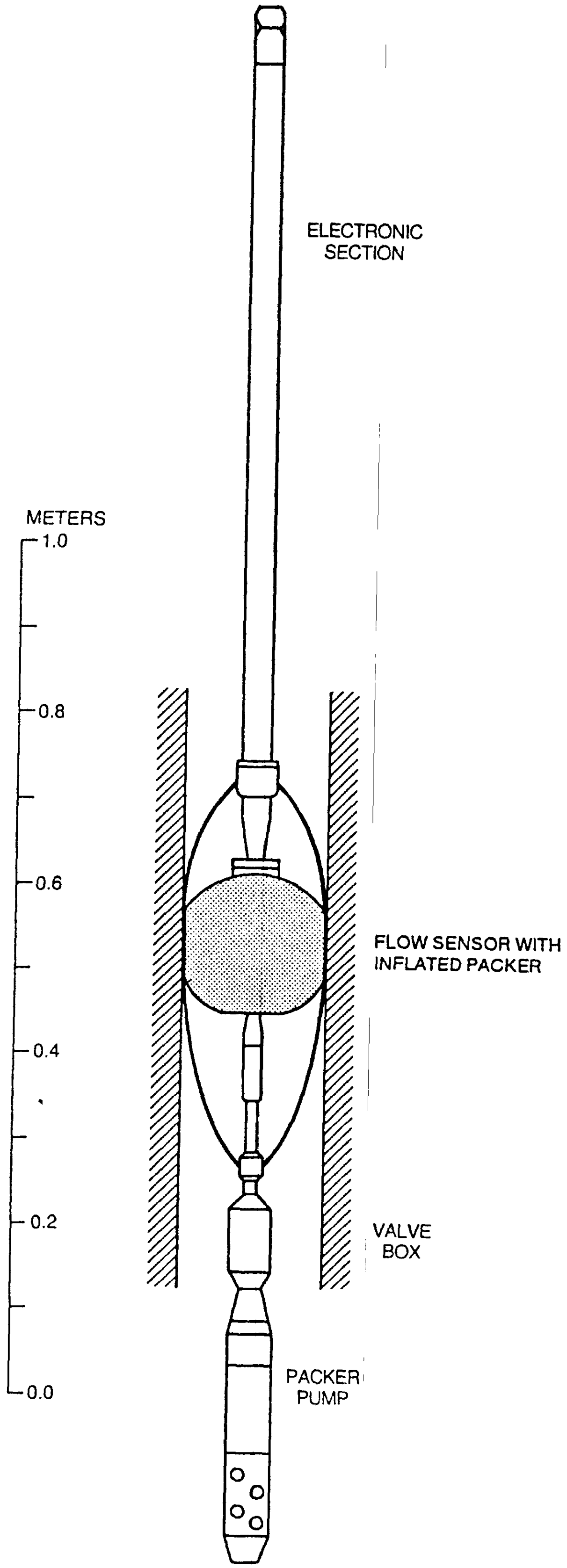

Figure 5. Sketch of thermal-pulse flowmeter with flow-concentrating packer.

