RRB-89-44

THE USE OF SHORT PACKER SPACINGS TO CHARACTERIZE HYDRAULICALLY OPEN FRACTURES IN THE LOCKPORT FORMATION, NIAGARA FALLS, NEW YORK

by

P.A. Lapcevic and K.S. Novakowski

National Water Research Institute
Canada Centre for Inland Waters
Burlington, Ontario, L7R 4A6

June 1989
NWRI Contribution #89-144

ABSTRACT

Two boreholes which were drilled in Niagara Falls, New York, were used to examine the nature of fracturing and fracture permeability in flat-lying sedimentary rock. The boreholes were drilled in the vertical orientation, through the entire length of the Lockport formation, a highly permeable Silurian dolostone. The study was conducted in cooperation with the U.S. Geological Survey as part of their ongoing study of the regional groundwater flow system in the Niagara Falls, New York region. Fracture permeability was determined using the constant-head injection method. An initial set of tests using a 2-m test interval was conducted to characterize the transmissivity along the entire depth of each borehole (a total of 34 tests) and identify high permeability zones. A second set of tests was conducted on selected higher permeability zones to identify and characterize specific hydraulically open fractures, if any. A 0.50-0.60 m test interval was used for these tests with up to 45 cm overlap of adjacent test zones allowing identification of fracture intersections to within 0.05 m in some cases. In zones where the predominance of the permeability is due to fractures, fracture aperture width was also calculated. The results of the constant-head injection tests were compared to borehole acoustic televiewer (BAT) logs and fracture logs obtained from core examination.

The results show that the bulk of the permeability in the Lockport dolostone is due to relatively few fractures. The vertical

distribution of transmissivity ranges from $<1x10^{-10}$ to $2x10^{-4}$ m^2/s. Transmissivities in zones with no observable fractures ranged from $<1x10^{-10}$ to $7x10^{-8}$ m^2/s, suggesting a relatively hetereogeneous rock matrix. Comparison of the hydraulic test results to fracture and BAT logs showed good correlation between the different methods with respect to determining the location of the fracture intersections. While BAT logs can be used to determine the location of potential permeable features, no indication of the magnitude of the transmissivity of the fracture or nature of the matrix permeability are determined. Hydraulic testing is therefore essential for characterizing permeable features in fractured rock.

RESUMÉ

Deux trous forés à Niagara Falls dans l'État de New York ont permis d'examiner la nature et la perméabilité des fractures présentes dans les roches sédimentaires horizontales. Les trous, forés à la verticale, traversent toute la formation de Lockport, dolomie très perméable du Silurien. Cette étude a été réalisée en collaboration avec le U.S. Geological Survey dans le cadre de l'étude permanente du système d'écoulement des eaux souterraines que mène celle-ci dans la région de Niagara Falls. La perméabilité attribuable aux fractures a été déterminée à l'aide de la méthode d'injection à pression constante. Une première série d'essais, (34 au total) réalisés à intervalles de 2 m, a servi à déterminer les caractéristiques de la transmissivité sur toute la longueur du trou de sondage et à cerner les zones à perméabilité élevée. Une deuxième série d'essais a été effectuée sur certaines des zones à forte perméabilité dans le but de découvrir les éventuelles fractures ouvertes par force hydraulique et d'en définir les caractéristiques. Pour ces essais, un intervalle de 0,50-0,60 m (le chevauchement des zones d'essais atteignant parfois 45 cm) a été utilisé, ce qui a permis de trouver les intersections des fractures avec une précision de 0,05 m dans certains cas. Dans les zones où la majeure partie de la perméabilité est attribuable aux fractures, la largeur de l'ouverture des fractures a également été mesurée. Les résultats des essais d'injection à pression constante ont été comparés aux diagraphies réalisées à l'aide d'une sonde de

reconstitution acoustique et aux diagraphies de fractures obtenues après examen des carottes prélevées.

Les résultats montrent que la majeure partie de la perméabilité dans la dolomie de Lockport est attribuable à un nombre relativement restreint de fractures. La distribution verticale de la transmissivité varie de $<1X10^{-10}$ à $2X10^{-4}$ m^2/s. Les transmissivités dans les zones où aucune fracture n'a été observée variaient de $<1X10^{-10}$ à $7X10^{-8}$ m^2/s, reflétant peut-être la présence d'une roche relativement hétérogène. La comparaison des résultats des essais hydrauliques et des diagraphies de fractures et diagraphies obtenues par sonde de reconstitution acoustique a montré que les diverses méthodes permettaient de déterminer sensiblement de la même façon l'emplacement des intersections de fractures. Bien que les diagraphies obtenues par sonde de reconstitution acoustique puissent servir à déterminer l'emplacement des éléments potentiellement perméables, elles ne permettent pas de déterminer l'importance de la transmissivité de la fracture ni la nature de la perméabilité du milieu. Il appert donc que la méthode des essais hydrauliques est essentielle lorsqu'il s'agit de déterminer les caractéristiques des éléments perméables dans une roche fracturée.

MANAGEMENT PERSPECTIVE

The work described in this report was carried out by NWRI personnel in co-operation with the U.S. Geological Survey.

The identification and characterization of hydraulically open fractures in sedimentary rock is essential in understanding groundwater flow and contaminant transport in bedrock aquifers. This study looks at the use of short interval constant head injection tests as a method of characterizing open fractures. The results show that short interval tests are an effective means of identifying and characterizing fractures. The study also contributes to the understanding of the controls on groundwater flow, and ultimately contaminant transport, in the bedrock of the Niagara Region.

PERSPECTIVE-GESTION

L'étude décrite ici a été réalisée par les membres du personnel de l'INRS en collaboration avec le U.S. Geological Survey.

La recherche des fractures ouvertes par force hydraulique dans les roches sédimentaires et la détermination de leurs caractéristiques sont essentielles à la compréhension de l'écoulement des eaux souterraines et du transport des contaminants dans les aquifères du substratum rocheux. La présente étude évalue les essais d'injection à pression constante réalisés à intervalles rapprochés comme moyen de déterminer les caractéristiques des fractures ouvertes. Les résultats montrent que les essais réalisés à intervalles rapprochés constituent un moyen efficace de recherche et de détermination des caractéristiques des fractures. L'étude contribue également à la compréhension des facteurs qui contrôlent l'écoulement des eaux souterraines, donc finalement le transport des contaminants, dans le substratum rocheux de la région de Niagara.

INTRODUCTION

Fractures in rocks of low matrix permeability can provide major pathways for the migration of toxic contaminants from disposal areas in overlying sediments to bedrock aquifers and surface water supplies. The heavily industrialized regions of southern Ontario and western New York State surrounding Lake Ontario are underlain by fractured dolostones, limestones, shales, and sandstones. Sedimentary rocks are often flat lying and fracturing takes place along bedding plane partings. These bedding plane partings can be very extensive and hydraulically connected over large areas. In rock with relatively few fractures, individual fractures may play large roles in controlling the fate and transport of contaminants in groundwater at both local and regional scales. The identification and characterization of individual fractures in the subsurface is essential in understanding groundwater flow and predicting the fate of toxic contaminants in fractured sedimentary rock.

Fracture characterization techniques in the subsurface include fracture identification in rock core, borehole geophysical methods such as acoustic televiewer, acoustic waveform analysis, flowmeter, seismic and electrical logs (Scott and Keys, 1971; Paillet, 1985; Hardin et al., 1987; Morin et al., 1988) and hydraulic testing methods such as constant-head injection tests, slug tests and pulse tests (Doe et al., 1987). Perhaps the most useful of the geophysical methods is the borehole acoustic televiewer (BAT). This is because

BAT logs provide information on the location and orientation of specific fractures using an acoustically determined 'picture' of the borehole wall; other geophysical methods can not provide as much detail. Identifying hydraulically open fractures using this method is often subjective and rarely attempted. BAT logs are expensive in comparison to hydraulic tests and not conducted on a routine basis. However, in combination with hydraulic test results and good quality core logs, the BAT log can be a very powerful tool in aiding local or regional correlation of specific hydraulically open fractures. BAT logs generally provide information on the location and orientation of specific fractures but give no indication of the fracture aperture width. Often open fractures look no different than other features on BAT logs making identification of significant features difficult (Paillet, 1985).

Constant-head injection tests involve introducing water at a constant flowrate into a packer isolated interval and measuring the resulting pressure change in the interval. The ratio of flow to pressure change is proportional to the permeability of the test interval. The information obtained by constant head injection tests is dependent on the size of the test interval. For example, a large test interval (5-10 m) allows testing of large lengths of borehole in a rapid fashion but may not give representative information about the rock in general. This is because rock aquifers are characterized by large differences in permeability as a result of fracturing. Therefore, the permeability of a test interval containing a single open

fracture with a large transmissivity will be dominated by this fracture and hydraulic test results will give no information on smaller fractures, vertical connectivity of the fractures or matrix permeability. By reducing the length of the test interval, more information can be gained on the location of permeable fractures and matrix permeability not possible with large test intervals. The packer spacing required to effectively characterize a given portion of rock will be dependent on the fracture density. The smaller the fracture spacing the smaller the required test interval. For example, if fractures were spaced 0.5 m apart a test interval less than 0.5 would yield results reflecting individual fractures and include zones with no fractures. Constant-head injection tests, while easily conducted and analyzed, can be time consuming to carry out in the field. For this reason, it is essential that an effective hydraulic testing program be planned using all available geological and geophysical data on the boreholes studied.

Other fracture characterization studies generally have shown that even in rock with a high density of fractures usually only one or two fractures provide the bulk of the permeability in the rock (Magnussun and Durnan, 1984; Jones, 1985; Paillet, 1985; Paillet et al., 1985). Magnusson and Durnan found no relationship between fracture frequency and hydraulic conductivity in a study of fractures in a granite. Zones containing a single isolated fracture exhibited a range of hydraulic conductivities from less than 10^{-9} m/s to greater than 10^{-7} m/s. In sedimentary rock, fracturing most frequently occurs

along bedding plane partings. For example, in a detailed study of the contributions of fractures to groundwater flow in a sandstone aquifer, over 80% of the fractures mapped in borehole investigations were bedding plane partings (Francis et al., 1988).

The boreholes employed for this study intersect the Middle Silurian Lockport group of dolostone and limestones which make up the bedrock directly underlying most of the Niagara Falls, NY, region. In this region, the Lockport group is composed of 4 formations (Gasport, Goat Island, Eramosa, and Oak Orchard from bottom to top). Total thickness ranges from 6-50 m (Yager and Kappel, 1987). Regional groundwater flow in the Lockport dolostone is within a network of horizontal bedding plane separations (Johnson, 1964). The horizontal fractures are well-connected in the upper 3-8 m of rock and are less connected at depth (Yager and Kappel, 1987). The geology and hydrogeology of the region is discussed in greater detail in Novakowski and Lapcevic (1988) and Yager and Kappel (1987).

