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PRELIMINARY RESULTS OF THE FALL 1995 DRILLING AND HYDRAULIC TESTING PROGRAM AT THE SMITHVILLE PHASE IV BEDROCK REMEDIATION SITE

P. Lapcevic, K. Novakowski, G. Bickerton and J. Voralek

NWRI Contribution No. 96-50

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NWRI Contribution # 96-50

January 8, 1996

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EXECUTIVE SUMMARY

During the Fall of 1995, a drilling program was undertaken at the CWML waste site in Smithville, Ontario. The purpose of the drilling program, was to undertake the preliminary characterization necessary for the development of a detailed conceptual model for groundwater flow and contaminant transport in the Lockport Dolostone which underlies the site. To develop the conceptual model, it is necessary that the properties of the fracture framework and the unfractured rock matrix be characterized in such detail that the properties of individual fractures and competent beds are measured.

To conduct the preliminary characterization, one vertical borehole and six inclined boreholes (57°) were drilled to the base of the Lockport Formation (approximately 50 m depth) in the immediate vicinity of the Smithville site. Three of the boreholes were clustered together at a location approximately 400 m upgradient from the existing pumping centre. The boreholes were drilled using triple-tube diamond core methods which leaves a borehole 76 mm in diameter. During the drilling, the core was logged for structural features important to groundwater flow such as bedding plane and vertical fractures, vuggy zones, other variations in porosity, stylolites and bituminous partings.

Core samples of approximately 0.1 m length were obtained during the drilling of two of the boreholes located in the cluster site. A total of 19 samples were obtained with representation from all members of the Lockport Formation. The core samples are preserved in a saturated state in an anaerobic environment for future measurement of matrix porosity.

Following completion of the drilling, the boreholes were developed by surging and pumping. The holes were also logged using standard geophysical sondes including caliper, gamma, inductance, resistivity, temperature and inclinometer.

Upon completion of the geophysical investigations, constant-head injection tests were conducted in five of the seven boreholes using standard methodology. Preliminary hydraulic measurements were conducted by consecutively testing from the bottom of the hole to the water table using a 2-m packer separation. In addition, 32 tests were conducted in an upgradient borehole, using a 0.5 m test interval. These tests were conducted to investigate the discrete features in the Eramosa and Upper Vinemount units of the Lockport Formation. Hydraulic testing is ongoing at the time of this report and it is anticipated that the 2-m tests will be completed in all boreholes by the end of March, 1996.

Rose diagrams of the strikes of all measured vertical fractures were constructed and two fracture populations observed. The two major sets occur at 090-110° and 000-010°. The major set oriented in the NW-SE direction is observed to be diffuse and orientations as southerly as 160° are present in some boreholes. Trends in orientation between units are not observed, however, a significant decrease in fracture frequency with depth is noted. The orientations of the vertical

fractures determined from the subsurface differ from that determined from local surface and quarry outcrop but correlate well with regional trends.

The results of constant-head tests conducted using a 2-m interval in the five boreholes tested so far, indicate a range in transmissivity from below detection limit (approximately $1x10^{-10}$ m^2/s) to the upper detection limit ($1x10^{-2}$ m^2/s). Measured transmissivities in the Eramosa and Upper Vinemount units range between 10^{-6} and 10^{-2} m^2/s. A 2-m zone of low permeability rock at the top of the Lower Vinemount was observed in every borehole across the site. The presence of vertical fractures through this low permeability bed was not observed in the drill core. It is also important to note that the general degree of fracturing and presence of high permeability fractures is only marginally different between the upper and lower Lockport Formation. The Gasport unit exhibits a range of transmissivity between 10^{-8} and 10^{-2} m^2/s with a 4-m zone of high permeability that can be correlated across the site. This lower feature is a discrete fracture zone of significant lateral extent. Other correlations will become evident with the completion of shorter packer spacing tests. For example, the results of the hydraulic tests conducted using a 0.5 m test interval in borehole 54A, when compared to the core log, show that the Upper Vinemount unit is characterized by a 1.5 m zone of uniformly high transmissivity, 14 fractures and numerous broken core zones. The Eramosa member is characterized by a greater variation in transmissivity and fewer distinct bedding plane fractures. The zones of higher transmissivity correlate to 1-2 fractures observed in the core. The two most transmissive zones (~ 180 masl and 177 masl) are observed to be associated with vertical fractures.

INTRODUCTION

The development of a site conceptual model based on the subsurface characterization of the fractured bedrock is essential to the design and implementation of containment or remediation schemes at the Smithville Phase IV site. Due to the heterogeneous nature of fractured rock, it is necessary that the properties of the fractures be characterized in detail in order that realistic predictions of the hydrogeological conditions of the groundwater flow system, be determined. Of particular interest is the permeability and continuity of individual bedding plane fractures, vertical fractures and the properties of the rock matrix.

Previous characterization of the bedrock at the site has focussed primarily on the Eramosa and Vinemount submembers of the Lockport Formation. In general, the interpretation of the groundwater flow in the formations has been undertaken using classical porous media aquifer/ aquitard models with little investigation of the fracture framework (Golders, 1995). The primary goal of the present field program is to develop a conceptual model for groundwater flow and solute transfer by explicitly considering the fracture framework of the bedrock beneath the site. The program was designed to verify and extend the existing geological and hydrogeological data base by obtaining site-specific geological information including the collection of good quality continuous core. Inclined boreholes were installed to investigate the extent of vertical fracturing beneath the site. The boreholes transect the entire Lockport Formation and terminate in the Rochester shale. Sampling of several sections of core immediately following retrieval from the core barrel was conducted to obtain samples of the rock for diffusion measurement which will be representative of in-situ conditions. Structural features important to groundwater flow such as bedding plane fractures, vuggy zones, styolites and bituminous partings were also identified in the core record. A suite of geophysical logs was conducted in each borehole. Hydraulic testing to determine the variation in permeability of the different formations is presently being undertaken using a 2-m packer spacing. Individual fractures that are contributing to the flow system will be identified in future testing conducted using packer spacings of 0.5-m and 0.1-m. This report summarizes preliminary results obtained to date.

DRILLING PROGRAM

Six 76 mm (N-sized) diameter inclined boreholes and one vertical borehole were completed by Marathon Drilling Inc. using a Longyear 38 skid mounted rig between October 24, 1995 and November 19, 1995. The location and orientation of the new boreholes are shown in Figure 1. Boreholes 54A, 54B, and 54C are 40-50 m apart and are clustered north of the CWML site. The remaining four boreholes are located south of the CWML site. A summary of borehole elevations, orientations and depths is presented in Table 1. Each borehole was constructed by driving steel

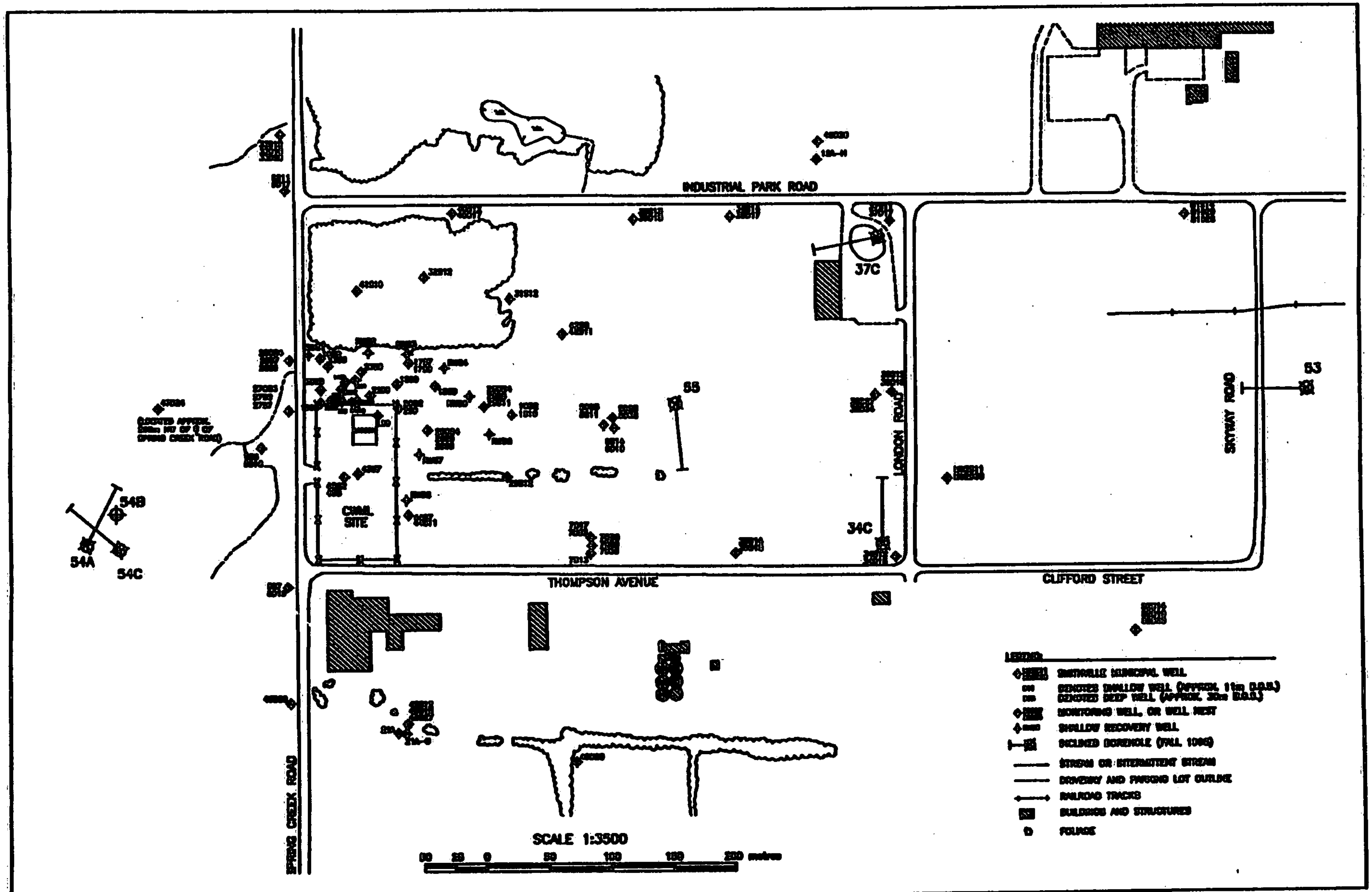

Figure 1. Site map showing location of new boreholes.

Table 1. Summary of borehole characteristics.

Borehole	TOC Elevation (masl)	Plunge (°)	Orientation (°N)	Bottom Depth (fbgs)	Bottom Depth (mbgs)	Casing Length (ft)	Casing Length (m)	Casing Stick-up (m)
53	191.76	57	21	204.5	62.33	42.49	12.95	0.9
54A	194.94	56.5	137	196	59.74	29.49	8.99	1
54B	194.60	-	-	226	68.88	24.53	7.48	0.78
54C	194.68	56	50	185	56.39	26.49	8.08	0.82
55	192.93	57	264	244.5	74.52	34.49	10.51	0.94
37C	192.19	55	4	184	56.08	42.56	12.97	0.76
34C	192.94	57	106	185	56.39	34.00	10.36	0.63

TOC-top of casing fbgs-feet below ground surface
masl-metres above sea level mbgs-metres below ground surface

casing with a diamond shoe through the overburden and several feet into the bedrock. The casing was grouted in place using cement. The rock was then cored to the top of the Rochester shale (~60 mbgs) using triple-tube wireline techniques. Water used during drilling was obtained from the town of Smithville water tower. Return water in all boreholes was negligible due to the presence of high permeability zones just below the bedrock/ overburden contact. Core was photographed and examined while still in the split tube to minimize disruption of fracture positions. The core logs include notation of all breaks which are further distinguished as mechanical in origin (ie. due to drilling), bedding plane fractures (natural or induced) or vertical fractures (including sub-vertical fractures). Lithological features such as rock type, colour, texture, porosity and mineralization were also noted. Stratigraphic contacts were determined based on core in conjunction with previous studies in the area (Blair and McFarland, 1992). Total core recovery in each borehole ranged from 97-100% (Table 2). The low core recovery (70%) at the bottom of borehole 55 was due to mechanical malfunctions of the coring apparatus.