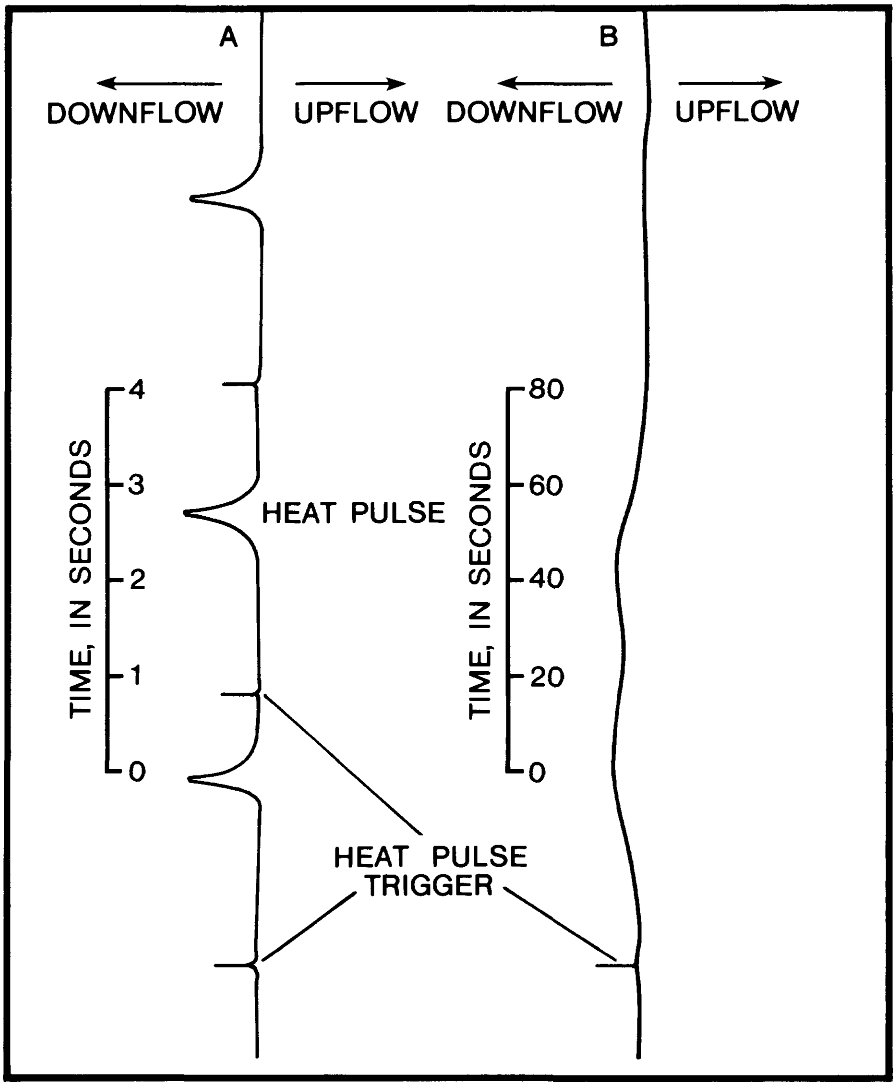

Figure 6. Diagram showing examples of thermal-flowmeter response.

tests. This hydraulic head is the difference between the water level in the borehole during the pumping or injection testing and the pretest static level, corrected for velocity friction losses in the borehole. Water levels are difficult to measure accurately with an electric tape during injection; therefore, the water level and possible friction losses need to be measured by using a pressure logging device. This probe contains a piezoelectric transducer that responds to changes in pressure. We used two different pressure transducers. One transducer was rated at 0.7 kPa and was used to provide greater resolution at shallow depths in the borehole. A second transducer, rated at 6.2 kPa, was used to obtain pressure measurements in the lower part of the borehole. The relatively slow vertical flows at depths greater than 1,000 m were not expected to produce substantial velocity friction loss.

Acknowledgments

The authors acknowledge the assistance of the NAGRA in conducting the geophysical measurements described in this report. NAGRA provided valuable assistance by arranging for the shipping of equipment, winch, and associated equipment to the site; providing suitable pumps and monitoring gages for the injection tests; and on-site fabricating of a cablehead adapter. We are especially indebted to Peter Blumling for supervising all of these details, and to Heinrich Haferland for his careful workmanship in fabricating the cablehead adapter that worked throughout the test period.

TECHNIQUE USED TO ESTIMATE RELATIVE PERMEABILITY DISTRIBUTION

The vertical distribution of permeability in the Siblingen borehole can be correlated to the distribution of outflow during steady injection. The resolution limits of the flowmeter required that the injection tests be conducted by using two different injection rates. The use of different injection rates was necessary because the permeability of shallow fracture zones would allow downflow rates to exceed the capacity of the flowmeter before flow in the lower part of the borehole would be large enough to measure. We started by using an injection rate of 8 L/min. This flow rate was near the upper limit of flowmeter resolution. Flow could not be detected below a depth of about 1,200 m with this injection rate; therefore, a second set of measurements was made at an injection rate of 57 L/min, the limit of the capacity of the available pump. At this faster injection rate, flow could be measured all the way to the bottom of the borehole.

Hydraulic heads were measured during the test by using the pressure probe. Both transducers were depth-calibrated in the borehole before injection began. The transducers then were used to measure hydraulic-head increases in the borehole during each of the two injection tests to monitor the approach to steady-state conditions. They also were used to determine the hydraulic-head changes and friction losses along the borehole after steady-state conditions had been achieved.

Borehole Flow Under Static Conditions

Before beginning the injection tests, the Siblingen borehole was surveyed using the two pressure transducers. Transducer-calibration measurements are summarized in table 1. These surveys provided an effective calibration of transducer response, in millivolts, per meter of hydraulic

Table 1.--Pressure-transducer response at various depths before start of injection tests