The purpose of this study is to 1) investigate the use of hydraulic tests conducted with short-packer-spacings to identify discrete hydraulically open fractures, 2) compare the results of the hydraulic tests to the results of geophysical methods, in particular the borehole acoustic televiewer method in terms of ability to identify open fractures in sedimentary rock terrain and 3) identify fracture characteristics such as fracture frequency and fracture spacing that may help in the comparison. The length of each borehole was tested using a 2 m test interval to hydraulically characterize the

Lockport dolostone. To examine the use of short interval constant head injection tests in characterizing hydraulically open fractures in the rock, selected permeable intervals were re-tested using short test intervals (0.50-0.60 m). The results of this set of tests is compared to borehole acoustic televiewer logs and fracture logs determined from rock core.

METHODS

The location of boreholes WF3 and LW1, used for this study, are shown on Figure 1. Each borehole is vertical in orientation, 96 mm in diameter, and was diamond drilled and cored using triple-tube techniques. The total depths of boreholes WF3 and LW1 are 71.8 and 77.9 m respectively. These boreholes were selected for this study because they intersect the Lockport dolostone in its entirety. The installation of the boreholes, fracture logging of the core and borehole geophysics were carried out by the U.S. Geological Survey. The boreholes are part of the U.S. Geological Survey's monitoring well network in the Niagara Falls, NY region (Yager et al., 1987).

Constant-head injection tests were conducted by injecting water at a constant flowrate into an isolated test interval and measuring the resulting change in hydraulic head at a steady-state flow condition. A schematic of the testing apparatus used to conduct the constant-head tests is shown in Figure 2. Each test interval was isolated using two pneumatic packers. Each packer consists of an

expandable rubber gland with a reinforced kevlar cuff and a seal length of 0.6 m. A pressure transducer located above the packers was used to measure the pressure within the test interval. At the surface, a series of five tanks of different diameter was pressurized with a regulated source of compressed nitrogen to provide constant injection flowrate. Flowrate was measured using sight tubes on the side of the injection tanks. Transmissivities between $1x10^{-10}$ m^2/s and 10^{-4} m^2/s can be determined using this test apparatus. During the test procedure, imposed injection heads ranged between 0.5 and 60 m above initial static conditions. Injection heads at the high end of the range represent tests conducted in low-permeability zones where large head changes were required to obtain a measurable flowrate. Two to three different steps in injection pressure (i.e., different flow-rates) were employed during most tests. The field methodology employed for constant-head injection tests is discussed in more detail in Zeigler (1976), Doe and Remer (1980), and Doe et al. (1987). The results of constant-head injection tests were used to obtain the vertical distribution of transmissivity near the borehole. An initial set of hydraulic tests using a 2-m test interval (long interval tests) were conducted to characterize the permeability along the length of each borehole (14 tests in LW1 and 19 tests in WF3) and to locate and identify high permeability zones. Following this, a second set of tests was completed in which higher permeability zones were tested ($T>1x10^{-7}$ m^2/s) to identify and characterize specific, permeable fractures. A 0.5 to 0.6 m test interval, with up to 45 cm overlap of

adjacent test zones, was used for this set of tests. In zones where the bulk of the transmissivity of the rock is due to individual fractures, the fracture aperture width can be calculated from the results of the short-packer spacing tests.

Logs showing the location of open fractures and probable open fractures were constructed by D. Tepper of the U.S. Geological Survey for each borehole based on core examination alone (Figures 5 and 6). The criteria used to distinguish open fractures from core breaks induced by drilling, included closeness of fit of core pieces, presence of infilling or staining and the roughness of fracture surfaces (D. Tepper, pers. comm.).

Borehole acoustic televiewer (BAT) logs are also presented for comparison with the hydraulic test results (Figures 5 and 6). The method and interpretation of BAT logs is described in detail in Zemanek et al. (1969), Kierstein (1984) and Paillet (1985). The BAT logs show solid lines, dashed lines and short dashes to indicate fractures. A solid line was interpreted as identifying an open fracture. Dashed lines and short dashes represent fractures that may be open on only one side of the borehole, or vugs or chips in the borehole wall and thus cannot be clearly interpreted as indicating open fractures (D. Tepper, pers. comm.).

RESULTS AND DISCUSSION

The results of the constant-head injection tests were interpreted using the ratio of injection flow rate to the resulting head

difference over static conditions ($Q/\Delta H$). A modified version of the Theim equation for steady state radial flow was used to obtain the equivalent transmissivity, T, (m^2/s) for each given isolated interval. The expression used is as follows:

$$T = \frac{Q}{\Delta H 2\pi} \bullet \ln (r_e/r_w) \qquad (1)$$

where Q = steady state flowrate (m^3/s), ΔH = difference in hydraulic head between static initial conditions and a steady flow condition (m), r_e = radius of influence (m), and r_w = radius of well (m). The radius of influence, or outer flow boundary, was assumed to be 10 m in all tests (Bliss and Rushton, 1984). While the radius of influence is unknown in most field situations, because it appears as a logarithmic term in equation (1), large errors in estimation of r_e will result in only small errors in the calculation of T (Zeigler, 1976; Doe et al., 1987).

An equivalent single fracture aperture 2b (m) can be determined from the test results by using the cubic law (Witherspoon et al., 1980). The fracture aperture is related to transmissivity according to:

$$2b = [\frac{12\mu}{\rho g} \bullet T]^{1/3} \qquad (2)$$

where T = transmissivity (m^2/s), ρ = fluid density (kg/m^3), g = gravitational acceleration (m/s^2) and μ = kinematic viscosity (m^2/s).

A total of 157 constant-head injection tests were completed in the two boreholes. The results of the tests are presented in Appendix A. In some instances tests were not completed where initial test results showed the formation to be at or below the testing apparatus limits. The locations of these test intervals are indicated by a blank in Appendix A but were assigned a T of $1x10^{-10}$ m^2/s for plotting and statistical purposes. Transmissivities or apertures obtained from this type of hydraulic testing are representative of hydraulics conditions near the borehole only (Novakowski, 1988). In borehole LW1, 4 fractures were characterized with the short interval tests (Figures 4 and 6). In borehole WF3, 11 fractures were characterized with the short interval tests (Figures 3 and 5).

Transmissivities obtained from the long interval tests in borehole WF3 show a vertical variation in the permeability of the Lockport dolostone from $<1x10^{-10}$ to $2x10^{-4}$ m^2/s with an arithmetic mean log (T) of -6.3 (N=19). Two tests were below detection limit (10% of all tests) and therefore a truncation bias is incurred. No evaluation of this error was conducted, however the magnitude of the error with respect to the mean is believed to be small. In borehole LW1 the transmissivities ranged from $<1x10^{-10}$ to $1x10^{-4}$ m^2/s with an arithmetic mean log (T) of -7.1 (N=14). Three tests were below detection limit (21% of all tests).

The results of the long interval tests (2 m packer spacing) are compared to the short interval tests (0.5 m packer spacing) in Figures 3 and 4. The results of the short interval tests are

presented in a consolidated format in Figures 3-6 due to the overlap of test intervals. This means that in zones which have where more than one test was conducted as a result of overlapping test intervals, the lowest transmissivity calculated was taken to be representative of the zone. Plots of individual tests showing the overlap are given in Appendix B. Overlapping of test intervals ensures that no portion of the borehole studied is omitted, but may introduce bias. For example, if a large fracture at the edge of zone is tested twice this will imply that two adjacent zones have high permeabilities. A comparison of the long interval tests to the short interval tests (Figures 3 and 4) shows that permeability variations within the rock are more evident with the short interval tests. The characteristics of the fractures identified by the short interval tests are summarized in Table 1. Comparison of the fracture log to the short interval test results shows that in the permeable zones identified with the long interval tests the majority of the transmissivity can be attributed to a single fracture (Figures 5 and 6). Zones which were tested and show no indication of open fractures in the core were used to determine matrix permeability. Transmissivities in test intervals with no observed fractures ranged from $<1x10^{-10}$ to $7x10^{-8}$ m^2/s. Only results from borehole WF3 were used to examine matrix permeability since borehole LW1 was not studied in its entirety with the short interval tests. The large range of transmissivities suggests a hetereogeneous matrix with the differences possibly due to the presence of microfractures, variations in cementation, and changes in lithology.

The results of the short interval tests are compared to BAT logs and fracture logs in Figures 5 and 6. In all cases open fractures identified by the hydraulic tests were identified as open fractures in the core. In borehole WF3, 6 of the 11 fractures identified by the constant-head tests conducted using short intervals are clearly identified in the BAT log (Figure 5). The other 5 fractures are identified as possible fractures on the log. The 6 fractures identified clearly (A,B,D,E,G, and K) all have transmissivities greater than $1x10^{-5}$ m^2/s or apertures greater than 250 microns. Of the remaining features, J and I have apertures greater than 250 microns while C, F and H have apertures less than 250 microns. In borehole LW1, the 4 fractures identified on the transmissivity log are not clearly identified on the BAT log, but are indicated as possible fractures (Figure 6). Comparisons in both boreholes indicate that the constant-head injection tests using a short interval are effective in identifying discrete fractures. While the BAT logs clearly identify fractures with transmissivities greater than $1x10^{-5}$ m^2/s in borehole WF3, the interpretation of the logs becomes ambiguous below this value. In borehole LW1, fractures A, B and D have transmissivities greater than $1x10^{-5}$ m^2/s and are not clearly identified on the BAT log. The identification of fractures in sedimentary rock can be more difficult relative to other types of rock due to poor acoustic reflectivity of sediments, variable background reflectivity and possible drilling damage of more friable rocks (Paillet _et al_., 1985). It should be noted that other geophysical logs were collected in the boreholes which may supplement the BAT log interpretation but are not considered in this study.

A comparison of transmissivities obtained in zones with one identifiable fracture in the long interval tests and the same fracture in the short interval tests shows that the results of the short interval tests show consistently higher transmissivities (and therefore larger apertures) than the long interval tests. The difference observed in the comparison between the two sets of tests can probably be attributed to the borehole development history. That is, rock-flour from the drilling of the boreholes may artificially reduce the near well permeability if the borehole is not sufficiently cleaned prior to hydraulic testing. The first set of hydraulic tests (long interval tests) probably moved the rock flour farther into the fractures and thus higher transmissivities were obtained from the second set tests. The repeatability of the constant head injection tests should be examined in further field studies.