A 1.5" diameter submersible pump (Grundfos®) was used to develop each well by pumping after the completion of drilling. Boreholes were pumped at 10 L/min for 4-5 hrs each. In all boreholes, a strong sulphurous odour was noted from the discharge water. Gas bubbles were also noted in several of the boreholes. Downhole pressure responses observed during hydraulic testing suggest that the gas originates in the Rochester shale at the base of the boreholes. While the presence of gas will not effect the proposed hydraulic and tracer experiments to be conducted in the boreholes, it is advisable to seal the bottom of the boreholes using bridge plugs to eliminate any risk from gas release below downhole packers.

Table 2. Summary of core recovery.

Borehole	Total Core Recovery	Total Length of Core (ft)	Lost Core (ft)	Run #	Core Recovery	Unit
53	100%	168.25	165-166.5	15, 16	95%	Gasport
54A	100%	174.58				
54B	99%	209.33	27.08-28.67	3	84%	Eramosa
54C	99%	167.5	75-75.08	8	89%	Upper Vinemount
55	98%	216.5	44-44.5	3	95%	Eramosa
			54-54.5	4	95%	Eramosa
			100.08-101.33	9, 10	88%	Upper Vinemount
			241.5-244.5	24	70%	Rochester
34C	97%	162.08	27.67-29.08	2	86%	Eramosa
			52.17-53.33	4A, 4B	88%	Eramosa
			~1'3" lost in zone of 74'6" to 78'1"	7	88%	Eramosa
			~ 8" lost in zone of 94'6" to 97'6"	9	93%	Upper Vinemount
37C	99%	147.33	62.58-63.08	4A, 4B	95%	Eramosa
			93.83-94.25	7	96%	Upper Vinemount
			98.08-99.08	8A, 8B	90%	Upper Vinemount

Boreholes 54B and 34C were found to be blocked following the removal of the drilling rods. In 54B, a complete blockage occurred around 34 metres below casing top (mbct). Marathon Drilling used a tricone drill bit to clear the blockage by reaming the entire hole. Shortly after the completion

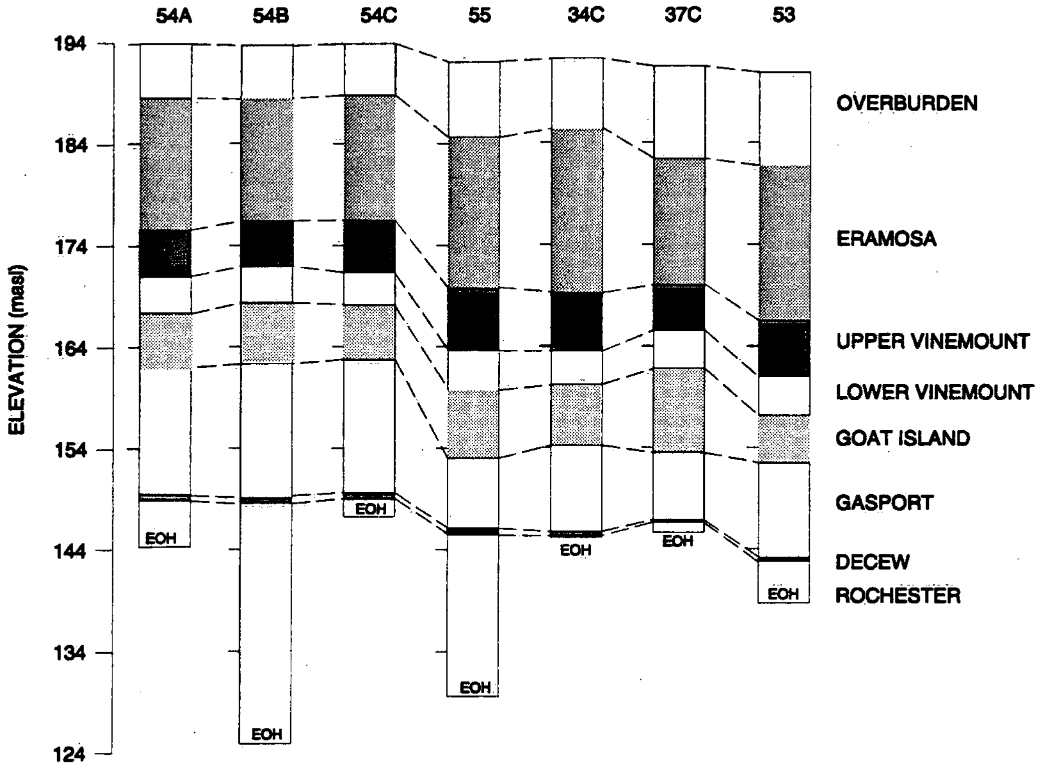

Figure 2. Stratigraphy of new boreholes.

of the borehole recovery, the hole was found to be blocked again. The new blockage was cleared by manually pounding on the obstruction. A blockage around 20 m was found in borehole 34C shortly after completion of drilling. The blockage was cleared by hammering the obstruction to the bottom of the borehole. In both cases it is suspected that incompetent rock caused the blockage. This was verified by 3-arm caliper logs which indicate cavities of up to 25 cm in 34C and 12 cm in 54B (Figures B6 and B3). No problems were encountered in the other boreholes either during well development or hydraulic testing. The competency of the open holes is a significant concern as extensive hydraulic and tracer experiments are planned prior to the installation of permanent instrumentation.

The casing top elevations of the new boreholes were determined by surveying to a site bench mark located at RWS2 (shallow recovery well #2). Horizontal positions were surveyed to centre of road intersections.

A summary of the stratigraphy as determined from the core obtained from the new boreholes is shown in Figure 2. The contacts are based on core only and may be refined slightly when the results of the borehole geophysical surveys are made available. The observed geology is consistent with previous studies (Blair and McFarland, 1990; Golders, 1995). The upper Lockport units dip to the south and are uniform in thickness across the site.

Core Sample Collection:

There are two objectives for the diffusion experiments to be conducted using the core samples obtained during the drilling program: 1) to determine the effective porosity of the unfractured rock, and 2) to determine, for a range of tracers, apparent diffusion coefficients and possible retardation factors. A total of 19 core samples were collected during the drilling of boreholes 54A and 54B. Thirteen samples were obtained from borehole 54A and the remaining 6 from borehole 54B. The samples were kept water saturated and placed under anaerobic conditions immediately following collection. The samples ranged in length from 0.10 m to 0.18 m, were collected at intervals of approximately 3 to 6 m and provide representation from each member of the Lockport Formation, the Decew Formation and the upper unit of the Rochester Formation. Only competent sections of core were sampled. This selection procedure was intended to minimize the potential for sample damage during the preparation required for the diffusion experiments. The protocol for sampling the core is described in Appendix A.

BOREHOLE GEOPHYSICAL SURVEYS

Gartner Lee Ltd. carried out a suite of geophysical logs in the new boreholes. Caliper logs were obtained from each borehole immediately following the completion of drilling. The interpretation of these logs was used to assess the condition of the borehole walls prior to hydraulic testing. Preliminary caliper logs are included in Appendix B. After completion of the drilling program, gamma, inductance, temperature and inclinometer logs were obtained from each borehole. These logs are presently being processed by Gartner Lee Ltd.

ANALYSIS OF VERTICAL FRACTURES

The true orientations of vertical and sub-vertical fractures observed in the drill core were obtained using a geometric method described by Lau (1983). In this approach, the angular relationships between the apparent orientations of the fractures, the plunge and trend of the borehole and a reference line were used to calculate the true attitudes of the fractures. The trend and plunge of each borehole was measured using a Brunton® compass and the reference line was obtained using bedding-plane features observed in the core.

A reference line is required to spatially orient the drill core after it has been recovered from the borehole. A line representing the top of core was selected as the reference line. Assuming the bedding in the rock is approximately horizontal, the top of the core can be determined from the rock core retrieved from an inclined borehole. Argillaceous bands, partings , stylolites or other features parallel to bedding were used to determine bedding. When intersected by an inclined borehole, these features produce an elliptical outline in the core. The two points where the major axis of an ellipse intersects the circumference of the core indicates the top and bottom of the core. The top is easily decerned by orienting the core such that the bedding-plane feature is horizonal.

Once the orientation of the core was determined, the true attitude of each fracture was calculated from two measured angles, α and β (Figure 3). Alpha is the angle between the core axis and the major axis of the ellipse of intersection. Beta is measured from the top of core to the point were the downhole end of the major axis of the ellipse meets the core circumference. This is measured in the plane perpendicular to the core axis and clockwise from top of core when looking in the direction of drilling. Because β is difficult to measure accurately, an arc length along the core circumference was measured instead. The angle β was then calculated in radians from the relation $\beta = L / r$, where L is the arc length and r is the radius of the drill core (22.55 mm). Strike and dip angle for individual fractures were obtained using a FORTRAN program based on the flow chart provided by Lau (1983). The program was verified against data provided by Lau (1983). The strike and dip angle for all the of the 75 vertical or sub-vertical fractures noted in the rock core were determined.

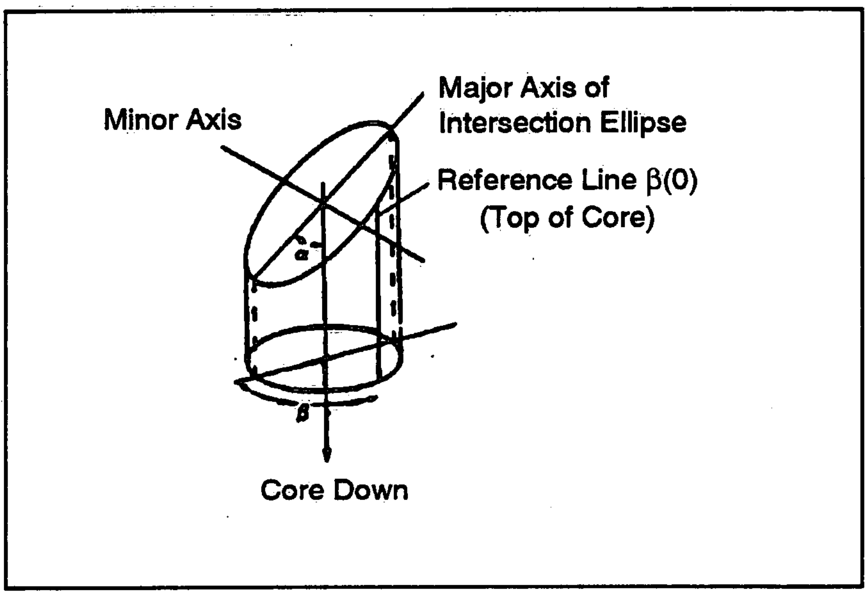

Figure 3. Schematic showing core angles measured to orient vertical fractures (from Lau(1983).

The majority of the vertical and sub-vertical fractures measured are close to vertical with dips greater than 75° (Figure 4). The majority of the fractures measured (77%) were in the Eramosa formation suggesting that the vertical features are concentrated in the shallow bedrock (Figure 5). While very few fractures were noted in the Vinemount units it should be noted that this formation is highly weathered and while discrete vertical fractures are not evident, the vertical permeability of the unit is probably comparable to the horizontal permeability. Detailed hydraulic testing will be