0.7-kilopascal transducer		6.2-kilopascal transducer	
Depth (meters)	Tranducer response (millivolts)	Depth (meters)	Transducer response (millivolts)
131.5	3.02 (out of water)	131.5	0.30 (out of water)
132.5	3.51	150.0	3.79
150.0	33.86	200.0	13.54
132.5	3.55	250.0	23.29
150.0	33.92	300.0	33.02
200.0	120.18	350.0	42.73
250.0	205.70	400.0	52.46
150.0	34.10	450.0	62.25
		500.0	72.04
		550.0	81.85
		600.0	91.67
		650.0	101.47
		700.0	111.36
		750.0	121.18
		800.0	131.93
		850.0	140.72
		900.0	150.53
		950.0	160.30
		1,000.0	169.94
		800.0	131.21
		600.0	91.82
		400.0	52.55
		200.0	13.44

head. After completing the pressure transducer calibration, the borehole was logged with the flowmeter in order to identify any flows occurring under ambient hydraulic-head conditions. Measurements were made with the large-diameter sensor because this sensor offered the largest range of calibrated flow sensitivity. The large-diameter sensor provides somewhat less resolution at small borehole discharges with the packer inflated, but can measure larger discharges with the packer deflated. Naturally occurring flow was measured, with about 1.1 L/min of flow entering the borehole in the depth interval between 690 and 700 m and exiting the borehole through fracture zones at depths of about 930 and 1,280 m. Individual flowmeter measurements are listed in table 2, and the vertical distribution of flow is shown in figure 7.

Injection Test 1

The first injection test was conducted using an injection rate of 8 L/min. Pressure-transducer measurements were made by stationing the transducer at a depth of 200 m. Transducer response began to increase a few minutes after injection started, but this response reversed after about 10 min. This reversal indicated a decline in water level that was not expected to occur during injection (table 3). Alternate measurements of water level in the borehole subsequently indicated that the pressure-transducer response was not indicating correct changes of hydraulic head in the borehole. This anomalous response was attributed to drift in transducer response caused by temperature changes or some other effect unrelated to water level. Electric-tape and flowmeter response on entering water during lowering of the probe were used to determine the water level, demonstrating that the water-level rise in the casing had stabilized at about 0.8 m above the static water level within an hour after the start of injection.

Flowmeter measurements made during injection at 8 L/min are listed in table 4. Measurements were made using the large-diameter sensor because of the better high-flow sensitivity of that sensor with the packer deflated, and because small flows towards the bottom of the borehole were not important in this first test. The flow in the upper section of the borehole was just at the upper limit of flowmeter resolution with the packer inflated. A flow slightly greater than 8 L/min was measured in the casing at depths of 200 and 320 m. Other measurements did not yield a repeatable series of pulses, apparently because the flow was so close to the upper limit of resolution that slight changes in borehole conditions caused flow conditions beyond flowmeter resolution. Pulse-arrival times were measured at these depths with the packer deflated. The change in pulse travel time (from 6.0 to 1.6 s) between the first two measurements with the packer deflated (depths of 200 and 320 m) results from the difference in diameter above and below the casing-diameter change (from 161.7 to 112.0 mm in diameter). A similar decrease in arrival time is associated with the transition from the lower part of the casing to the open hole where the diameter decreased from 112 to 96 mm.

The vertical distribution of flow measured during injection test 1 experiment is shown in figure 8. The vertical-flow profile indicates that fluid exited the borehole through fracture zones at depths of about 700, 840, 930, 940, and 1,080 m. The time of the measurements is included with the flowmeter measurements in table 4 because measured flow at a given depth

Table 2.--Flowmeter measurements before start of the injection tests indicating the distribution of naturally occurring flows
[--, no data]

Time[1/]	Depth[2/] (meters)	Packer[3/] condition	DT[4/] (seconds) Mean	DT[4/] (seconds) Variance	Inverse DT[4/] ($seconds^{-1}$)	Flow[5/] (liters per minutes)
15:25	520		>60	--	0	0.0
15:36	660	I	>60	--	0	.0
15:44	708	I	-3.1	0.021	-.32	-1.1
15:54	770	I	-3.4	.001	-.30	-1.1
16:07	840	I	-3.2	.015	-.31	-1.1
16:13	860	I	-3.7	.000	-.27	-.9
16:20	910	I	-3.4	.010	-.29	-1.0
16:28	920	I	-3.1	.017	-.32	-1.1
16:35	925	I	-3.2	.004	-.31	-1.1
16:56	938	I	-8.3	.858	-.12	-.3
17:15	980	I	-10.0	.260	-.10	-.3
17:25	1,062	I	-10.1	1.03	-.10	-.3
17:35	1,100	I	-12.6	1.04	-.08	-.2
17:53	1,210	I	-10.0	1.81	-.10	-.3
18:10	1,276	I	>60	--	0	.0
18:20	1,350	I	>60	--	0	.0
18:46	1,100	I	-7.6	2.15	-.13	-.4
19:14	935	I	-2.7	--	-.37	-1.4
19:25	700	I	>60	--	0	.0
19:34	704	I	-4.8	.029	-.21	-.6
19:38	708	I	-3.0	.000	-.33	-1.2

1/ Time at start of first measurement.
2/ Depth below land surface.
3/ I, Inflated; D, deflated; no calibration if deflated.
4/ DT is average of three or more measurements.
5/ All values ± 0.1 liter per minute; minus value indicates downflow.