Fracture frequencies and spacings obtained from each of the boreholes were also studied. The long interval constant-head test results were used for comparison with the fracture logs. Fracture frequency is defined herein as the number of open fractures identified in the core within a given hydraulic test interval. Fracture spacing is defined as the distance between successive fractures in the core. Fracture spacing in borehole WF3 ranged from 0.04 m to 6.37 m with an arithmetic mean value of 0.9 m. There is no trend in fracture spacing with depth (Figure 7a). The fracture frequency obtained from borehole WF3, ranges from 0-7 fractures/2 m and also shows no consistent trend with depth (Figure 7b). A comparison of fracture frequency with

transmissivity shows that permeable zones ($T>10^{-7}$ m^2/s) have fracture frequencies from 1-7 per 2 m but zones with transmissivities less than 10^{-7} m^2/s have 0-2 fractures per 2 m (Figure 7c). Therefore, in consideration of the results found in the comparison of BAT logs to the short interval tests, those zones having a transmissivity of 10^{-7} m^2/s or less may be determined on the basis of fracture frequency alone using the BAT logs. Further investigation of this interpretation is required.

In borehole LW1, fracture spacing ranged between 0.02 and 3.10 m. In contrast to borehole WF3, fracture spacing appears to increase with depth and fracture frequency decreases with depth (Figures 8a and b). Permeable zones in borehole LW1 ($T > 10^{-7}$ m^2/s) have 1-6 fractures (Figure 8c). Fracture frequencies obtained by examining the BAT logs in a similar manner (counting fractures and possible fractures only) shows frequencies to range from 0-3 fractures per 2 m in borehole WF3. In borehole LW1, frequencies range from 0-2 fractures per 2 m. This is in agreement with the overall characteristics of the permeability whereby the arithmetic means of the log(T) are -6.3 and -7.1 for boreholes WF3 and LW1, respectively.

CONCLUSIONS

In this study, constant head injection tests, carried out in two boreholes in the Niagara Region, were used to identify hydraulically open fractures in sedimentary rock. The results were compared to borehole acoustic televiewer (BAT) logs and fracture logs determined

from rock core. The tests yielded a range of transmissivities for the Lockport dolostone ranging from $<1x10^{-10}$ to $2x10^{-4}$ m^2/s. Testing of zones with no identifiable fractures suggest matrix transmissivities to range from $<1x10^{-10}$ to $7x10^{-8}$ m^2/s.

By using short interval tests, discrete open fractures can be identified. The fractures identified in this study compare with those fractures identified in the rock core and BAT logs. The injection tests identified the open fracture more consistently than the BAT logs. Constant head injection tests are straightforward to conduct and analyze. The information gained from short interval tests can be used to correlate permeable fractures between boreholes. While overlapping of test intervals ensures that no zones are missed, this method of testing makes it difficult to compare test results without introducing a bias. Further studies in different rock types and variable fracture densities will allow comparison of methods of fracture identification for characterization of fractured bedrock aquifers.

ACKNOWLEDGEMENTS

The borehole geophysics and core logs were provided by the U.S. Geological Survey Water Resources Division in Ithaca, NY. The generous assistance of D. Tepper, W. Kappel and R. Yager of the U.S. Geological Survey is gratefully acknowledged. Earl Walker provided valuable field assistance.

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Table 1. Summary of fracture characteristics.

Borehole	Fracture	Elevation (m.a.s.l.)	T (m^2/s)	Aperture (microns)
WF3	A	159.74	5.9×10^{-5}	464
	B	161.26	5.0×10^{-4}	948
	C	166.32	3.8×10^{-7}	86
	D	168.95	1.3×10^{-4}	604
	E	171.71	7.7×10^{-5}	507
	F	173.62	1.8×10^{-4}	673
	G	175.66	3.0×10^{-4}	799
	H	178.11	1.9×10^{-6}	149
	I	178.54	3.6×10^{-5}	392
	J	179.61	1.9×10^{-5}	318
	K	180.64	5.1×10^{-5}	442
LW1	A	160.55	2.1×10^{-4}	713
	B	167.65	1.6×10^{-5}	301
	C	169.90	1.2×10^{-7}	59
	D	170.50	9.2×10^{-5}	538

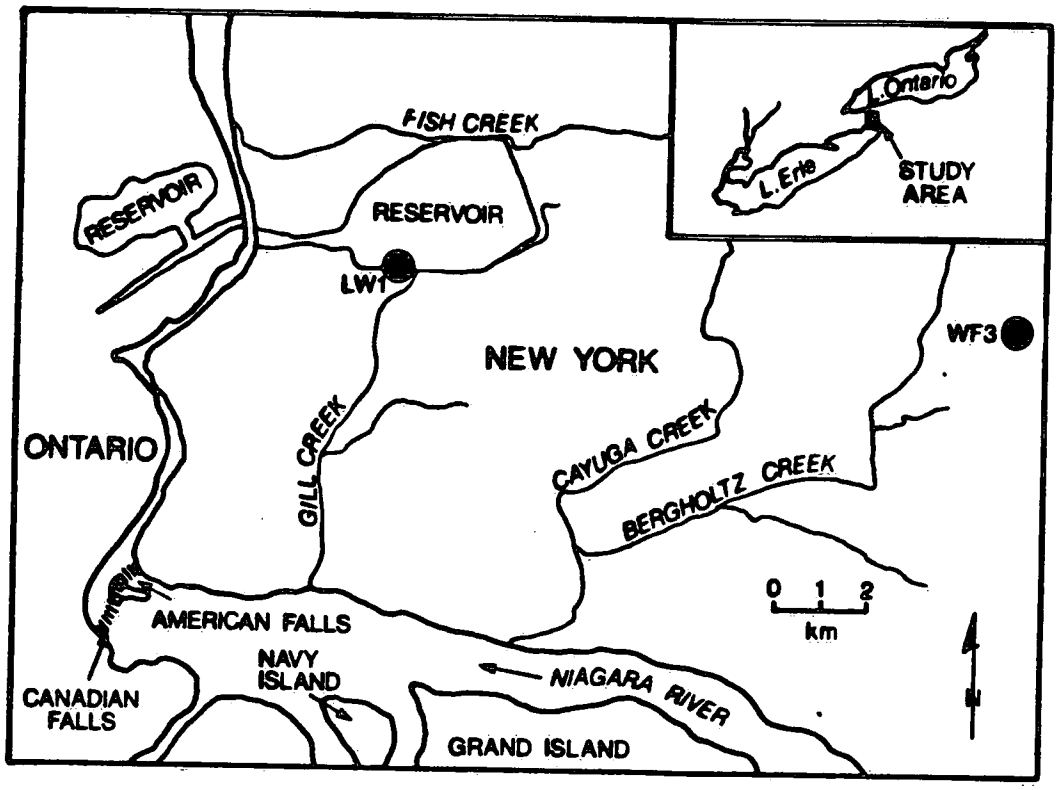


Figure 1. Area map showing location of boreholes (modified from Yager and Kappel, 1987).

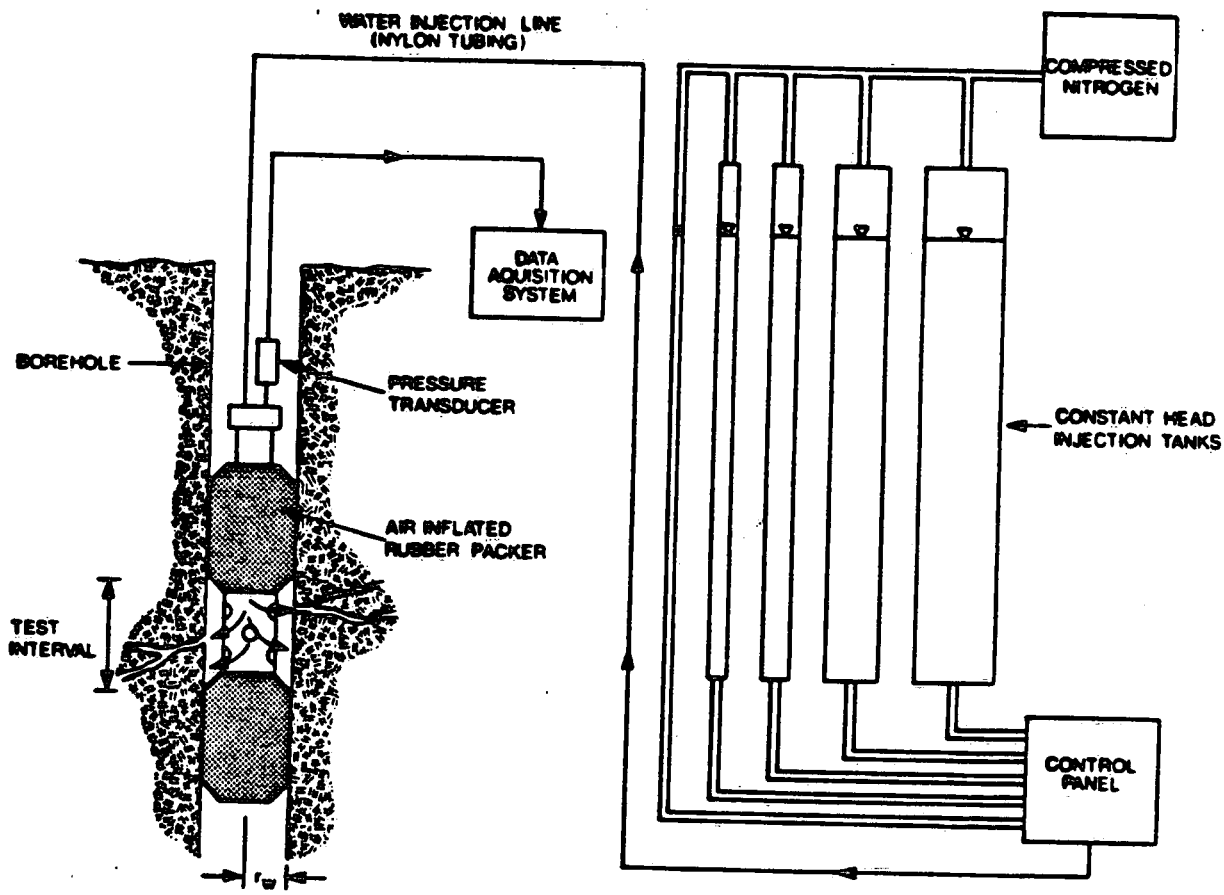


Figure 2. Schematics of constant-head injection testing setup.