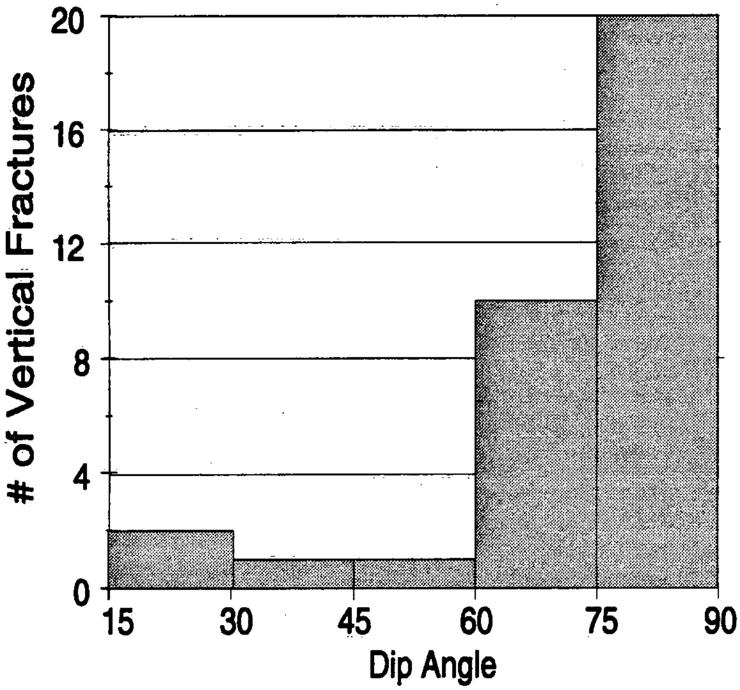

Figure 4. Dip angles of all vertical and sub-vertical fractures measured

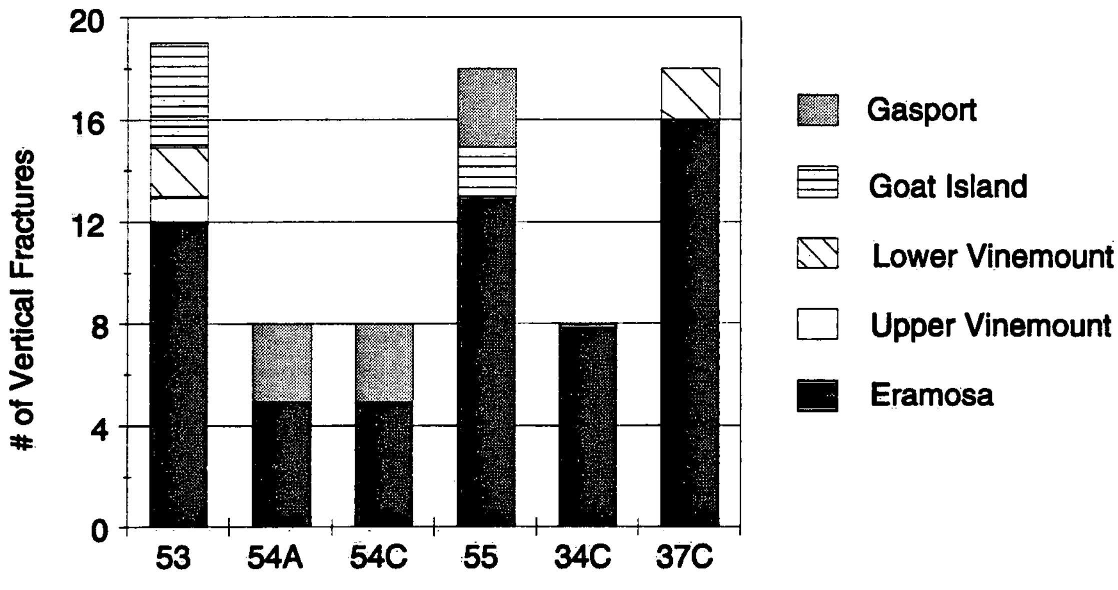

Figure 5. Distribution of vertical and sub-vertical fractures by stratigraphic unit.

conducted to verify this. The lower Vinemount unit is qualitatively more competent than the Upper Vinemount unit. Vertical fractures were noted at depth in the Goat Island and Gasport units in 4 of the 6 boreholes (Figure 5).

Rose diagrams of the strikes of the vertical fractures were constructed for three populations using a ten degree petal width. Figure 6 shows all the vertical fractures from all formations. Major sets are evident at 90-110° and 0-10°. The NW-SE set is diffuse with strikes from 90-160°. The fractures observed in the Eramosa unit alone (Figure 7) show similar major directions. Fractures from the Gasport and Goat Island units show similar sets (Figure 8). There is no obvious trend between the different units. The vertical fracture trends obtained from subsurface drilling differ from those measured in local surface and quarry outcrops but correlate well with regional trends (Gartner and Lee et al., 1995).

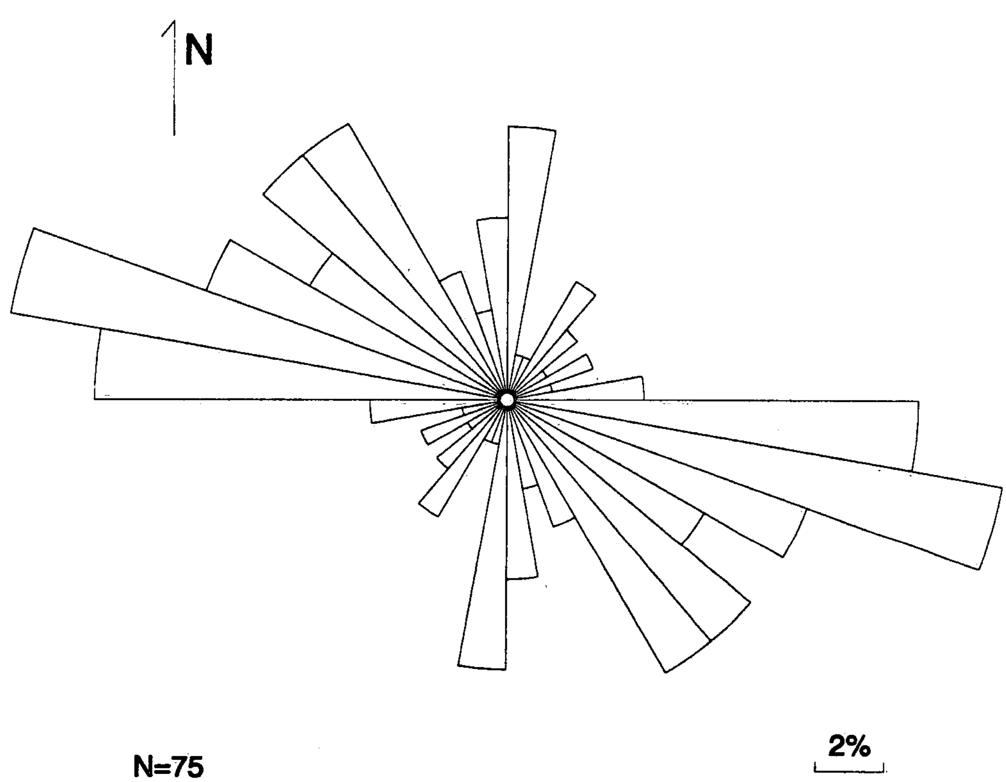

Figure 6. Rose diagram of strikes of all vertical fractures measured.

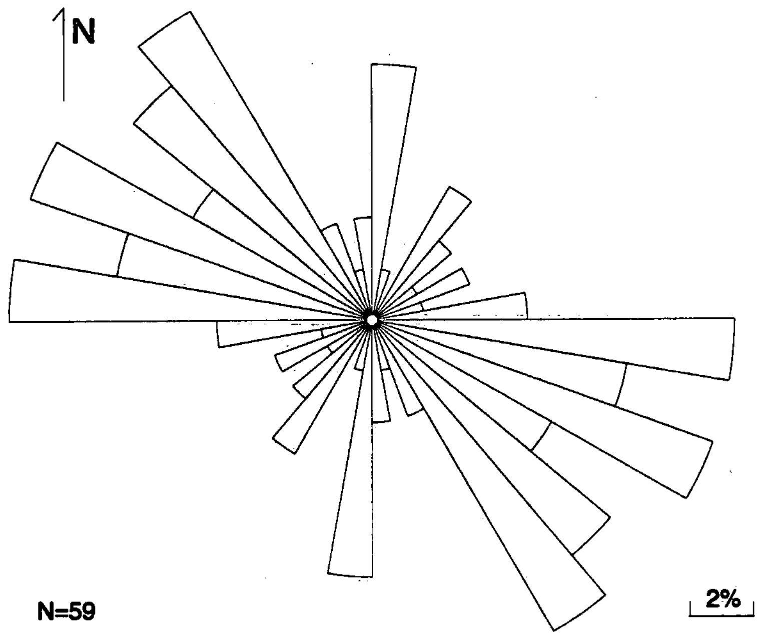

Figure 7. Rose diagram of strikes of all vertical fractures measured in the Eramosa unit.

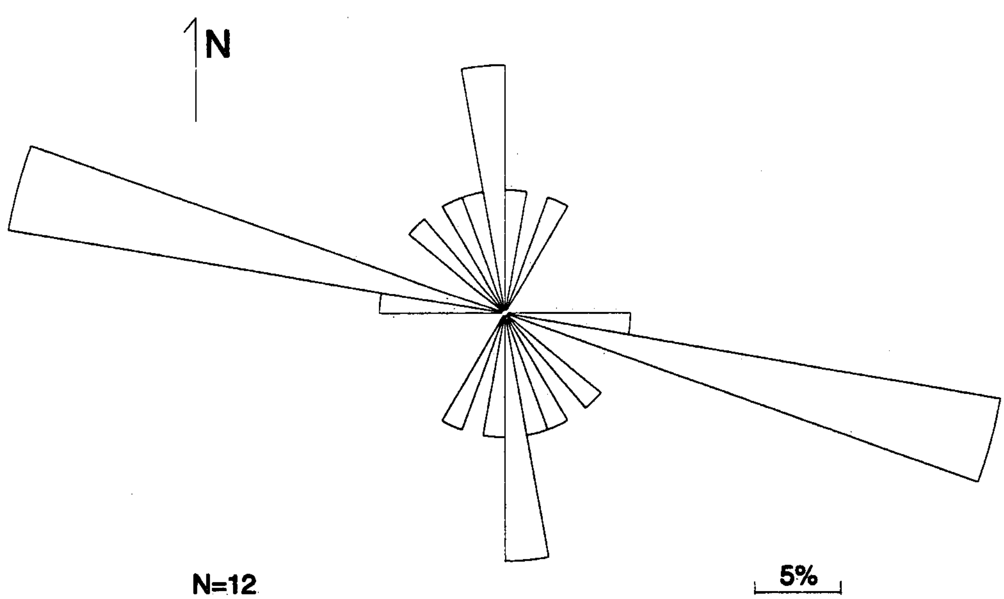

Figure 8. Rose diagram of strikes of all vertical fractures measured in the Goat Island and Gasport units.

HYDRAULIC TESTING

The purpose of the single-well hydraulic tests is to determine the vertical distribution of permeability in the rock mass and identify discrete fractures which contribute to the flow system. Constant-head injection tests were conducted using standard methodology as described by Novakowski (1988) and Lapcevic (1990). The injection tank system used for this study consists of a comprehensive five tank array mounted on a light trailer. Reliable measurements of transmissivity in the range of ~ 10^{-2} to 10^{-10} m^2/s are possible using this system. This is equivalent to a range of hydraulic apertures between 10μm and 2 mm. Hydraulic testing was conducted from the bottom of each hole to the water table using a 2-m packer separation. A single packer was used to test the bottom of the holes. In addition, 32 tests were conducted over the Eramosa and Upper Vinemount units using a 0.5-m test interval in borehole 54A. By December 15, 1995, initial hydraulic testing, using the 2-m test interval, had been completed in five of the seven boreholes. Weather permitting, testing in the remaining two boreholes will be completed by March, 1996.

The results of constant head tests conducted using a 2-m test interval in boreholes 53, 54A, 54C, 55 and 37C are shown in Figures 9 to13 and tabulated in Appendix C. Transmissivity ranges from below detection limit (approximately 1 x 10^{-10} m^2/s) to the upper detection limit (10^{-2} m^2/s). Measured transmissivities in the Eramosa and Upper Vinemount Units range between 10^{-6} and 10^{-2} m^2/s. In borehole 37C a 2-m zone of transmissivity > 10^{-2} m^2/s was measured (Figure 13). A 2-m zone of low permeability rock at the top of the Lower Vinemount can be correlated across the site (Figure 14). The presence of vertical fractures through this low permeability bed was not observed in the drill core. The Lower Vinemount / Goat Island is noticeably more permeable to the north of the site (54A and 54C) and at 37C and less permeable in boreholes 53 and 55. The Gasport unit exhibits a range of transmissivity between 10^{-8} and 10^{-2} m^2/s with a 4-m zone that can be correlated across the site (Figure 14). This feature is a discrete fracture zone of significant lateral extent. It is most permeable at 37C with a transmissivity of 8 x 10^{-3} m^2/s (Figure 13). It is important to note that the general degree of fracturing and presence of high permeability fractures is only marginally different between the upper and lower Lockport formation. Other correlations will become more evident with the completion of shorter (0.1-0.5 m) packer spacing tests. Borehole 55 intersects over 10 m of Rochester Shale. Constant- head tests conducted in the Rochester formation in this borehole were found to be below the detection limit suggesting that the shale is of very low permeability (< 10^{-10} m^2/s) (Figure 12). One zone of higher transmissivity in the Rochester shale (~ 10^{-7}) was measured in borehole 53 (Figure 9). In summary, the preliminary results of the hydraulic testing program which was conducted using 2-m test intervals show a heterogeneous system with transmissive features found at all depths in the Lockport Formation.