Table 3.--Pressure-transducer measurements obtained during start of both injection tests

Injection Test 1 (injection rate = 8 liters per minute; depth of transducer = 200 meters)			Injection Test 2 (injection rate = 57 liters per minute; depth of transducer = 190 meters)		
Time	Transducer reading (millivolts)	Hydraulic-head rise (meters)	Time	Transducer reading (millivolts)	Hydraulic-head rise (meters)
11:46	13.51	0.00	10:27	86.21	0.0
11:47	13.55	.20	10:29	89.10	1.7
11:50	13.59	.41	10:30	91.46	3.1
11:55	13.61	.51	10:32	94.04	4.6
12:00	13.60	.46	10:35	96.62	6.2
12:05	13.59	.41	10:40	99.01	7.4
12:10	13.58	.36	10:50	101.02	8.2
12:15	13.58	.36	11:00	101.85	9.1
12:30	13.56	.26	11:10	102.10	9.2
12:45	13.54	.15	11:30	102.48	9.5
			12:15	103.11	9.8
			12:30	103.46	10.0

Table 4.--Flowmeter measurements obtained during injection test 1; data obtained with the 41-millimeter-diameter sensor only
[--, no data]

Time[1/]	Depth[2/] (meters)	Packer[3/] Condition	DT[4/] (seconds) Mean	Variance	Inverse DT[5/] ($second^{-1}$)	Flow[5/] (liters per minute)
14:30	200	D	-6.0	.200	-0.17	--
14:35	200	I	-1.0	.001	-1.0	-8.7
14:55	320	D	-1.6	.000	-.63	--
14:59	320	I	-1.0	.001	-1.03	-9.1
15:14	520	D	-1.1	.000	-.91	--
15:25	600	D	-1.1	--	-.91	--
15:32	690	D	-1.1	--	-.83	--
15:34	700	D	-2.2	.016	-.45	--
15:37	700	I	-1.6	.002	-.63	-3.6
15:42	704	I	-1.6	.000	-.63	-3.6
15:45	708	I	-1.7	.000	-.59	-3.5
15:50	770	I	-1.7	.000	-.59	-3.5
15:50	840	I	-2.0	.002	-.50	-2.4
16:06	860	I	-2.0	.000	-.50	-2.4
16:20	910	I	-1.9	.002	-.52	-2.6
16:32	925	I	-2.2	.002	-.45	-2.0
16:28	920	I	-2.0	--	-.50	-2.4
16:38	929	I	-8.4	.122	-.12	-.3
16:43	938	I	-6.7	.043	-.15	-.4
16:48	950	I	-10.1	.877	-.10	-.3
16:53	980	I	-9.7	.427	-.10	-.3
17:00	1,062	I	-8.4	.126	-.12	-.3
17:06	1,100	I	-10.6	.080	-.09	-.3
18:12	840	I	-1.9	.000	-.53	-2.5
18:14	835	I	-1.7	.000	-.59	-3.5
18:25	690	D	-1.6	.003	--	--

1/Time at start of first measurement.
2/Depth below land surface.
3/I, inflated; D, deflated; no calibration if deflated.
4/DT is average of three or more measurements.
5/All values ± 0.1 liters per minute; minus value indicates downflow.

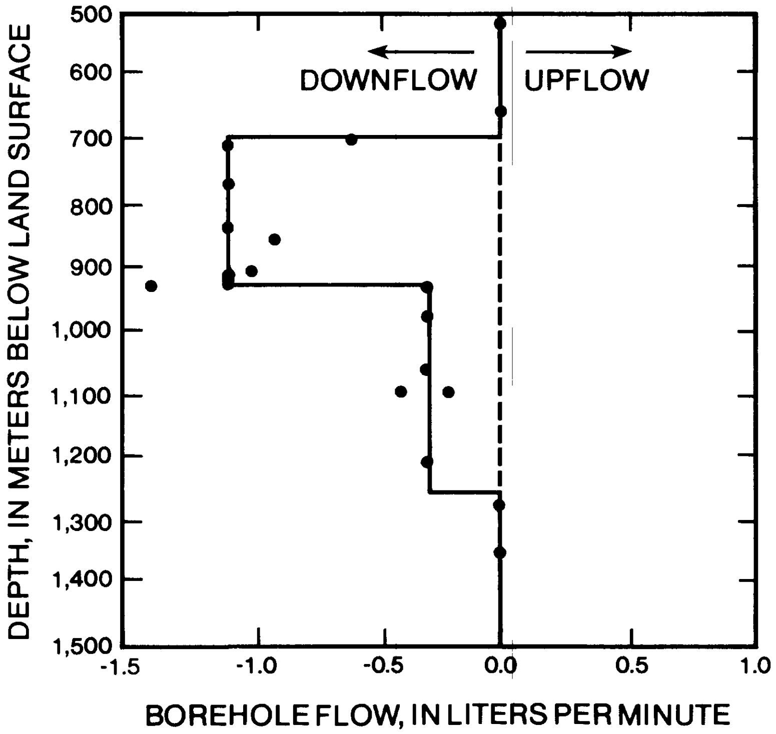

Figure 7. Graph showing vertical distribution of naturally occurring flow in the Siblingen borehole determined by thermal-pulse-flowmeter measurements before start of injection tests.