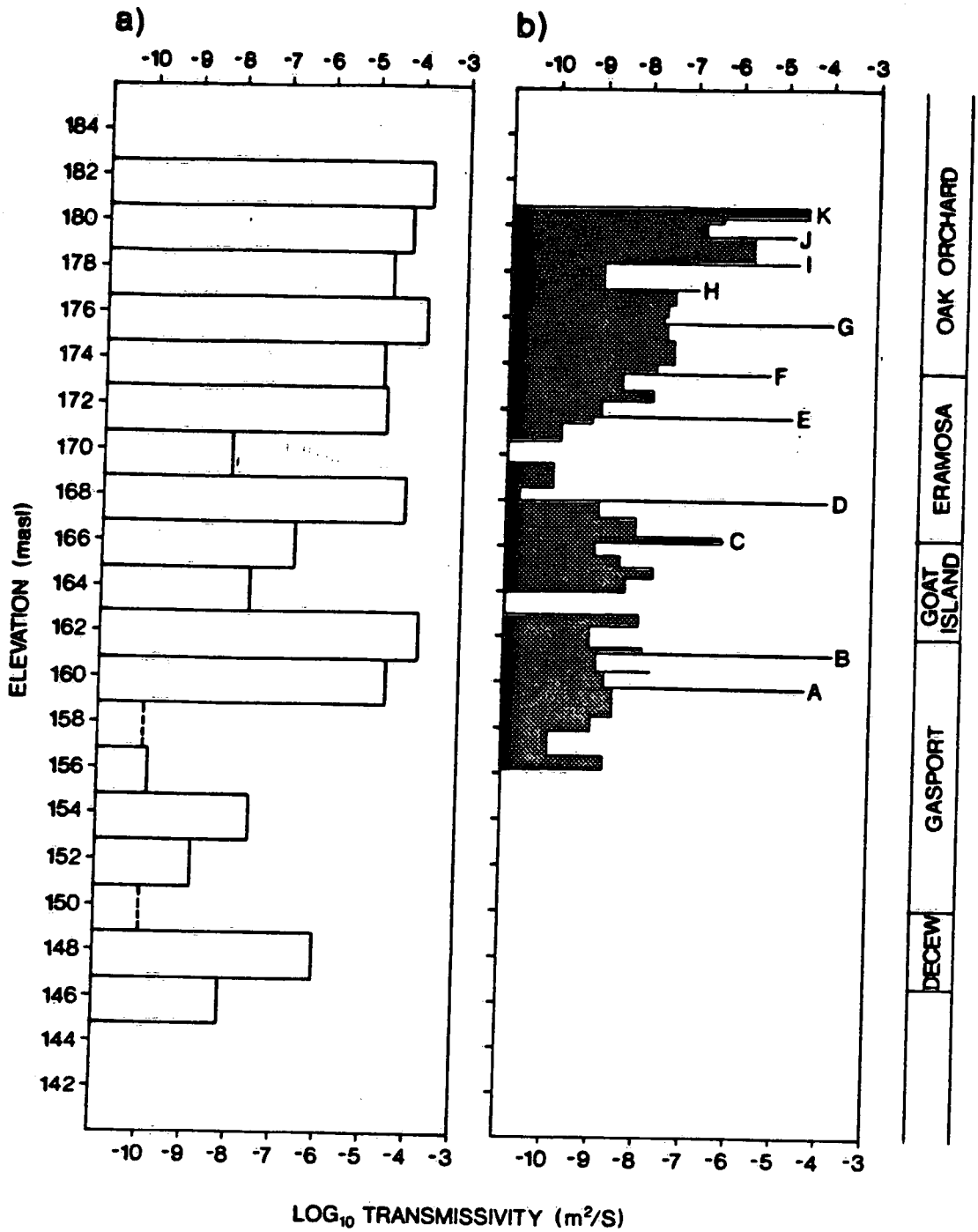


Figure 3. (a) Long interval test results in borehole WF3 (dashed lines indicate assumed values). (b) Short interval test results in borehole WF3.

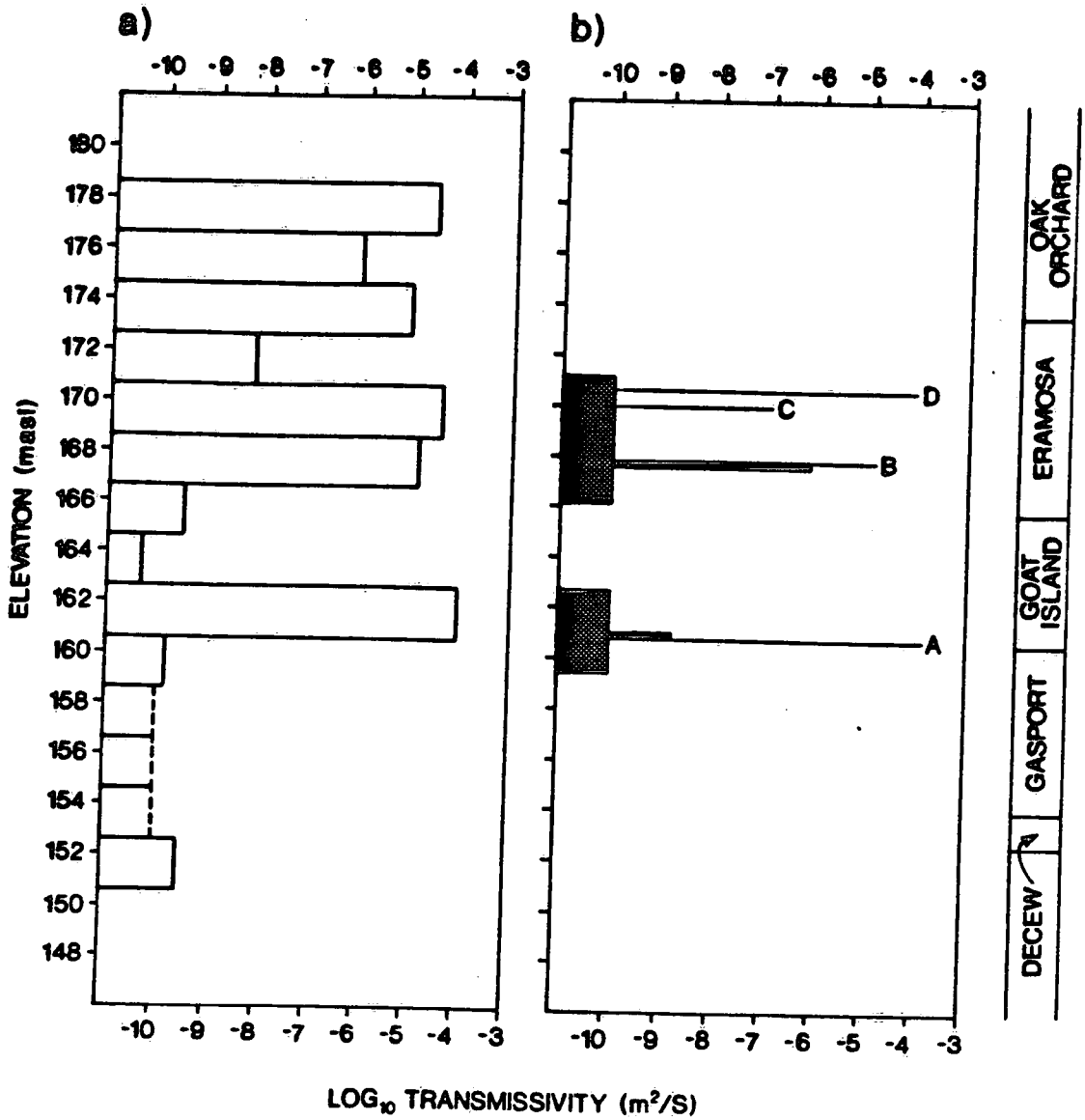


Figure 4. (a) Long interval test results in borehole LW1 (dashed lines indicate assumed values). (b) Short interval test results in borehole LW1.

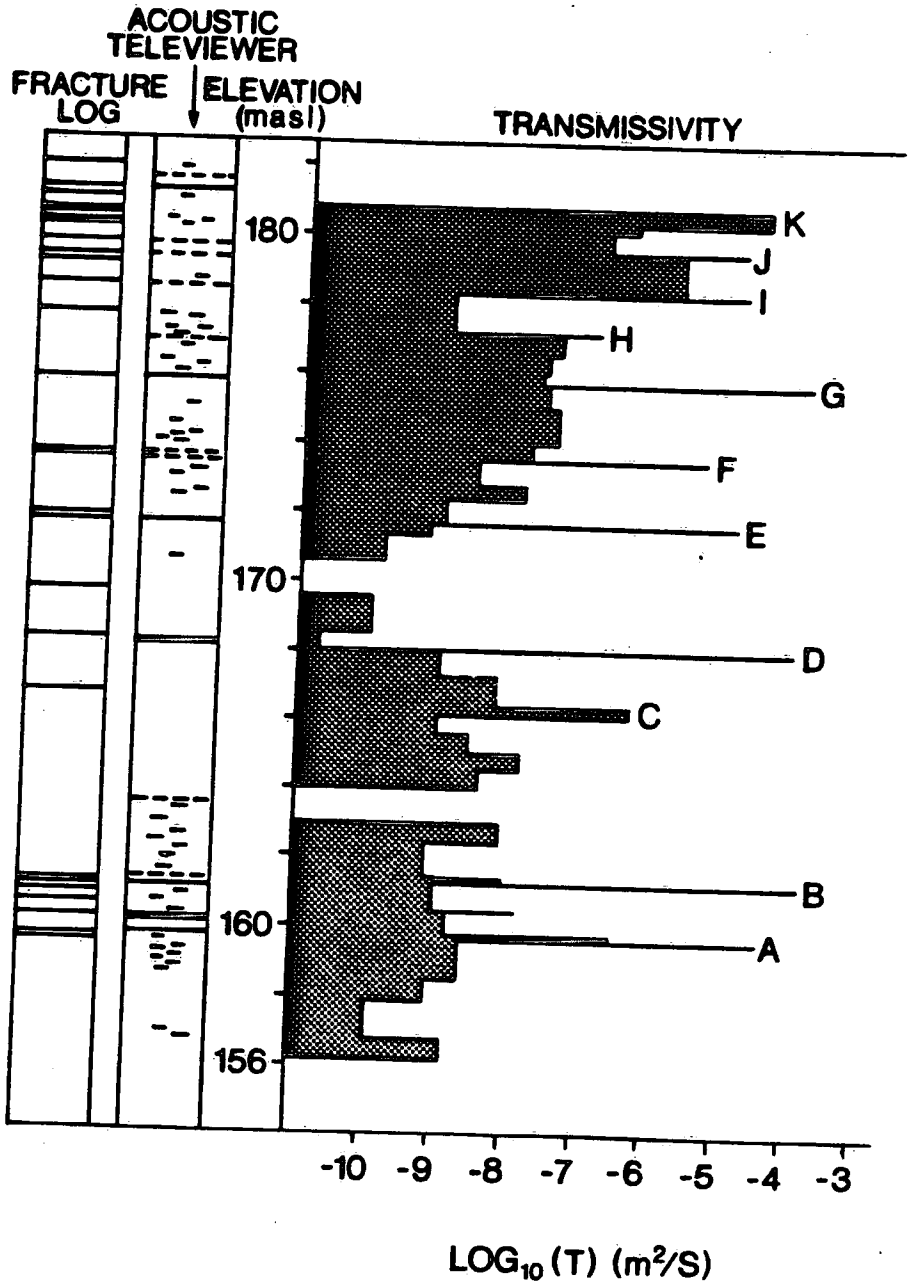


Figure 5. Fracture, BAT and transmissivity logs for borehole WF3.