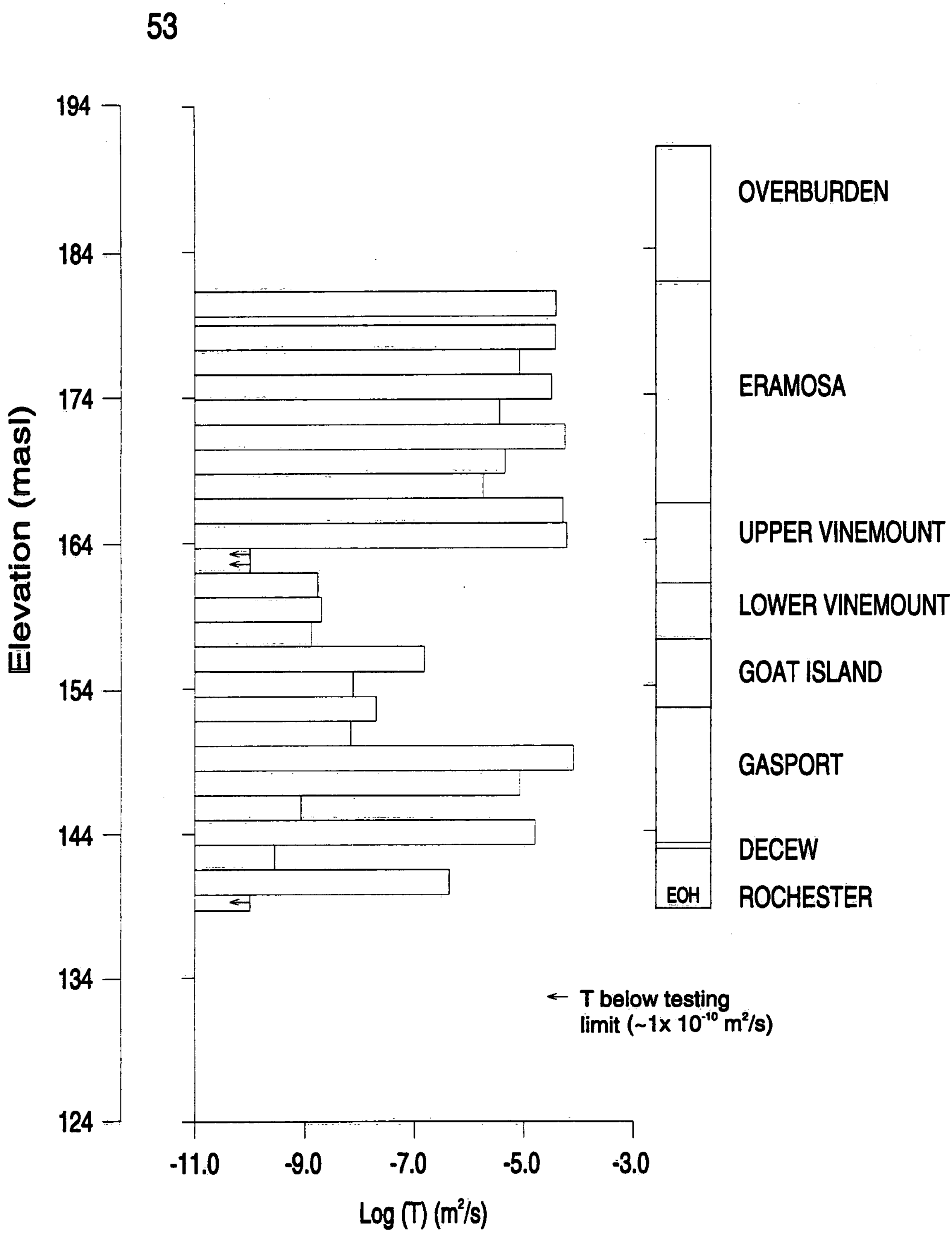

Figure 9. Results of 2-m constant-head injection tests in borehole 53.

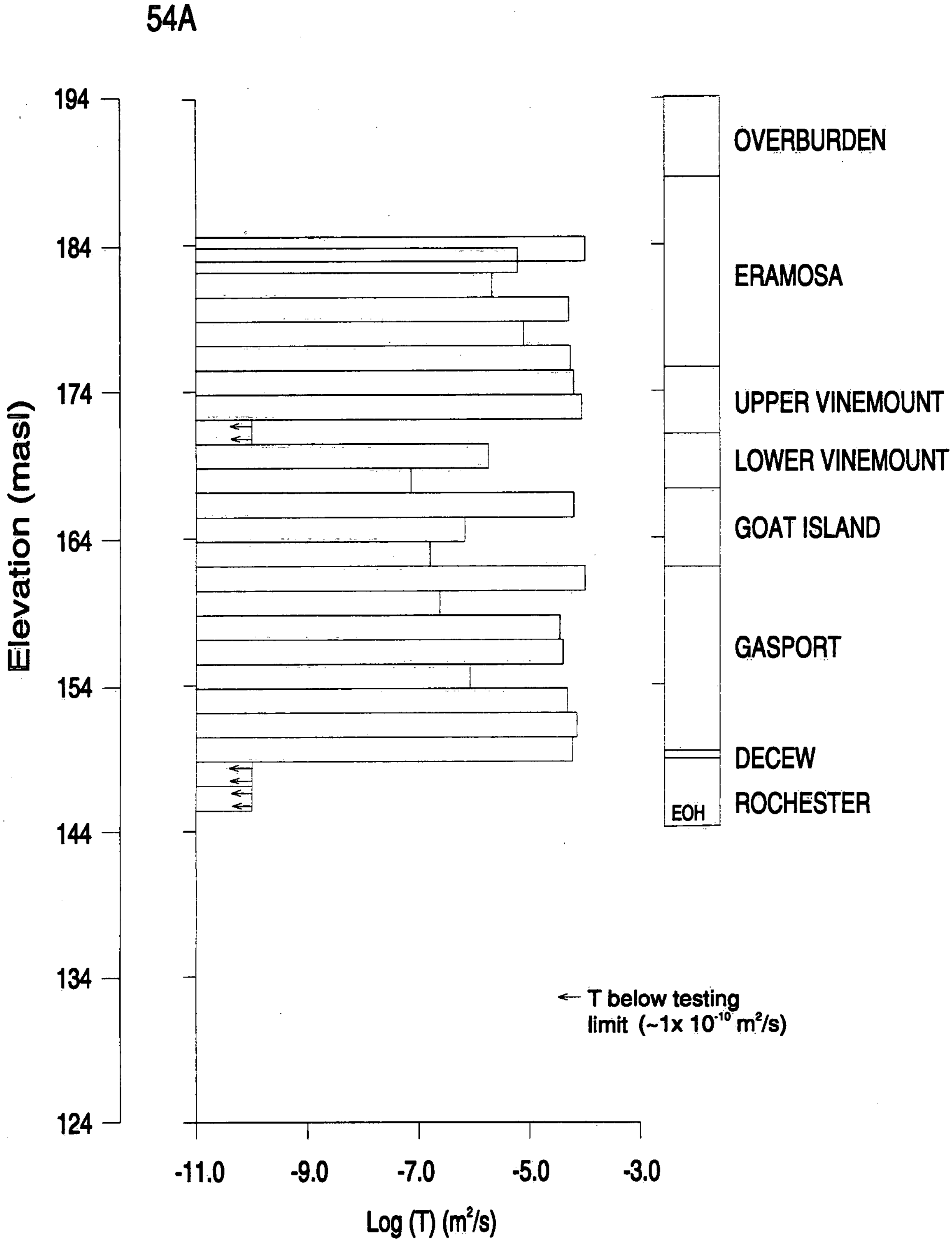

Figure 10. Results of 2-m constant-head injection tests in borehole 54A.

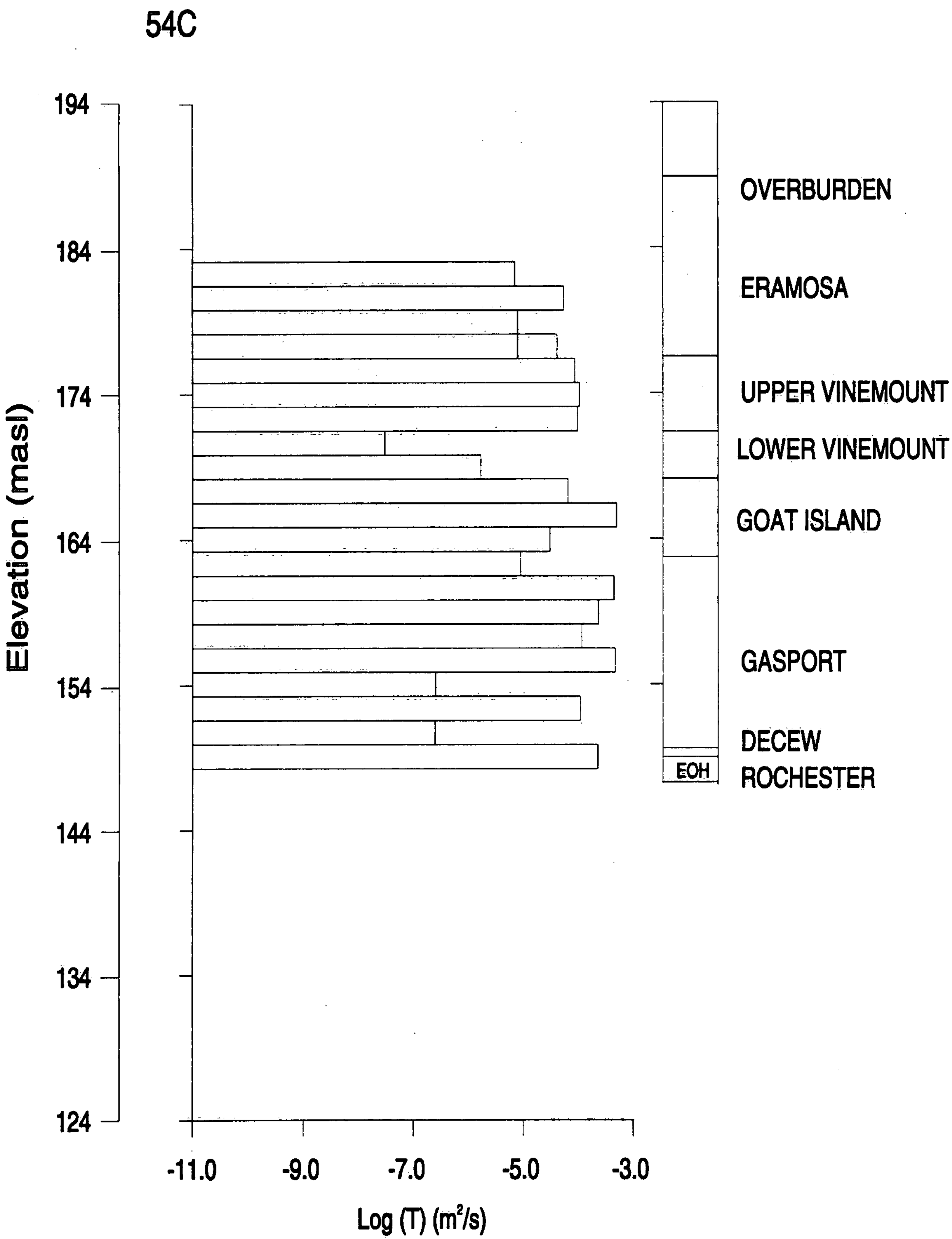

Figure 11. Results of 2-m constant-head injection tests in borehole 54C.