might have been time-dependent. In that instance, differences in flow measured above and below exit points in the borehole might be confused with differences attributed to the change in sensor response. In most instances, this drift is attributed to the collection of debris including small rock particles, rust from the casing, and other material, such as electric-tape fragments and pieces of rubber or fabric from drill strings and packers. Most of the flow differences indicated in figure 8 are attributed to exits of fluid from the borehole because almost all of the measurements were made during a single lowering of the sensor from the top to the bottom of the borehole.

Injection Test 2

The second injection test was conducted using an injection rate of 57 L/min in order to track vertical flow to greater depths. After injection was started, the measurements made with the 0.7-kPa pressure transducer appeared to provide an accurate indication of water-level rise in casing. After about 2 hours, the hydraulic-head increase appeared to stabilize at about 10.0 m (table 3). The pressure transducer then was replaced with the flowmeter, and flow measurements were begun. Measurements were made at depths below 980 m to provide overlap with the measurements made during injection test 1. Subsequent water-level measurements made after the completion of flowmeter logging (11 hours after the start of injection) indicated a total water-level rise of about 17.0 m, or an additional rise of 7.0 m after the start of logging. Measurements of this additional water-level rise were made by noting the depth where the flowmeter responded to contact with the water. This response could have been affected by water cascading in the casing, so the additional 7.0-m water-level rise after completion of flowmeter logging might not be reliable.

Flowmeter measurements made during injection test 2 are listed in table 5. Flowmeter logs were made using the small-diameter sensor in order to maximize flow sensitivity with packer inflated. The flowmeter was able to detect downflow to within a few meters of the bottom of the borehole indicating that further measurements with greater injection rates were not necessary. The vertical distribution of downflow within the lower part of the Siblingen borehole during this second injection test is indicated in figure 9.

PERMEABILITY-PROFILE ANALYSIS USING FLOWMETER DATA

The flowmeter measurements made during the injection tests indicate the location of fluid exit through fracture zones, and the magnitude of the exit flows. These data can be analyzed to infer the relative permeability of the fracture zones at each location. The different injection rates at which measurements were made and the possibility that frictional hydraulic-head losses along the borehole affected the rate of fluid exit through various fractures need to be considered before the data in tables 4 and 5 can be interpreted in the form of a single distribution profile of vertical permeability for the Siblingen borehole. If accurate pressure logs were available, we could normalize the rate of fluid exit at various fracture zones with respect to the hydraulic-head difference driving the exit flow. During the injection tests at the Siblingen borehole, we did not have accurate pressure logs, and water-level measurements in the casing are not