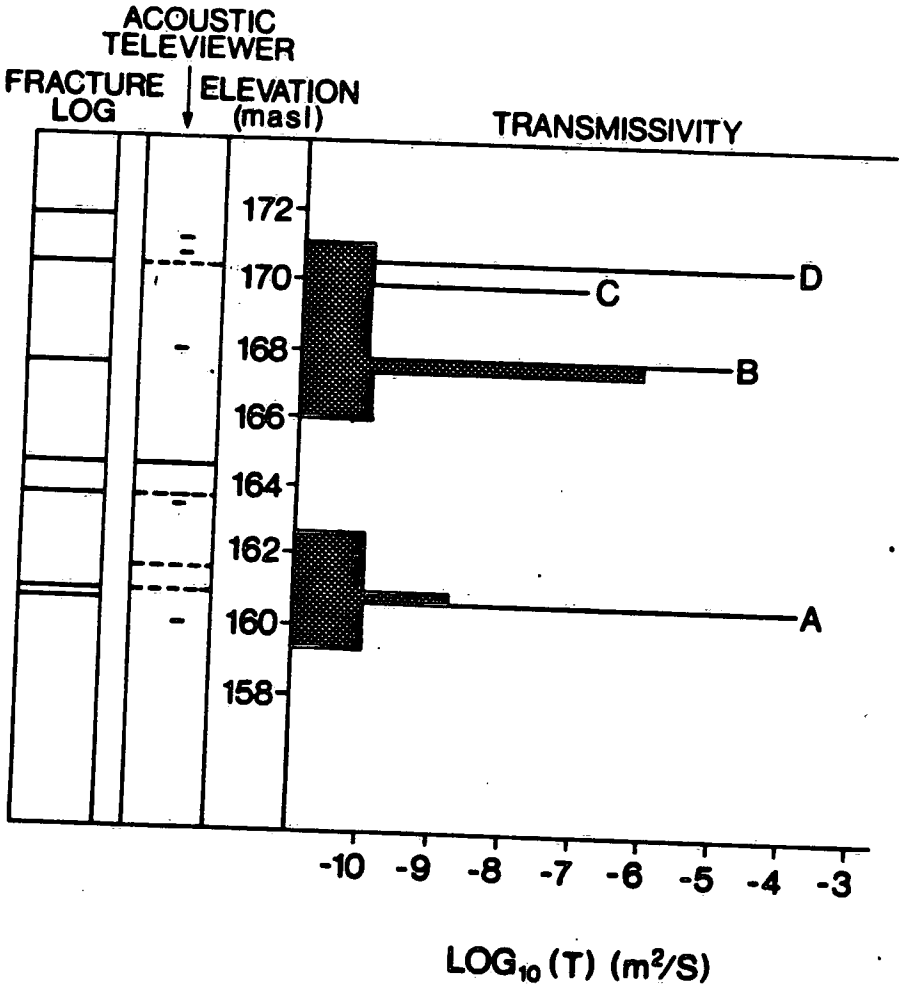
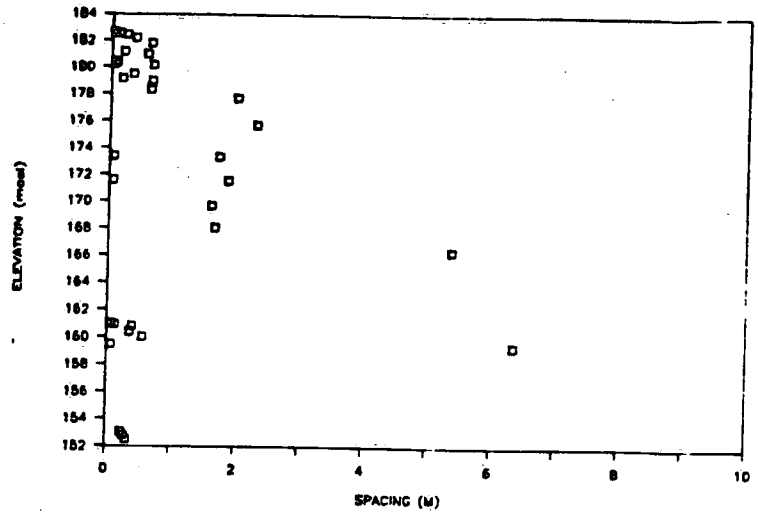
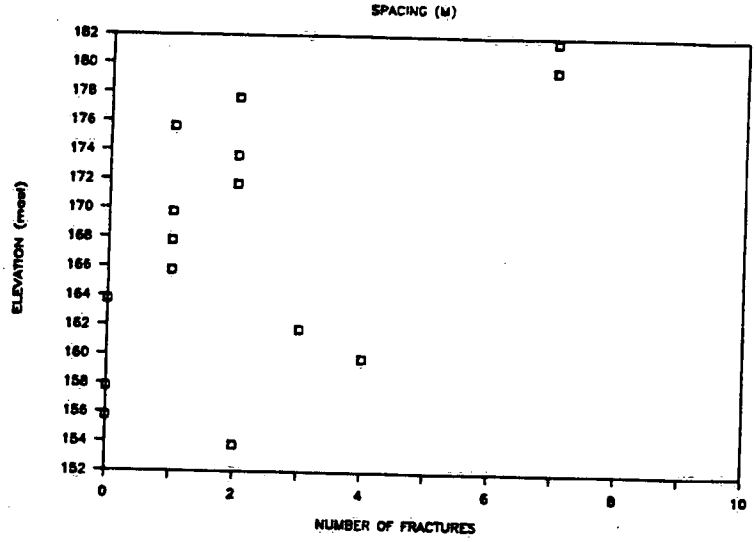


Figure 6. Fracture, BAT and transmissivity logs for borehole LW1.

(a)



(b)



(c)

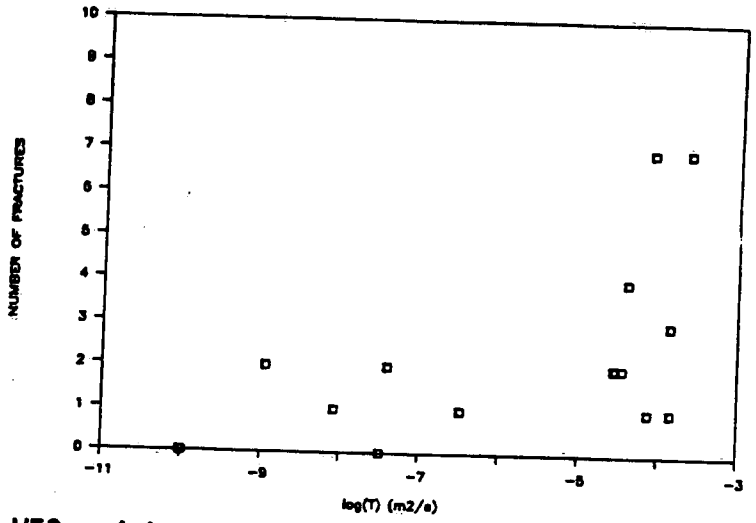
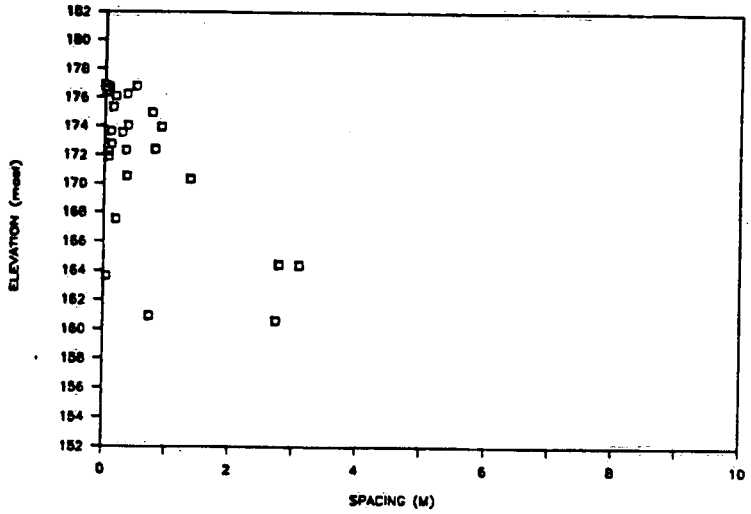


Figure 7. Borehole WF3: (a) Fracture spacings vs. elevation.

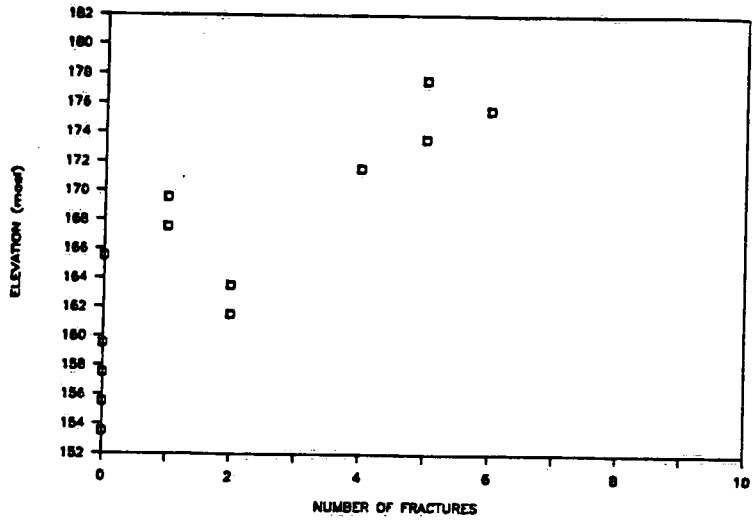
(b) Fracture frequency vs. depth.

(c) Log(T)m^2/s vs. fracture frequency.