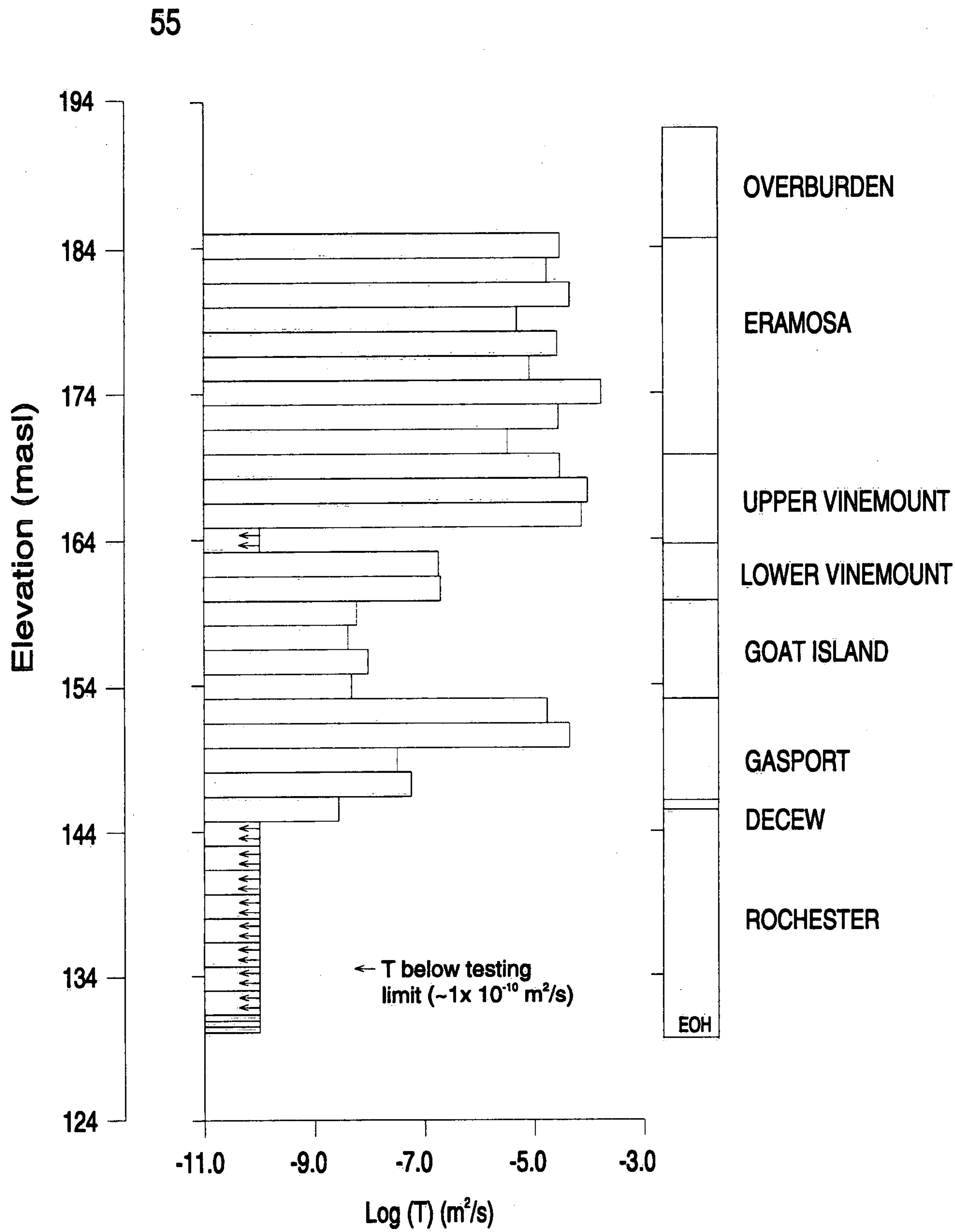

Figure 12. Results of 2-m constant-head injection tests in borehole 55.

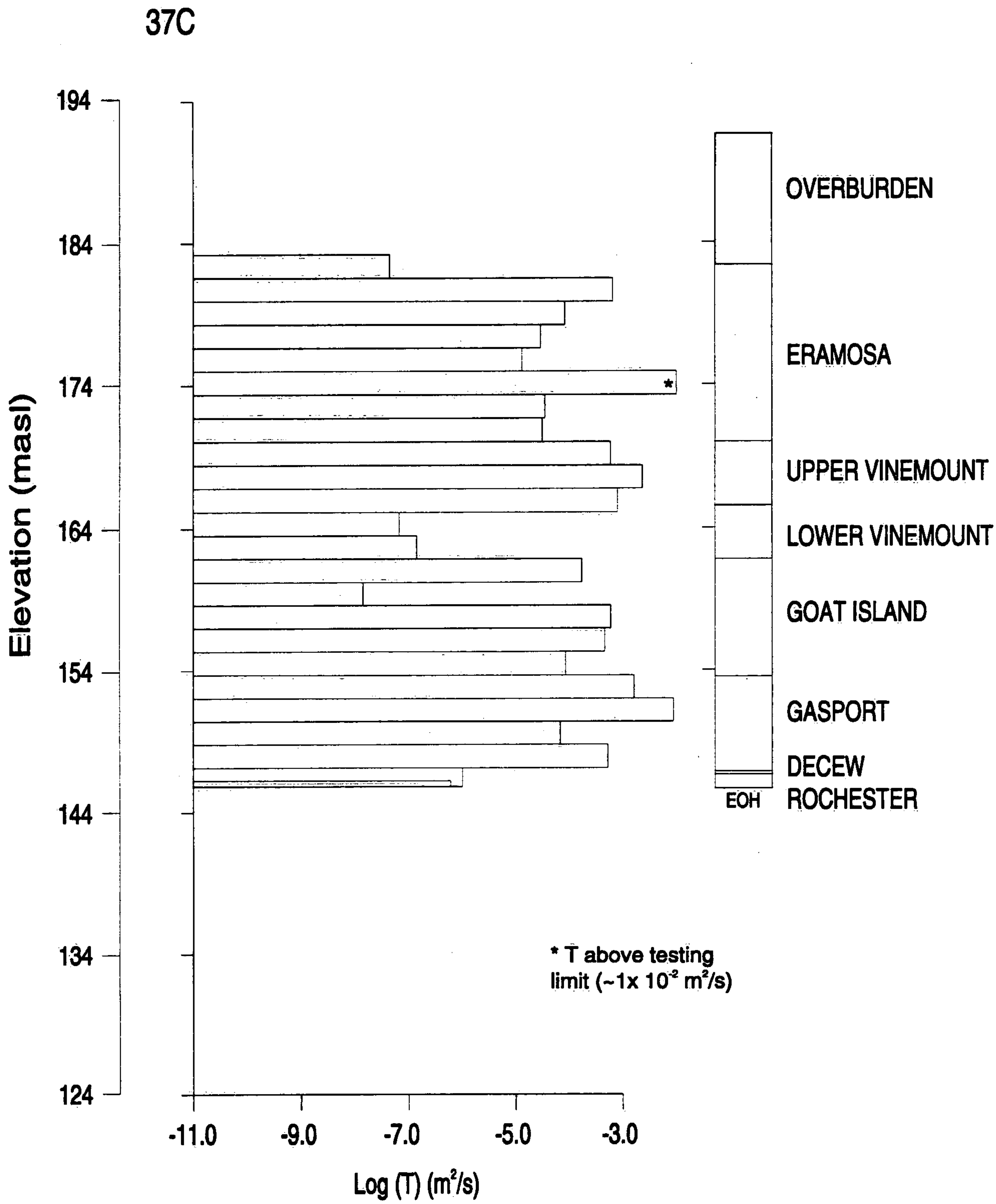

Figure 13. Results of 2-m constant-head injection tests in borehole 37C.

The results of the hydraulic tests conducted using a 0.5-m test interval in borehole 54A are compared to the results from 2.0-m tests and to the core logs in Figure 15. The Upper Vinemount unit is highly fractured and characterized by 1.5 m of uniformly high transmissivity, 14 fractures and numerous broken core zones (Figure 15). The Eramosa unit is characterized by a greater variation in transmissivity and fewer distinct bedding plane fractures. Zones of higher transmissivity correlate to 1-2 fractures noted in the core. It is important to note that the two most transmissive zones (~ 180 masl and 177 masl) are associated with vertical fractures.

PLANNED ACTIVITIES

The results presented in this progress report are preliminary in nature. Prior to presenting a conceptual model we are planning on continuing studies of the core and further hydraulic testing. This work includes:

(1) Re-examination of the rock core in all boreholes with a particular emphasis placed on investigation of the open bedding plane fractures.
(2) Completion of the 2-m constant head injection tests in boreholes 34C and 54B.
(3) Conduct constant-head injection tests using 0.5-m test intervals on selected intervals in all boreholes
(4) Conduct hydraulic tests over selected intervals using a 0.1-m packer separation.
(5) Conduct laboratory experiments to determine the diffusive properties of the rock matrix.
(6) Conduct point dilution experiments to determine in-situ velocities.
(7) Conduct preliminary hydraulic interference tests (ie. pulse and pumping tests) to determine the interconnectivity of identified discrete fractures and fracture zones.
(8) Incorporate results of borehole geophysics into geological and fracture conceptual models.
(9) Sample borehole 55 at specific fracture locations for the presence of volatile organic compounds.
(10) Prepare preliminary hydrogeological conceptual model.

ACKNOWLEDGEMENTS

The assistance of M. Hilverda, C. Talbot, and E. Walker on many aspects of this project is gratefully acknowledged. We also thank the Smithville Phase IV staff for their assistance in the field.

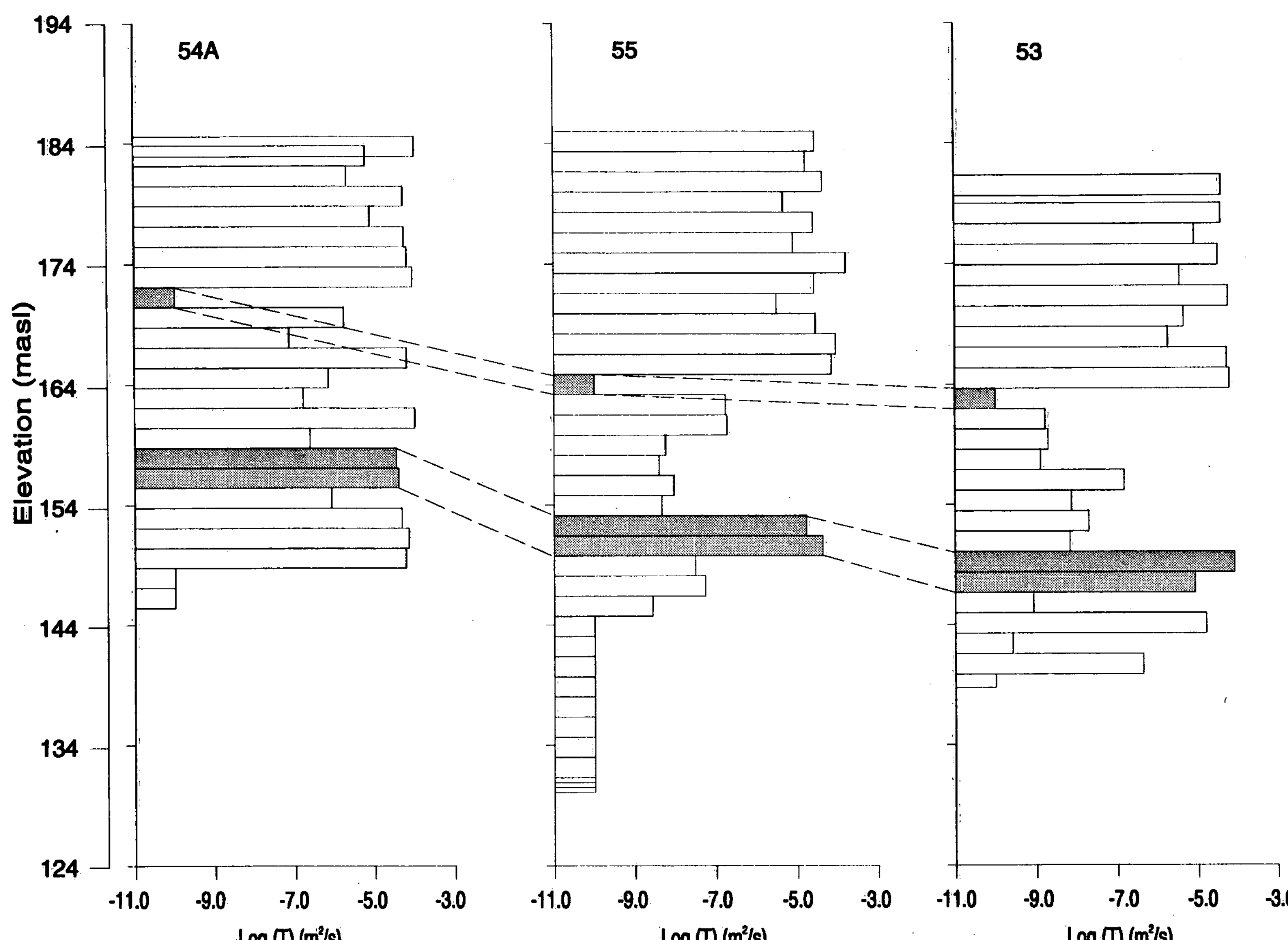

Figure 14. Comparison of transmissivity profiles across site (N to S).