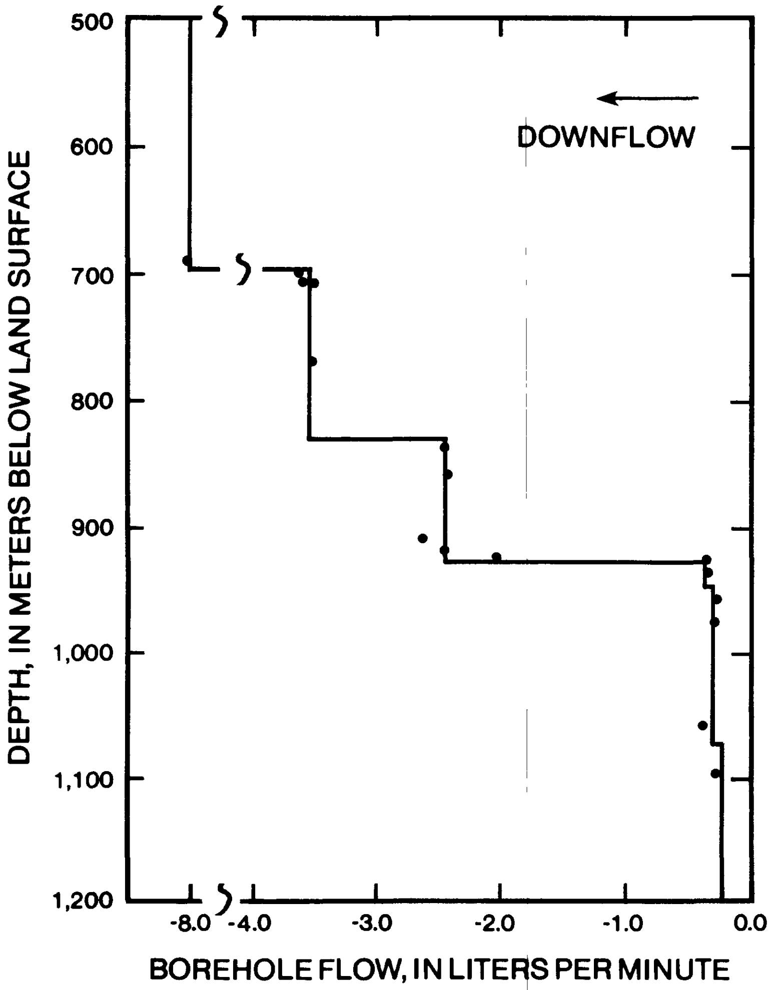

Figure 8. Graph showing vertical distribution of induced downflow in the Siblingen borehole during injection test 1.

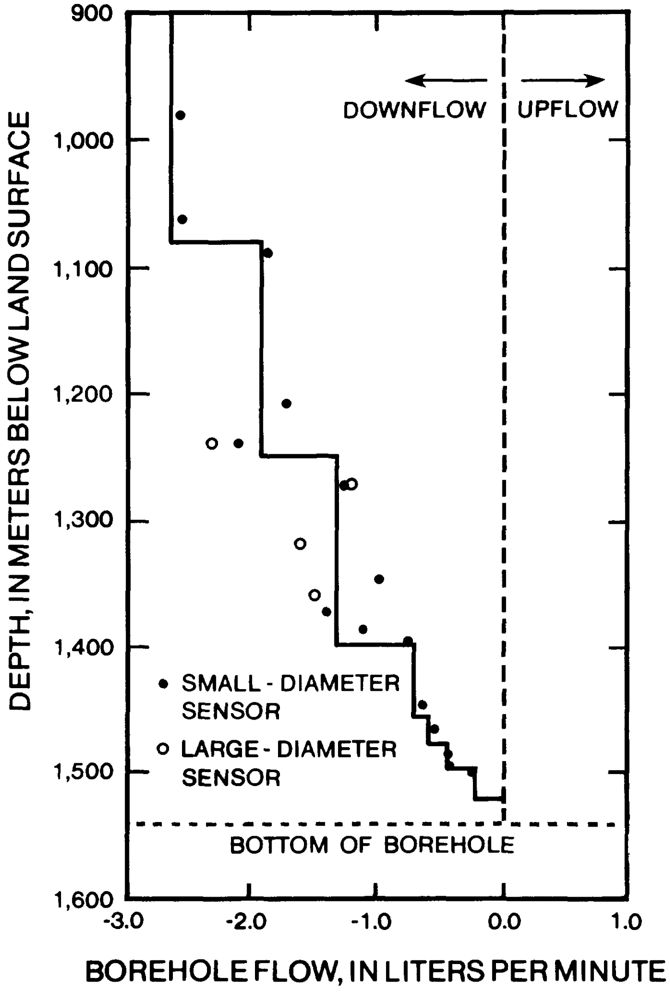

Figure 9. Graph showing vertical distribution of induced downflow in the Siblingen borehole during injection test 2.

Table 5.--Flowmeter measurements obtained during injection test 2; data obtained with 41- and 64-millimeter-diameter sensors

[--, no data]

Time[1/]	Depth[2/] (meters)	Packer[3/] condition	DT[4/] (seconds) Mean	Variance	Inverse DT[4/] ($second^{-1}$)	Flow[5/] (liters per minute)
			SMALL-DIAMETER SENSOR			
13:45	980	D	-4.0	0.002	-0.21	--
13:55	980	I	-0.9	.000	-1.11	-2.5
14:02	1,062	I	-0.9	.000	-1.11	-2.5
14:10	1,090	I	-1.1	.001	-.92	-1.8
14:22	1,210	I	-1.1	.002	-.89	-1.7
14:35	1,276	I	-1.4	.002	-.74	-1.2
14:40	1,350	I	-1.4	.001	-.64	-1.0
14:47	1,400	I	-1.9	.004	-.54	-.8
14:55	1,490	I	-2.9	.002	-.35	-.5
15:02	1,505	I	-5.7	.002	-.17	-.2
15:07	1,500	I	-2.9	.004	-.35	-.5
15:12	1,375	I	-1.3	.013	-.80	-1.4
15:23	1,390	I	-1.4	.012	-.70	-1.1
15:34	1,240	I	-1.0	.002	1.00	-2.1
15:40	1,450	I	-2.2	.001	-.46	-.6
15:47	1,470		-2.4	.003	-.43	-.6
			WITH LARGE-DIAMETER SENSOR			
18:45	980	D	-4.3	0.106	--	--
19:17	1,240	I	-2.0	.002	0.49	-2.3
19:22	1,276	I	-2.9	.096	-.34	-1.2
19:37	1,320	I	-2.5	.001	-.40	-1.6
19:36	1,350	I	-2.6	.000	-.39	-1.5
19:40	1,400	I	-3.3	.009	-.30	-1.1