(a)



(b)



(c)

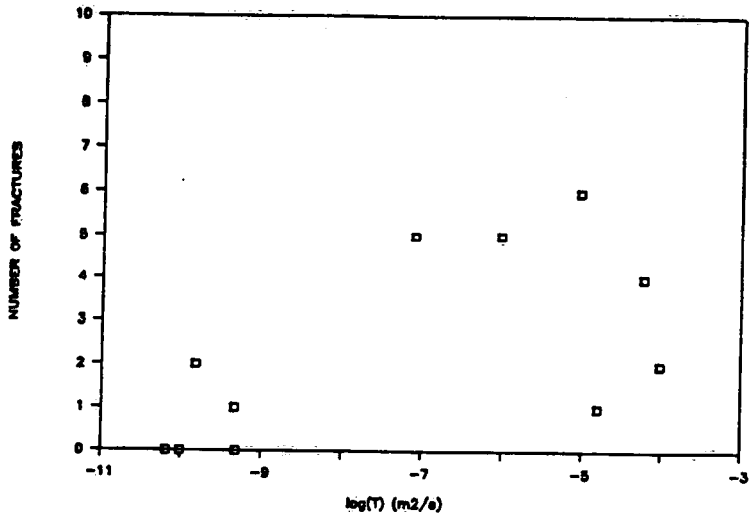


Figure 8. Borehole LW1: (a) Fracture spacings vs. elevation.

(b) Fracture frequency vs. depth.

(c) Log(T)m^2/s vs. fracture frequency.

APPENDIX A

CONSTANT-HEAD INJECTION TEST RESULTS

Niagara Falls Regional Hydrogeology - USGS boreholes

Borehole:WF3
Datum (gs): 189.67 masl

Test #	Depth (mbgs)		Elevation (masl)		T (m^2/s)	K (m/s)	2b (microns)
1	20.00	21.95	168.80	166.85	7.60×10^{-5}	3.90×10^{-5}	505
2	18.05	20.00	170.75	168.80	8.50×10^{-9}	4.36×10^{-9}	24
3	16.10	18.05	172.70	170.75	2.91×10^{-5}	1.49×10^{-5}	367
4	14.15	16.10	174.65	172.70	2.79×10^{-5}	1.43×10^{-5}	362
5	42.00	44.00	146.80	144.80	8.31×10^{-9}	4.16×10^{-9}	24
6	40.00	42.00	148.80	146.80	8.88×10^{-7}	4.44×10^{-7}	115
7	38.00	40.00	150.80	148.80			
8	36.00	38.00	152.80	150.80	1.14×10^{-9}	5.71×10^{-10}	12
9	34.00	36.00	154.80	152.80	3.95×10^{-8}	1.97×10^{-8}	41
10	32.00	34.00	156.80	154.80	1.05×10^{-10}	5.25×10^{-11}	6
11	30.00	32.00	158.80	156.80			
12	28.00	30.00	160.80	158.80	4.02×10^{-5}	2.01×10^{-5}	409
13	26.00	28.00	162.80	160.80	1.41×10^{-4}	7.05×10^{-5}	621
14	24.00	26.00	164.80	162.80	3.32×10^{-8}	1.66×10^{-8}	38
15	22.00	24.00	166.80	164.80	3.30×10^{-7}	1.65×10^{-7}	82
16	12.15	14.15	176.65	174.65	1.46×10^{-4}	7.28×10^{-5}	628
17	10.15	12.15	178.65	176.65	3.58×10^{-5}	1.79×10^{-5}	393
18	8.15	10.15	180.65	178.65	7.97×10^{-5}	3.99×10^{-5}	513
19	6.15	8.15	182.65	180.65	2.32×10^{-4}	1.16×10^{-4}	733
20	32.00	32.55	156.80	156.25	1.33×10^{-9}	2.42×10^{-9}	13
21	31.45	32.00	157.35	156.80	1.13×10^{-10}	2.05×10^{-10}	6
22	30.90	31.45	157.90	157.35			
23	30.35	30.90	158.45	157.90	8.71×10^{-10}	1.58×10^{-9}	11
24	29.76	30.31	159.04	158.49	3.76×10^{-9}	6.84×10^{-9}	19
25	29.21	29.76	159.59	159.04			
26	28.66	29.21	160.14	159.59	5.91×10^{-5}	1.07×10^{-4}	464
27	28.86	29.41	159.94	159.39	4.92×10^{-5}	8.95×10^{-5}	437
28	29.06	29.61	159.74	159.19	1.34×10^{-6}	2.43×10^{-6}	131
29	29.16	29.71	159.64	159.09	1.92×10^{-6}	3.49×10^{-6}	148
30	29.21	29.76	159.59	159.04	1.56×10^{-5}	2.84×10^{-5}	298
31	28.56	29.11	160.24	159.69	5.99×10^{-5}	1.09×10^{-4}	467
32	28.46	29.01	160.34	159.79	9.88×10^{-7}	1.80×10^{-6}	119
33	28.36	28.91	160.44	159.89	1.43×10^{-9}	2.60×10^{-9}	13
34	28.16	28.71	160.64	160.09	1.90×10^{-8}	3.45×10^{-8}	32
35	27.96	28.51	160.84	160.29	2.15×10^{-8}	3.90×10^{-8}	33
36	27.76	28.31	161.04	160.49	2.45×10^{-10}	4.46×10^{-10}	7
37	27.56	28.11	161.24	160.69			
38	27.36	27.91	161.44	160.89	5.02×10^{-4}	9.13×10^{-4}	948
39	27.16	27.71	161.64	161.09	3.91×10^{-4}	7.11×10^{-4}	872
40	27.06	27.61	161.74	161.19	2.91×10^{-5}	5.30×10^{-5}	367
41	26.96	27.51	161.84	161.29	3.40×10^{-8}	6.18×10^{-8}	39
42	27.46	28.01	161.34	160.79	2.33×10^{-4}	4.23×10^{-4}	734
43	26.76	27.31	162.04	161.49	6.41×10^{-10}	1.17×10^{-9}	10
44	26.26	26.81	162.54	161.99	1.89×10^{-9}	3.43×10^{-9}	15
45	25.76	26.31	163.04	162.49	9.72×10^{-9}	1.77×10^{-8}	25
46	24.23	24.78	164.57	164.02	6.31×10^{-9}	1.15×10^{-8}	22
47	23.73	24.28	165.07	164.52	1.91×10^{-8}	3.47×10^{-8}	32
48	23.23	23.78	165.57	165.02	4.43×10^{-9}	8.05×10^{-9}	20
49	22.73	23.28	166.07	165.52			

Niagara Falls Regional Hydrogeology - USGS boreholes (cont'd)

Borehole:WF3
Datum (gs): 189.67 masl

Test #	Depth (mbgs)		Elevation (masl)		T (m^2/s)	K (m/s)	2b (microns)
50	22.23	22.78	166.57	166.02	$1.33x10^{-8}$	$2.42x10^{-8}$	28
51	22.03	22.58	166.77	166.22	$3.80x10^{-7}$	$6.91x10^{-7}$	86
52	21.83	22.38	166.97	166.42	$2.56x10^{-9}$	$4.66x10^{-9}$	16
53	21.63	22.18	167.17	166.62			
54	21.43	21.98	167.37	166.82	$3.29x10^{-9}$	$5.99x10^{-9}$	18
55	21.23	21.78	167.57	167.02			
56	21.03	21.58	167.77	167.22			
57	20.93	21.48	167.87	167.32			
58	20.83	21.38	167.97	167.42			
59	20.73	21.28	168.07	167.52			
60	20.60	21.15	168.20	167.65	$1.29x10^{-4}$	$2.35x10^{-4}$	603
61	20.53	21.08	168.27	167.72	$1.15x10^{-4}$	$2.10x10^{-4}$	581
62	19.64	20.19	169.16	168.61			
63	19.14	19.69	169.66	169.11			
64	17.61	18.16	171.19	170.64	$1.49x10^{-10}$	$2.70x10^{-10}$	6
65	17.31	17.86	171.49	170.94			
66	17.21	17.76	171.59	171.04	$1.81x10^{-9}$	$3.28x10^{-9}$	15
67	17.11	17.66	171.69	171.14	$8.20x10^{-10}$	$1.49x10^{-9}$	11
68	17.01	17.56	171.79	171.24	$2.60x10^{-5}$	$4.73x10^{-5}$	354
68a	16.91	17.46	171.89	171.34	$7.49x10^{-5}$	$1.36x10^{-4}$	503
69	16.81	17.36	171.99	171.44	$7.70x10^{-5}$	$1.40x10^{-4}$	507
70	16.71	17.26	172.09	171.54	$7.64x10^{-5}$	$1.39x10^{-4}$	506
71	16.61	17.16	172.19	171.64	$3.25x10^{-5}$	$5.91x10^{-5}$	381
72	16.51	17.06	172.29	171.74	$7.53x10^{-9}$	$1.37x10^{-8}$	23
73	20.43	20.98	168.37	167.82	$5.20x10^{-5}$	$9.45x10^{-5}$	445
74	20.33	20.88	168.47	167.92	$1.26x10^{-4}$	$2.29x10^{-4}$	598
75	20.23	20.78	168.57	168.02	$1.93x10^{-7}$	$3.50x10^{-7}$	69
76	20.13	20.68	168.67	168.12	$2.95x10^{-11}$	$5.37x10^{-11}$	4
77	19.83	20.38	168.97	168.42			
78	16.41	16.96	172.39	171.84	$9.33x10^{-10}$	$1.70x10^{-9}$	12
79	16.11	16.66	172.69	172.14			
80	15.81	16.36	172.99	172.44	$1.61x10^{-8}$	$2.93x10^{-8}$	30
81	15.61	16.16	173.19	172.64	$9.46x10^{-9}$	$1.72x10^{-8}$	25
82	15.41	15.96	173.39	172.84	$3.87x10^{-9}$	$7.03x10^{-9}$	19
83	15.31	15.86	173.49	172.94			
84	15.21	15.76	173.59	173.04	$5.42x10^{-9}$	$9.85x10^{-9}$	21
84a	15.11	15.66	173.69	173.14	$8.75x10^{-5}$	$1.59x10^{-4}$	530
85	15.01	15.56	173.79	173.24	$1.77x10^{-4}$	$3.22x10^{-4}$	670
86	14.91	15.46	173.89	173.34	$3.77x10^{-5}$	$6.85x10^{-5}$	400
87	14.77	15.32	174.03	173.48	$1.08x10^{-5}$	$1.97x10^{-5}$	264
88	14.71	15.26	174.09	173.54	$7.32x10^{-6}$	$1.33x10^{-5}$	232
89	14.61	15.16	174.19	173.64	$2.47x10^{-8}$	$4.49x10^{-8}$	35

Niagara Falls Regional Hydrogeology - USGS boreholes (cont'd)