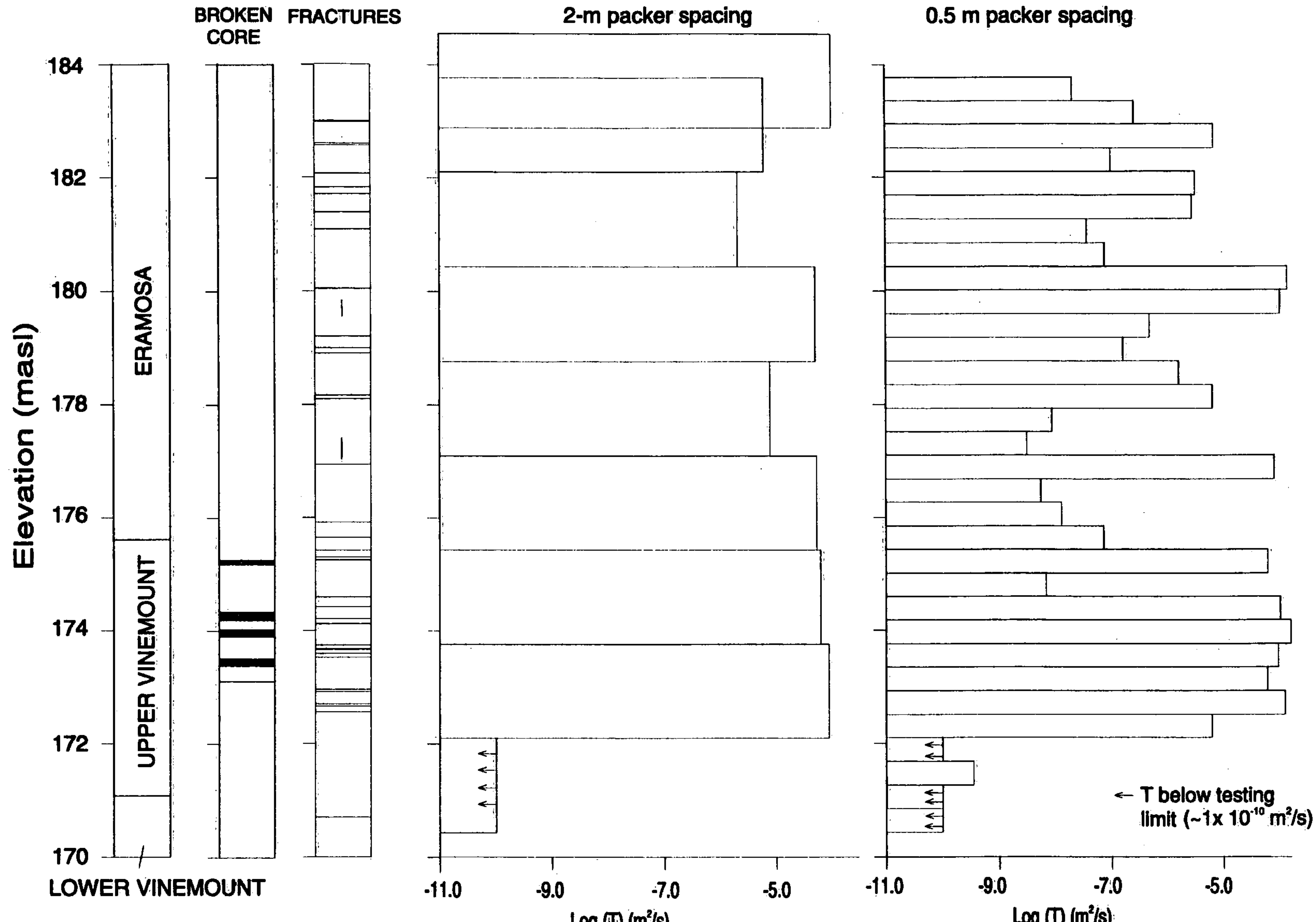

Figure 15. Lithology, fractures, 2-m and 0.5-m constant-head injection tests in borehole 54A.

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APPENDIX A

Description of core sampling protocol

Description of Core Sampling Protocol:

Within approximately 5 minutes of recovering the rock from the core barrel, samples were placed in a 1 L Nalgene® bottle filled with local groundwater from wells 52D and 52S. This procedure insured the core samples remained saturated. The groundwater was pre-treated with sodium azide (0.03-0.04% w/w) to inhibit bacterial growth during the storage of the samples. Within 24 hours prior to sampling, argon was bubbled through the water in each Nalgene® bottle for a minimum of 15 minutes in order to remove the dissolved oxygen. The bottles were then capped until required for sampling. Immediately after a sample was deposited in the Nalgene® bottle, the bottle was recapped and then placed inside a GasPak® anaerobic system. Before the lid was sealed on the system, a GasPak® disposable gas generator envelope was placed inside. Approximately 10 mL of groundwater was then added to the envelope with a syringe to initiate the generation of hydrogen and carbon dioxide. A BBL® dry anaerobic indicator strip was then taped inside the anaerobic system and the lid (with attached palladium catalyst) was then sealed in place. Within twenty-five minutes, water began to condense on the inside of the anaerobic system, indicating that oxygen was being consumed. The indicator strips confirmed the presence of anaerobic conditions within 3 hours. Note that the reaction involved in producing the colour change on the indicator strip requires several hours in an anaerobic environment. At the end of each day, the samples were transported to the National Water Research Institute for longer term storage in an anaerobic glove box.

APPENDIX B

Caliper logs (Draft only)

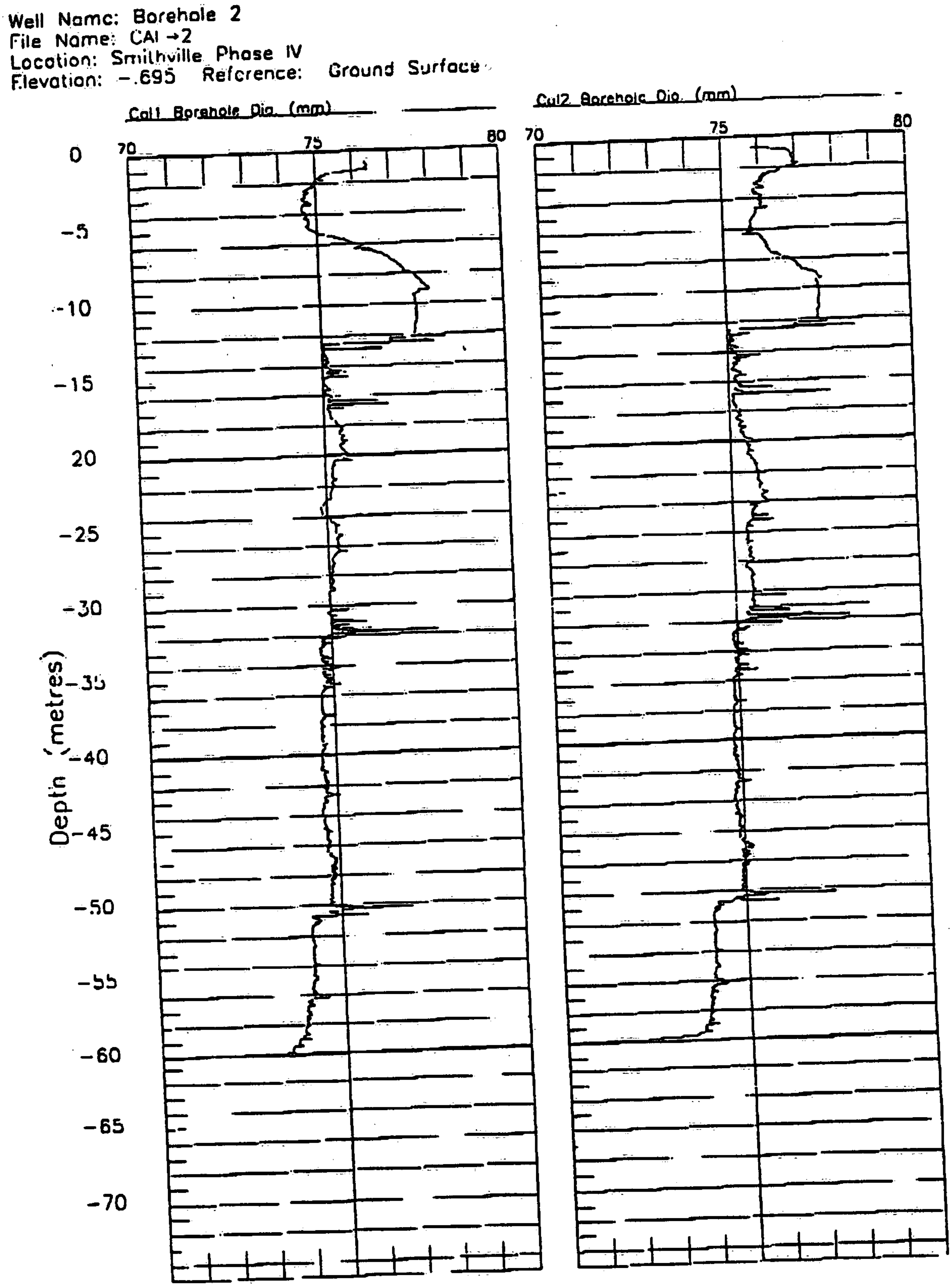

Figure B1: Caliper log for borehole 53.

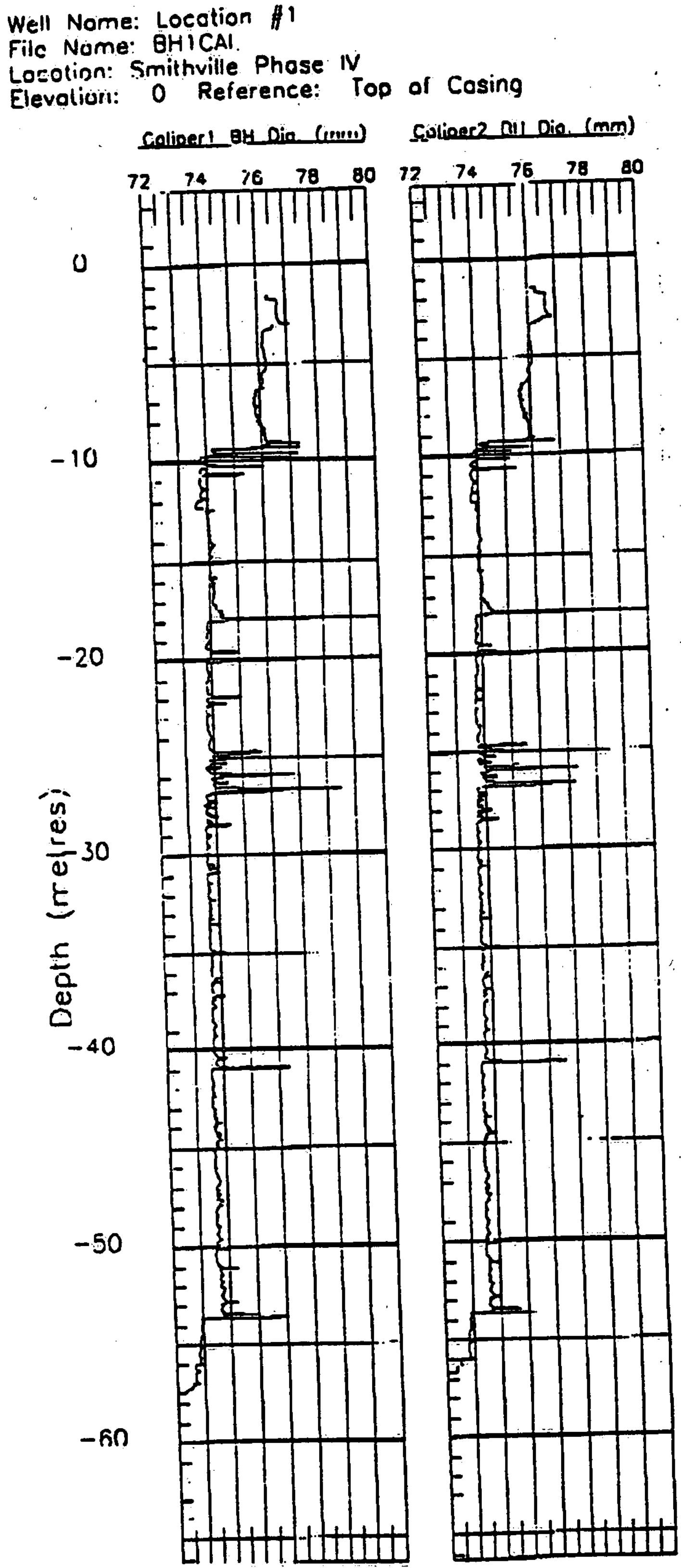

Figure B2: Caliper log for borehole 54A.