1/ Time at start of first measurement.
2/ Depth below land surface.
3/ I, inflated; D, deflated; no calibration if deflated.
4/ DT is average of three or more measurements.
5/ All values ± 0.1 liter per minute; minus values indicate downflow.

considered accurate. The only recourse available is to normalize flowmeter measurements by using the accurate measurements of injection rates during the tests. This normalization includes the implied assumptions that hydraulic-head changes in the borehole are not affected by friction losses, and that the hydraulic-head rises required to cause the measured flows increase linearly in proportion to the injection rate. We also noted that the hydraulic-head rise had not completely stabilized during injection test 2.

With the many qualifications listed in the previous paragraph, we believe that the flowmeter measurements made during the injection tests provide an indication of the relative vertical distribution of permeability along the Siblingen borehole. The distribution of exit flows normalized to 100 percent of the injection rate during test 2 is summarized in table 6 and illustrated in figure 10. The distribution of exit flows also are superimposed on the vertical-flow measurements shown in figures 8 and 9 by solid lines. The proper interpretation of the flowmeter measurements, however, requires the use of the plots of vertical-flow measurements with depth given in these figures and the vertical-flow measurements given in time sequence in tables 4 and 5. The depth distribution of the measurements is used to estimate the best value for the vertical flows within various depth intervals. There is some drift in measurements because the response of the flowmeter sensor appears to be affected by the random collection of debris from the borehole in the sensor section as described in a previous section of this report. Vertical flows also may be changing with time because of small background changes in hydraulic head within the fracture system. Averages of flowmeter values provide a more reliable indication of the average vertical flow in a given interval of the borehole. At the same time, those differences related to modified instrument response and background hydraulic-head fluctuations cannot be attributed to flow exit from the borehole. The best way in which to identify where flow exits from the borehole might be to search for differences in flows measured at adjacent depth stations at closely spaced time intervals. For these reasons we identified the depth intervals within which flow exited from the borehole by noting consistent differences between consecutive flow measurements at depth stations spanning the exit point. When the difference appeared uncertain, we checked the possibility of flow exiting from the borehole by repeating the measurements at a later time, when the measured values might have changed, but the consistent difference probably would remain.

SUMMARY

The vertical profile of fracture permeability obtained for the Siblingen borehole in this study provides an excellent opportunity to compare results from the vertical-flow profiling technique with other independent measurements of fracture permeability obtained by more established methods. Thermal-pulse-flowmeter measurements indicated the existence of a naturally occurring flow system within the borehole before injection tests were started. During injection at a rate of 8 L/min, the distribution of downflow was measured in the interval of borehole between the bottom of casing at 490 m and a depth of about 1,250 m. Injection at a rate of 57 L/min produced downflow that was too large to measure accurately with the thermal flowmeter at a depth above 980 m, but this injection rate induced measurable downflow below that depth that extended to the bottom of the borehole. Because of