Borehole:WF3
Datum (gs): 189.67 masl

Test #	Depth (mbgs)		Elevation (masl)		T (m^2/s)	K (m/s)	2b (microns)
90	14.41	14.96	174.39	173.84	4.89×10^{-8}	8.89×10^{-8}	44
91	14.11	14.66	174.69	174.14	7.16×10^{-8}	1.30×10^{-7}	50
92	13.81	14.36	174.99	174.44	5.39×10^{-8}	9.80×10^{-8}	45
92a	13.51	14.06	175.29	174.74	3.53×10^{-8}	6.42×10^{-8}	39
93	13.21	13.76	175.59	175.04	1.35×10^{-8}	2.46×10^{-8}	28
94	13.01	13.56	175.79	175.24	3.07×10^{-4}	5.58×10^{-4}	804
95	12.71	13.26	176.09	175.54	2.79×10^{-4}	5.07×10^{-4}	779
96	12.61	13.16	176.19	175.64	3.25×10^{-4}	5.91×10^{-4}	820
97	12.51	13.06	176.29	175.74	3.10×10^{-8}	5.63×10^{-8}	37
98	12.21	12.76	176.59	176.04	4.04×10^{-8}	7.35×10^{-8}	41
99	11.91	12.46	176.89	176.34	5.94×10^{-8}	1.08×10^{-7}	47
100	11.61	12.16	177.19	176.64	5.80×10^{-8}	1.06×10^{-7}	46
101	11.31	11.86	177.49	176.94	1.07×10^{-7}	1.95×10^{-7}	57
102	11.01	11.56	177.79	177.24	5.37×10^{-8}	9.76×10^{-8}	45
103	10.71	11.26	178.09	177.54	1.07×10^{-6}	1.95×10^{-6}	122
104	10.41	10.96	178.39	177.84	1.13×10^{-9}	2.05×10^{-9}	12
105	10.11	10.66	178.69	178.14	3.56×10^{-5}	6.46×10^{-5}	392
106	9.81	10.36	178.99	178.44			
107	9.51	10.06	179.29	178.74	3.27×10^{-6}	5.95×10^{-6}	177
108	9.21	9.76	179.59	179.04	2.70×10^{-6}	4.91×10^{-6}	166
109	8.91	9.46	179.89	179.34	1.87×10^{-5}	3.40×10^{-5}	316
110	8.61	9.16	180.19	179.64	2.39×10^{-7}	4.35×10^{-7}	74
111	8.31	8.86	180.49	179.94	6.65×10^{-7}	1.21×10^{-6}	104
112	8.01	8.56	180.79	180.24	5.07×10^{-5}	9.22×10^{-5}	442

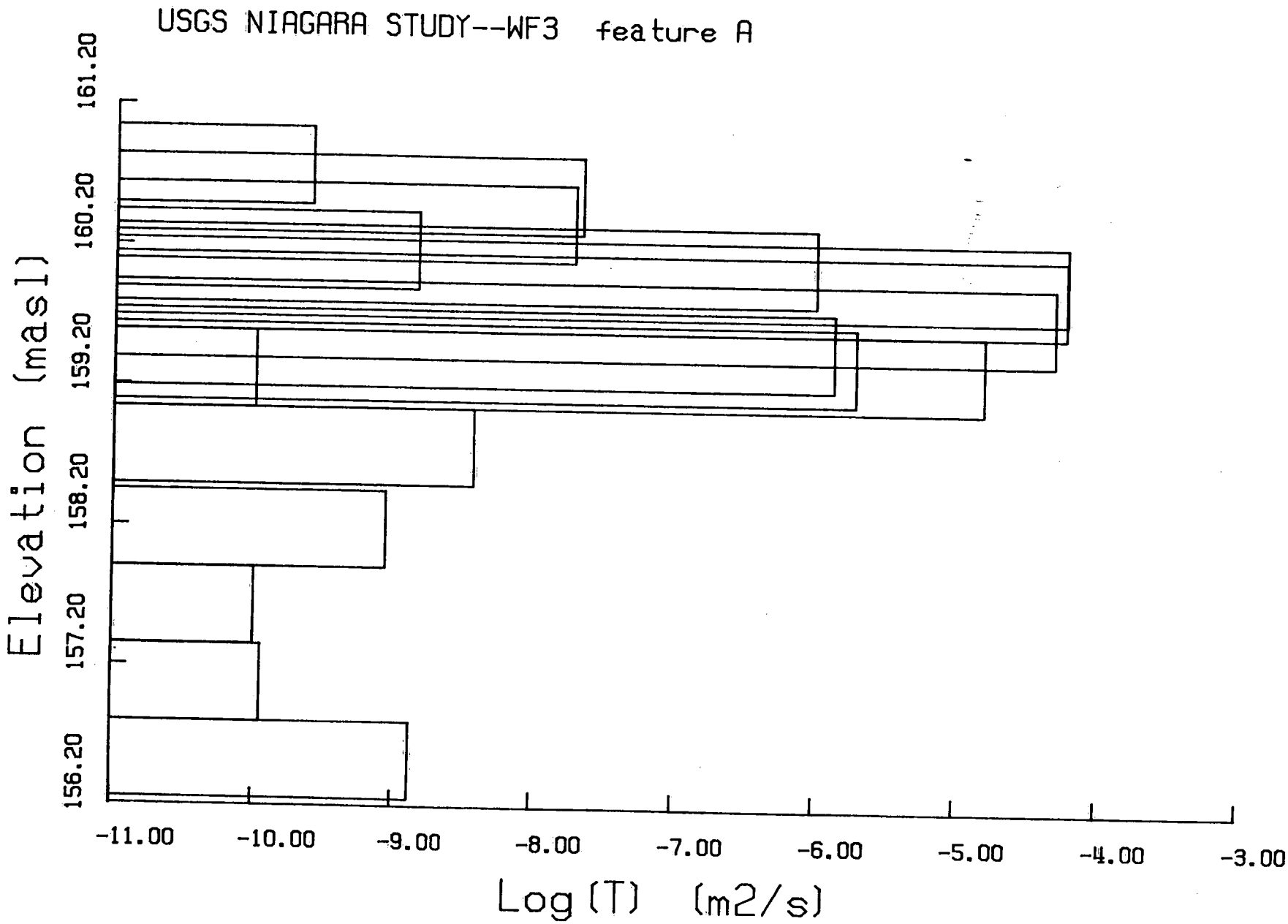
Niagara Falls Regional Hydrogeology - USGS boreholes