Well Name: 54B
File Name: CAL54B
Location: Smithville Phase IV
Elevation: 0 Reference: Top of Pipe

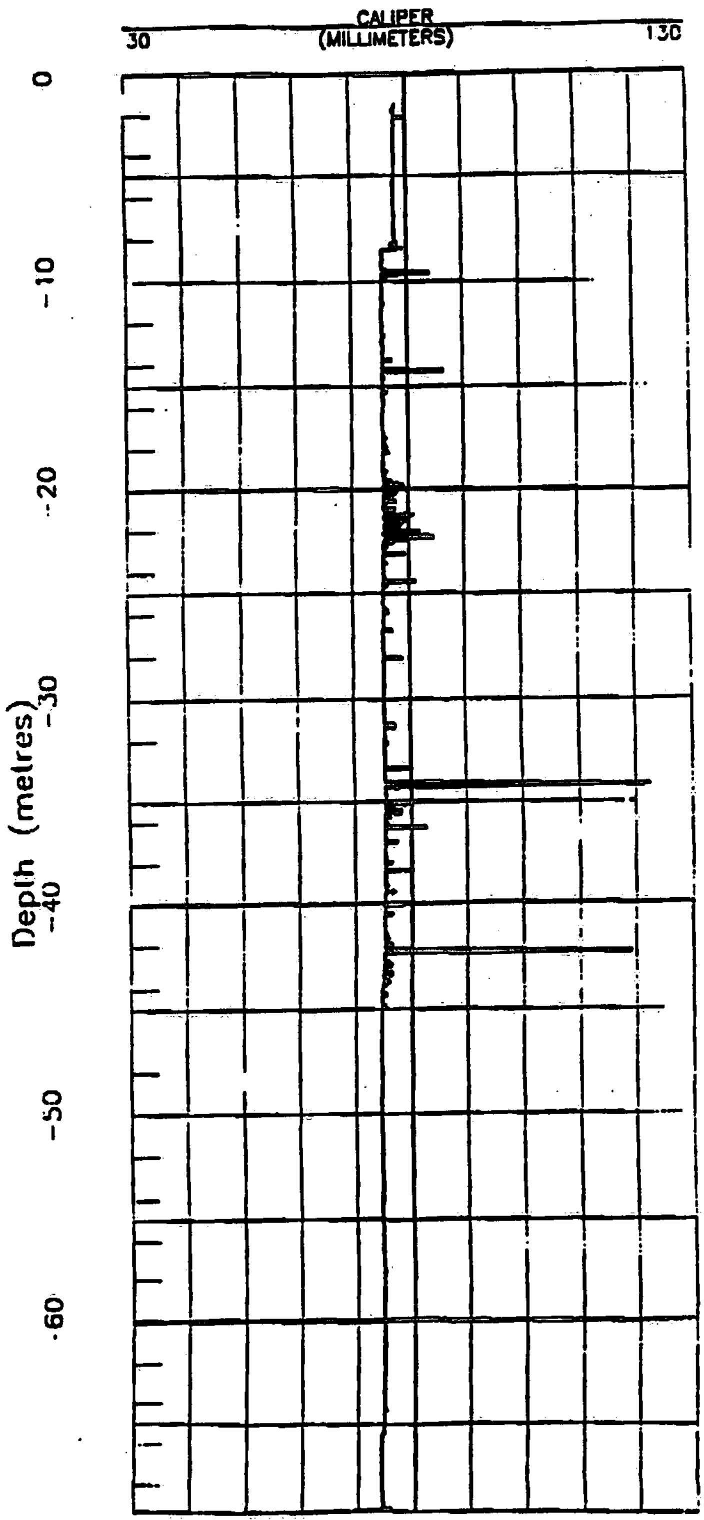

Figure B3: Caliper log for borehole 54B.

Well Name: Borehole 57
File Name: 57CAL
Location: Smithville Phase IV
Elevation: 0 Reference: Top of Casing

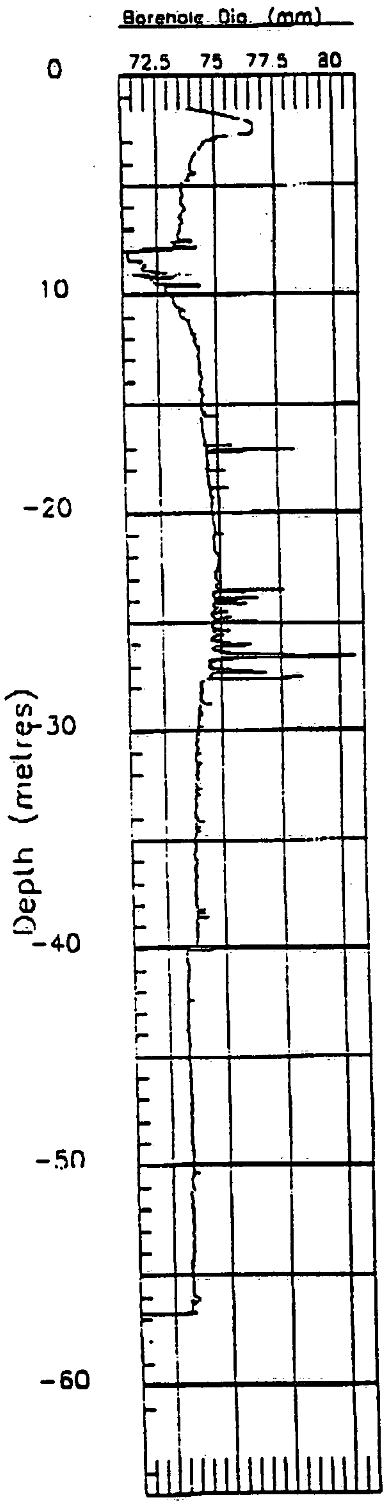

Figure B4: Caliper log for borehole 54C.

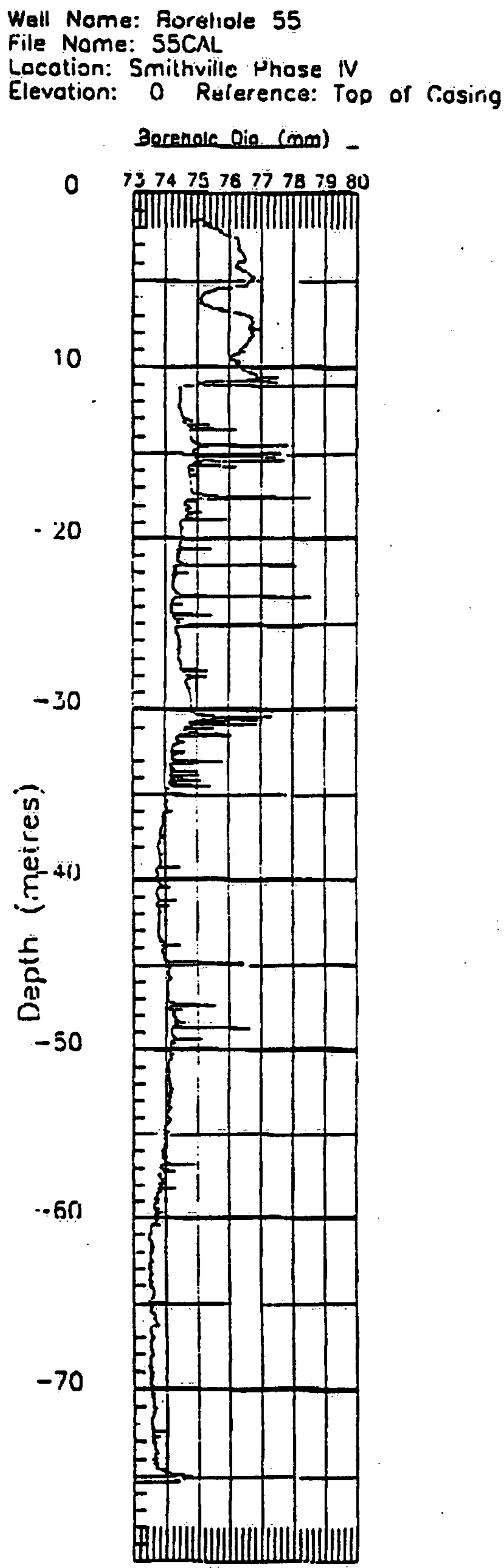

Figure B5: Caliper log for borehole 55.

Well Name: Borehole 34C
File Name: 34C-ALL
Location: Smithville Phase IV
Elevation: 0 Reference: Top of Pipe (0.61 m stickup added prior to logging)

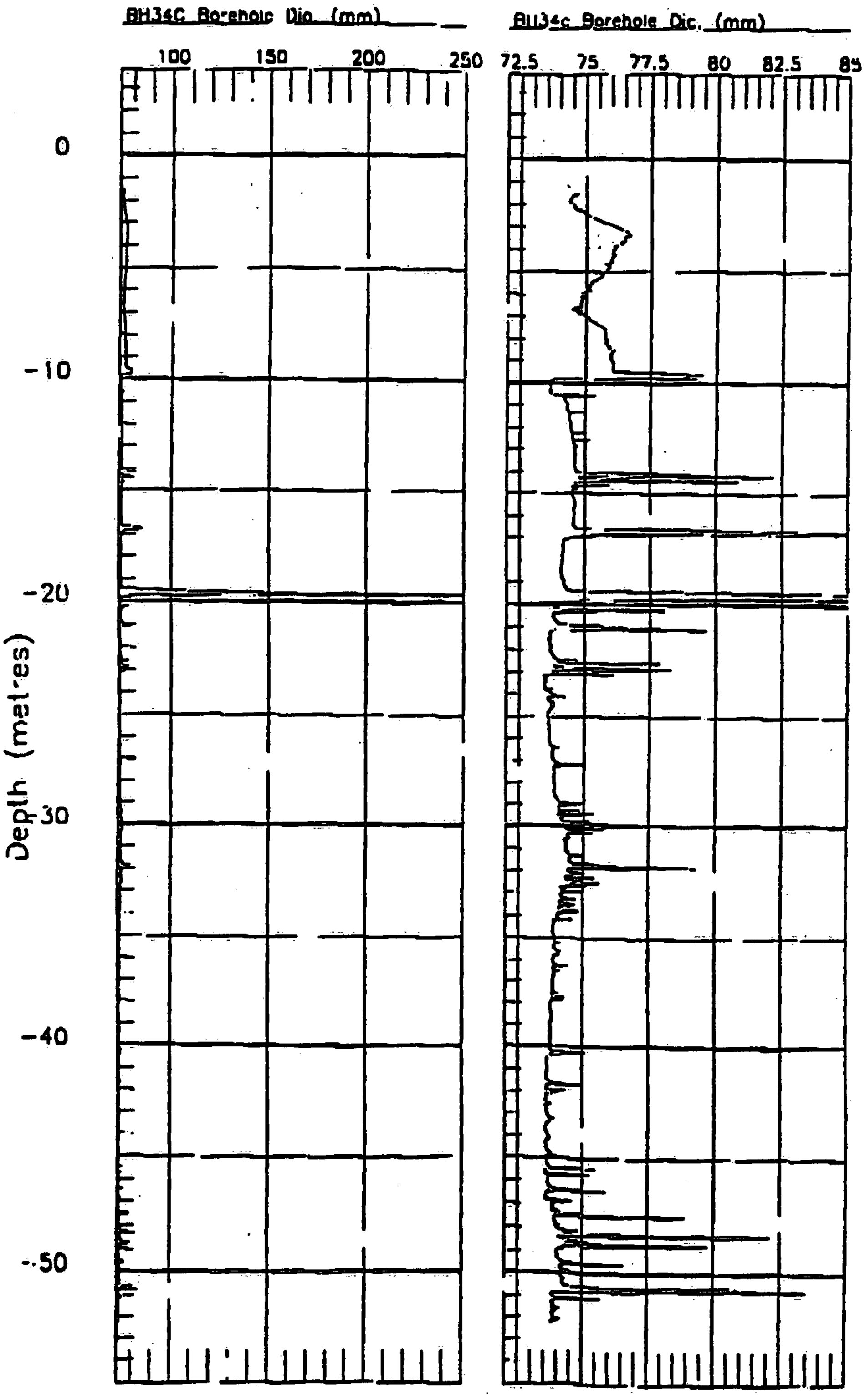

Figure B6: Caliper log for borehole 34C.