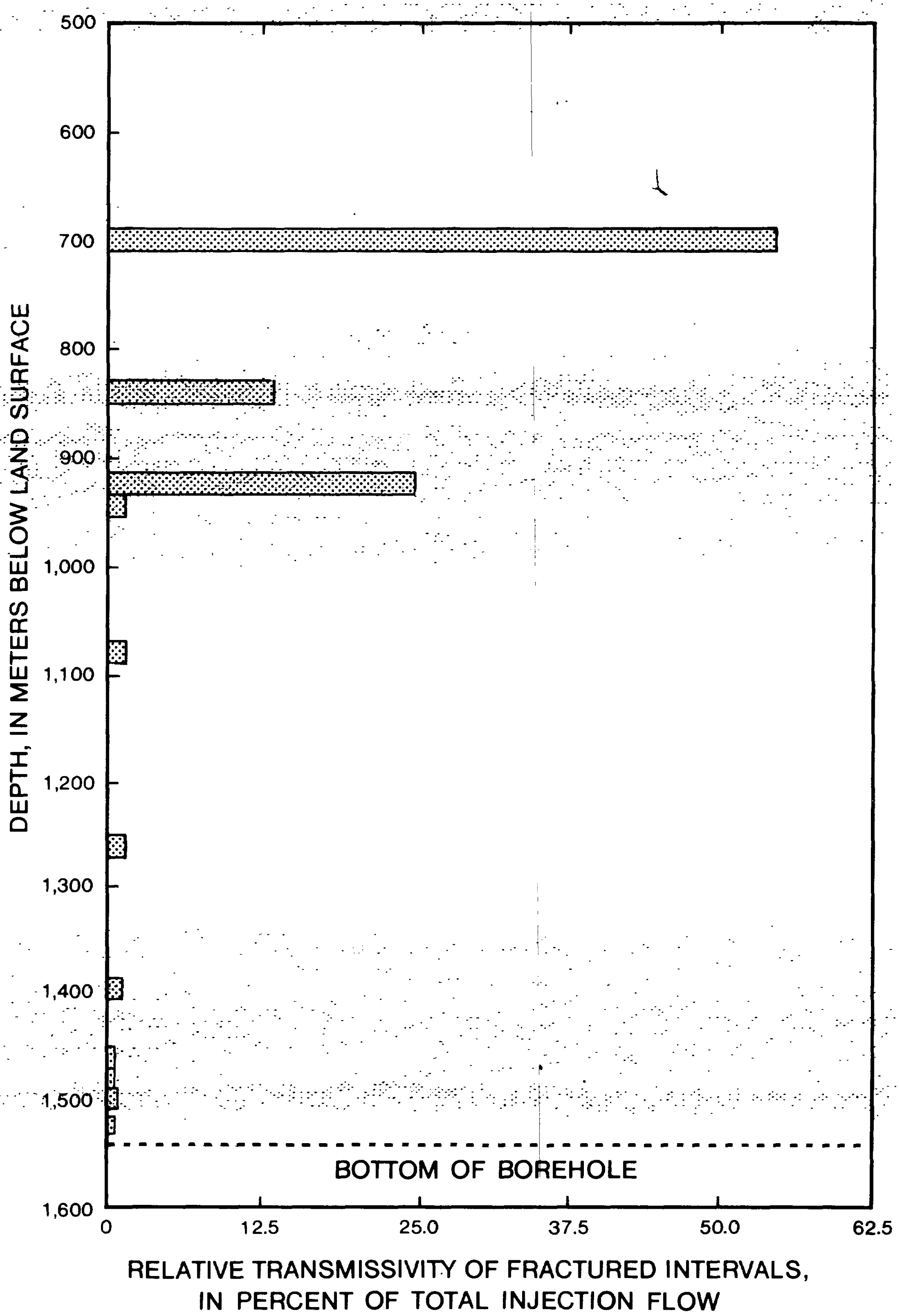

Figure 10. Graph showing vertical-permeability profile inferred from thermal-pulse flowmeter measurements; data normalized to conditions of injection test 2.

Table 6.--Vertical distribution of exit flows normalized to conditions of injection test 2 [--, no data]

Depth interval (meters)	Outflow (liters per minute) Injection test 1	Outflow (liters per minute) Injection test 2	Normalized outflow[1/] (liters per minute)
690- 700	4.4	--	31.4
835- 840	1.1	--	7.8
920- 929	2.0	--	14.3
938- 950	.1	--	.7
1,062-1,100	.1	0.8	[2/] .7
1,240-1,276	--	.7	.7
1,390-1,400	--	.5	.5
1,450-1,470	--	.1	.1
1,470-1,490	--	.1	.1
1,500-1,505	--	.3	.3
1,505-1,522	--	.2	.2

1/ Based on injection rate of 57-liters per minute.
2/ Average of data from both tests (after normalization).

drift problems with the pressure probe the quantity of flow exiting at various fracture zones could not be normalized by using measurements of hydraulic head. Normalization with respect to recharge rate during measurements, however, appeared to give consistent results. Exit flows measured in the region of overlap between the two injection tests differed almost exactly in accordance with the 7.125 ratio of the injection rates. This result also indicated that dynamic hydraulic-head losses produced by the larger injection rate were not significant. Calibration curves were verified by repeat measurement of flow rates with the small- and large-diameter flow sensors at the same depth. Comparison of flow rate determined from calibration charts for each of the different sensors with the packer inflated indicated that these measurements generally differed by less than 10 percent.

The vertical profile of relative permeability in the Siblingen borehole inferred from normalized flow measurements during steady injection was normalized with respect to the percentage of total injection flow. The distribution of flow differences at exit points identified from the normalized flow distribution can be used as a qualitative or semiquantitative measure of the vertical distribution of fracture transmissivity in the Siblingen borehole. These results are provided in this report so that they can be compared with other published estimates of fracture permeability in this borehole being produced by other researchers using more conventional permeability-measurement methods.

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