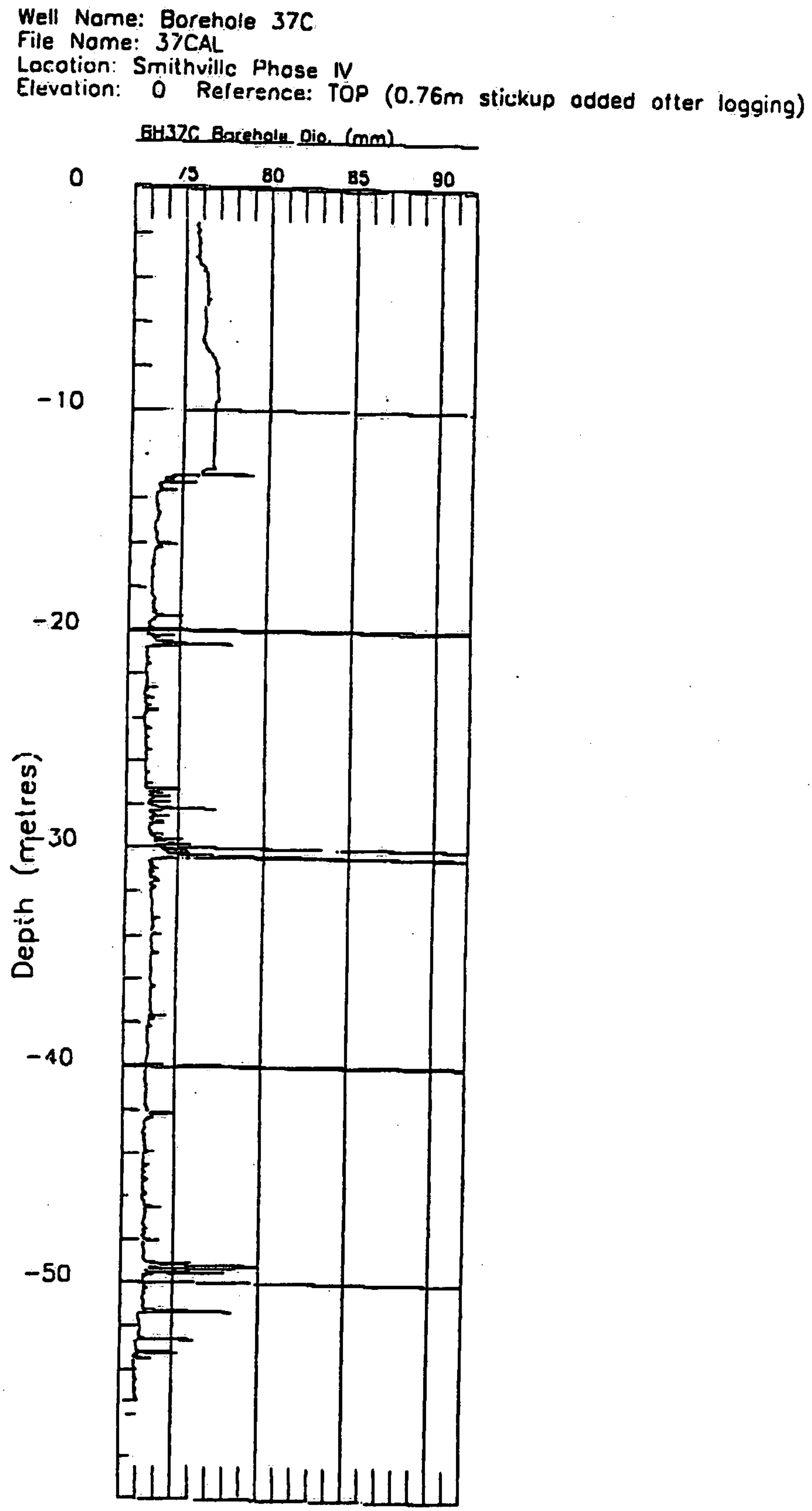

Figure B7: Caliper log for borehole 37C.

APPENDIX C

Results of 2-m constant-head injection tests

Table C1. Results of 2-m constant-head injection tests in borehole 53.

Test #	Depth (mbct)		Elevation (masl)		T (m^2/s)
27	61.92	63.26	139.83	138.71	<1e-10
1	59.89	61.92	141.54	139.83	4e-07
2	57.86	59.89	143.24	141.54	3e-10
3	55.83	57.86	144.94	143.24	2e-05
4	53.80	55.83	146.64	144.94	8e-10
5	51.77	53.80	148.35	146.64	8e-06
6	49.74	51.77	150.05	148.35	8e-05
7	47.71	49.74	151.75	150.05	7e-09
9	45.68	47.71	153.45	151.75	2e-08
10	43.65	45.68	155.16	153.45	7e-09
11	41.62	43.65	156.86	155.16	2e-07
13	39.59	41.62	158.56	156.86	1e-09
14	37.56	39.59	160.26	158.56	2e-09
15	35.56	37.59	161.94	160.24	2e-09
16	33.53	35.56	163.64	161.94	<1e-10
17	31.50	33.53	165.34	163.64	6e-05
18	29.47	31.50	167.05	165.34	5e-05
19	27.44	29.47	168.75	167.05	2e-06
20	25.41	27.44	170.45	168.75	5e-06
21	23.38	25.41	172.15	170.45	6e-05
22	21.35	23.38	173.86	172.15	4e-06
23	19.32	21.35	175.56	173.86	3e-05
24	17.29	19.32	177.26	175.56	8e-06
25	15.26	17.29	178.96	177.26	4e-05
26	12.50	14.53	181.28	179.58	4e-05

Table C2. Results of 2-m constant-head injection tests in borehole 54A.

Test #	Depth (mbct)		Elevation (masl)		T (m^2/s)
3	57.39	59.39	147.08	145.41	<1e-10
4	55.39	57.39	148.75	147.08	<1e-10
5	53.39	55.39	150.41	148.75	6e-05
6	51.39	53.39	152.08	150.41	7e-05
9	49.39	51.39	153.75	152.08	5e-05
10	47.39	49.39	155.42	153.75	8e-07
11	45.39	47.39	157.09	155.42	4e-05
12	43.39	45.39	158.75	157.09	3e-05
13	41.39	43.39	160.42	158.75	2e-07
18	39.39	41.39	162.09	160.42	1e-04
19	37.39	39.39	163.76	162.09	2e-07
20	35.39	37.39	165.42	163.76	7e-07
21	33.39	35.39	167.09	165.42	6e-05
22	31.39	33.39	168.76	167.09	7e-08
23	29.39	31.39	170.43	168.76	2e-06
24	27.39	29.39	172.10	170.43	<1e-10
25	25.39	27.39	173.76	172.10	9e-05
26	23.39	25.39	175.43	173.76	6e-05
27	21.39	23.39	177.10	175.43	5e-05
28	19.39	21.39	178.77	177.10	8e-06
29	17.39	19.39	180.43	178.77	5e-05
30	15.39	17.39	182.10	180.43	2e-06
31	13.39	15.39	183.77	182.10	6e-06
32	12.46	14.46	184.55	182.88	1e-04

Table C3. Results of 2-m constant-head injection tests in borehole 54C.

Test #	Depth (mbct)		Elevation (masl)		T (m^2/s)
4	54.00	56.00	149.91	148.25	2e-04
5	52.00	54.00	151.57	149.91	2e-07
6	50.00	52.00	153.23	151.57	1e-04
7	48.00	50.00	154.89	153.23	2e-07
8	46.00	48.00	156.55	154.89	5e-04
9	44.00	46.00	158.20	156.55	1e-04
10	42.00	44.00	159.86	158.20	2e-04
11	40.00	42.00	161.52	159.86	4e-04
12	38.00	40.00	163.18	161.52	9e-06
13	36.00	38.00	164.84	163.18	3e-05
14	34.00	36.00	166.49	164.84	5e-04
15	32.00	34.00	168.15	166.49	6e-05
16	30.00	32.00	169.81	168.15	2e-06
17	28.00	30.00	171.47	169.81	3e-08
18	26.00	28.00	173.13	171.47	1e-04
19	24.00	26.00	174.78	173.13	1e-04
20	22.00	24.00	176.44	174.78	8e-05
21	20.00	22.00	178.10	176.44	4e-05
22	18.00	20.00	179.76	178.10	8e-06
23	16.00	18.00	181.42	179.76	5e-05
24	14.00	16.00	183.07	181.42	7e-06
25	12.00	14.00	184.73	183.07	1e-05

Table C4. Results of 2-m constant-head injection tests in borehole 55.

Test #	Depth (mbct)		Elevation (masl)		T (m^2/s)
1	74.46	74.96	130.48	130.06	<1e-10
2	74.00	74.96	130.87	130.06	<1e-10
3	73.50	74.96	131.29	130.06	<1e-10
4	71.50	73.50	132.96	131.29	<1e-10
5	69.50	71.50	134.64	132.96	<1e-10
6	67.50	69.50	136.32	134.64	<1e-10
7	65.50	67.50	138.00	136.32	<1e-10
8	63.50	65.50	139.67	138.00	<1e-10
9	61.50	63.50	141.35	139.67	<1e-10
10	59.50	61.50	143.03	141.35	<1e-10
11	57.50	59.50	144.71	143.03	<1e-10
12	55.50	57.50	146.38	144.71	3e-09
13	53.50	55.50	148.06	146.38	6e-08
14	51.50	53.50	149.74	148.06	3e-08
15	49.50	51.50	151.41	149.74	4e-05
16	47.50	49.50	153.09	151.41	2e-05
17	45.50	47.50	154.77	153.09	5e-09
18	43.50	45.50	156.45	154.77	9e-09
19	41.50	43.50	158.12	156.45	4e-09
20	39.50	41.50	159.80	158.12	6e-09
21	37.50	39.50	161.48	159.80	2e-07
22	35.50	37.50	163.16	161.48	2e-07
23	33.50	35.50	164.83	163.16	<1e-10
24	31.50	33.50	166.51	164.83	7e-05
25	29.50	31.50	168.19	166.51	9e-05
26	27.50	29.50	169.87	168.19	3e-05
27	25.50	27.50	171.54	169.87	3e-06
28	23.50	25.50	173.22	171.54	3e-05
29	21.50	23.50	174.90	173.22	2e-04
30	19.50	21.50	176.57	174.90	8e-06
31	17.50	19.50	178.25	176.57	3e-05
32	15.50	17.50	179.93	178.25	5e-06
33	13.50	15.50	181.61	179.93	4e-05
34	11.50	13.50	183.28	181.61	2e-05
35	9.50	11.50	184.96	183.28	3e-05

Table C5. Results of 2-m constant-head injection tests in borehole 37C.

Test #	Depth (mbct)		Elevation (masl)		T (m^2/s)
1	56.11	56.61	146.23	145.82	6e-07
2	55.00	56.61	147.14	145.82	1e-06
3	53.00	55.00	148.78	147.14	5e-04
4	51.00	53.00	150.42	148.78	7e-05
5	49.00	51.00	152.06	150.42	9e-03
6	47.00	49.00	153.69	152.06	2e-03
7	45.00	47.00	155.33	153.69	8e-05
8	43.00	45.00	156.97	155.33	5e-04
9	41.00	43.00	158.61	156.97	6e-04
10	39.00	41.00	160.25	158.61	1e-08
11	37.00	39.00	161.89	160.25	2e-04
12	35.00	37.00	163.52	161.89	1e-07
13	33.00	35.00	165.16	163.52	7e-08
14	31.00	33.00	166.80	165.16	8e-04
15	29.00	31.00	168.44	166.80	2e-03
16	27.00	29.00	170.08	168.44	6e-04
17	25.00	27.00	171.72	170.08	3e-05
18	23.00	25.00	173.35	171.72	4e-05
19	21.00	23.00	174.99	173.35	>1e-02
20	19.00	21.00	176.63	174.99	1e-05
21	17.00	19.00	178.27	176.63	3e-05
22	15.00	17.00	179.91	178.27	8e-05
23	13.00	15.00	181.55	179.91	7e-04
24	11.00	13.00	183.18	181.55	4e-08

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