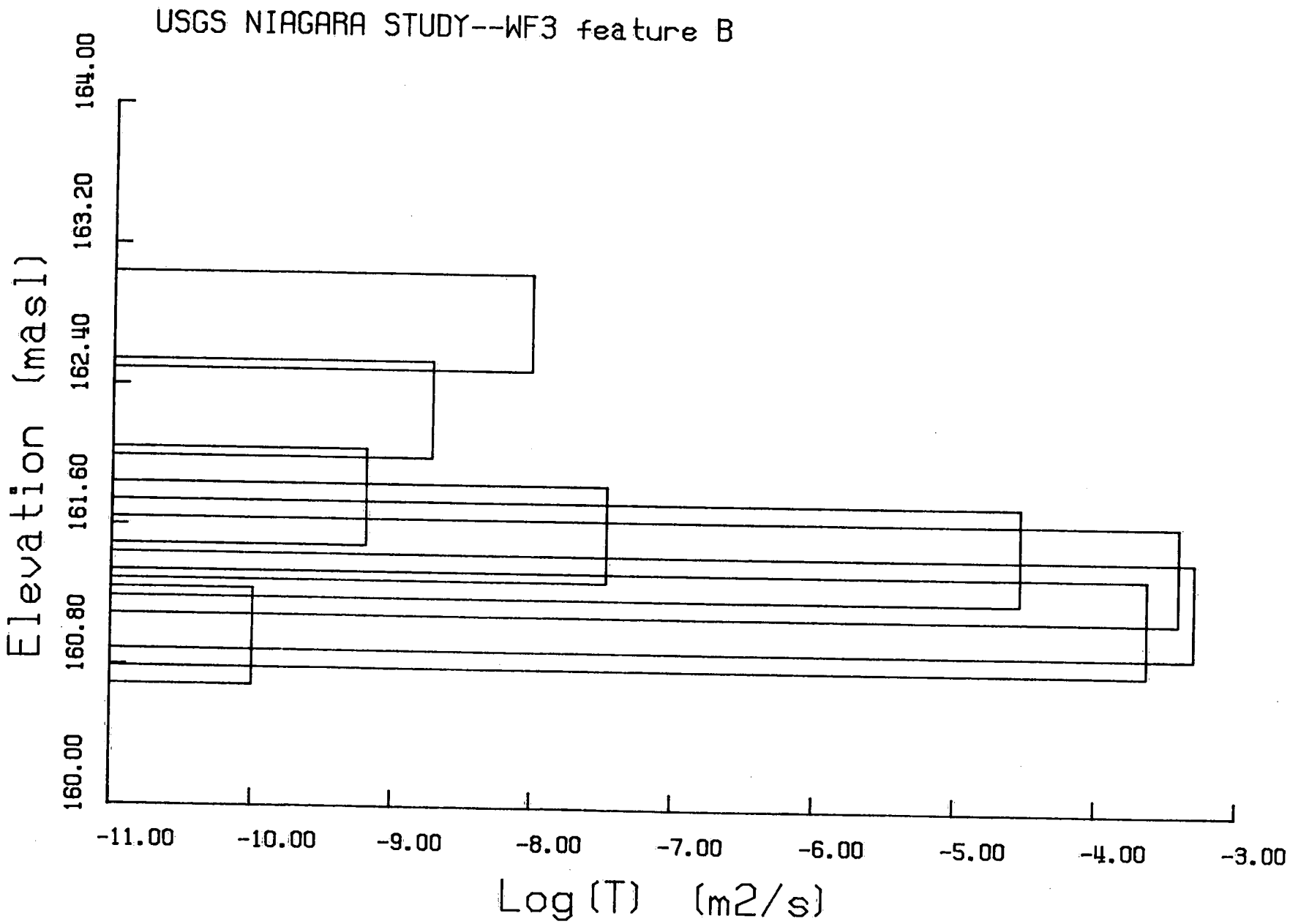
Borehole:LW1
Datum (gs): 202.55 masl

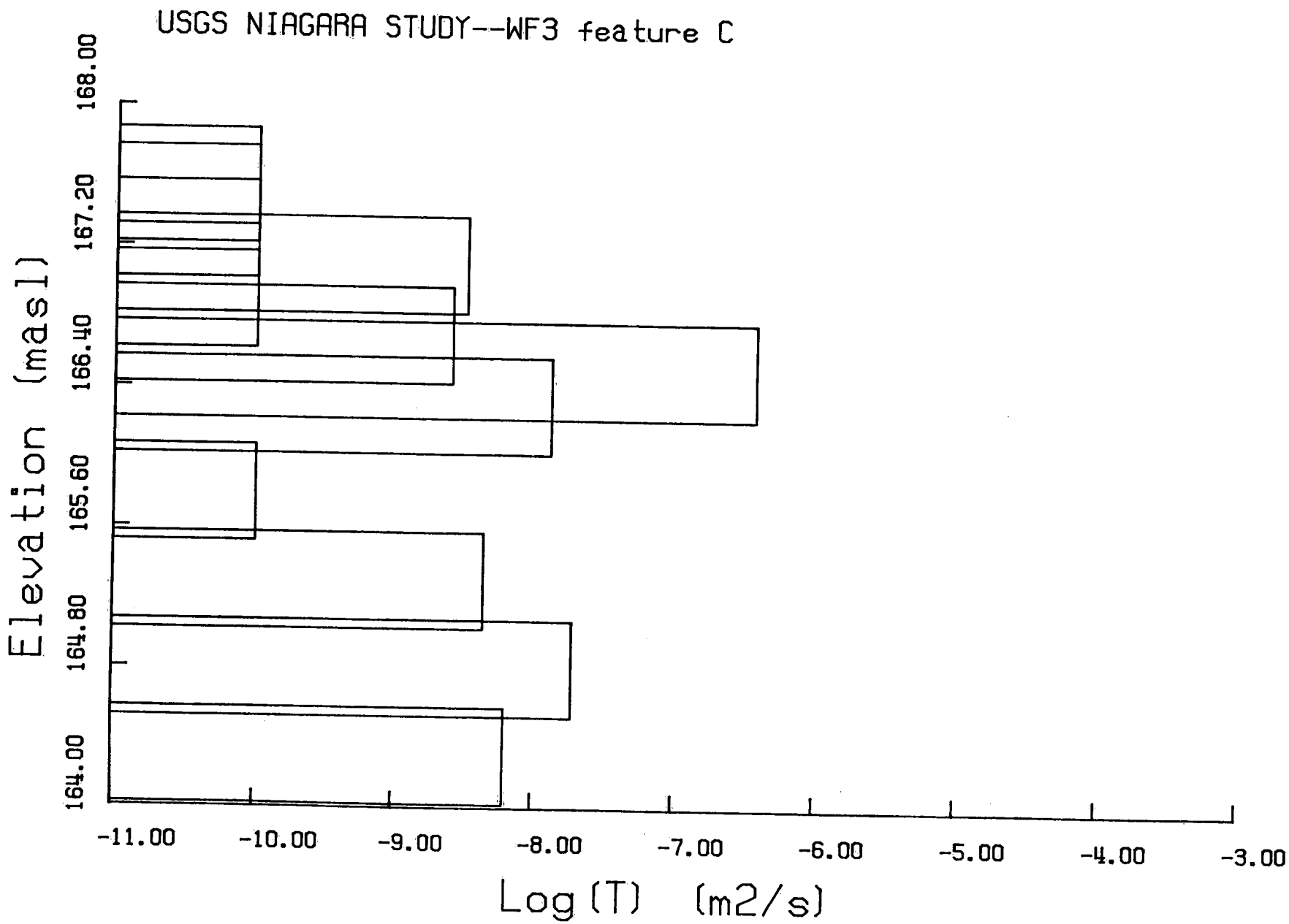
Test #	Depth (mbgs)		Elevation (masl)		T (m^2/s)	K (m/s)	2b (microns)
1	50.00	52.00	152.55	150.55	4.92×10^{-10}	2.46×10^{-10}	9
2	48.00	50.00	154.55	152.55			
3	46.00	48.00	156.55	154.55			
4	44.00	46.00	158.55	156.55			
5	42.00	44.00	160.55	158.55	1.54×10^{-10}	7.71×10^{-11}	6
6	40.00	42.00	162.55	160.55	9.82×10^{-5}	4.91×10^{-5}	550
7	38.00	40.00	164.55	162.55	6.67×10^{-11}	3.33×10^{-11}	5
8	36.00	38.00	166.55	164.55	4.71×10^{-10}	2.35×10^{-10}	9
9	34.00	36.00	168.55	166.55	1.61×10^{-5}	8.05×10^{-6}	301
10	32.00	34.00	170.55	168.55	6.08×10^{-5}	3.04×10^{-5}	469
11	30.00	32.00	172.55	170.55	8.15×10^{-8}	4.08×10^{-8}	52
12	28.00	30.00	174.55	172.55	9.41×10^{-6}	2.01×10^{-6}	252
13	26.00	28.00	176.55	174.55	9.67×10^{-7}	4.83×10^{-7}	118
14	24.00	26.00	178.55	176.55	4.47×10^{-5}	2.23×10^{-5}	423
15	42.50	43.00	160.05	159.55	4.01×10^{-10}	8.03×10^{-10}	9
16	42.20	42.70	160.35	159.85			
17	41.90	42.40	160.65	160.15			
18	41.60	42.10	160.95	160.45	2.14×10^{-4}	4.29×10^{-4}	714
19	41.40	41.90	161.15	160.65	2.69×10^{-9}	5.38×10^{-9}	17
20	41.10	41.60	161.45	160.95	4.45×10^{-10}	8.90×10^{-10}	9
21	40.80	41.30	161.75	161.25	5.76×10^{-11}	1.15×10^{-10}	5
22	40.50	41.00	162.05	161.55			
23	40.20	40.70	162.35	161.85			
24	39.90	40.40	162.65	162.15			
25	36.00	36.50	166.55	166.05	5.13×10^{-10}	1.06×10^{-9}	10
26	35.70	36.20	166.85	166.35			
27	35.40	35.90	167.15	166.65	4.23×10^{-11}	8.46×10^{-11}	4
28	35.10	35.60	167.45	166.95			
29	34.80	35.30	167.75	167.25	8.88×10^{-7}	1.78×10^{-6}	115
30	34.50	35.00	168.05	167.55	1.56×10^{-5}	3.13×10^{-5}	298
31	34.20	34.70	168.35	167.85	2.60×10^{-10}	5.20×10^{-10}	8
32	33.90	34.40	168.65	168.15			
33	33.60	34.10	168.95	168.45			
34	33.30	33.80	169.25	168.75			
35	33.00	33.50	169.55	169.05			
36	32.70	33.20	169.85	169.35			
37	32.40	32.90	170.15	169.65	1.18×10^{-7}	2.36×10^{-7}	58
38	32.10	32.60	170.45	169.95			
39	31.80	32.30	170.75	170.25	9.26×10^{-5}	1.85×10^{-4}	540
40	31.50	32.00	171.05	170.55			
41	24.00	24.50	178.55	178.05	3.57×10^{-8}	7.14×10^{-8}	39
42	23.70	24.20	178.85	178.35	1.38×10^{-8}	2.76×10^{-8}	29

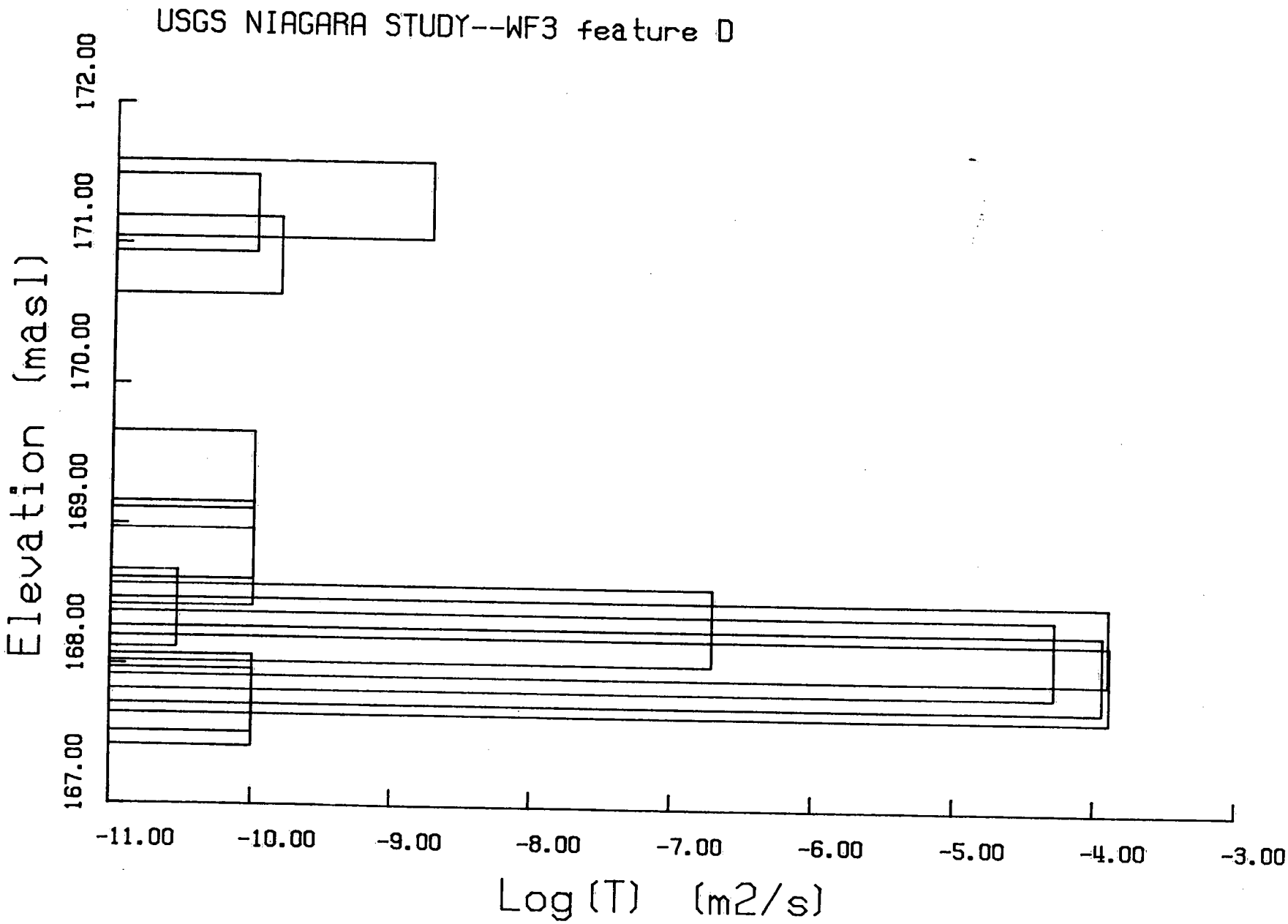
APPENDIX B

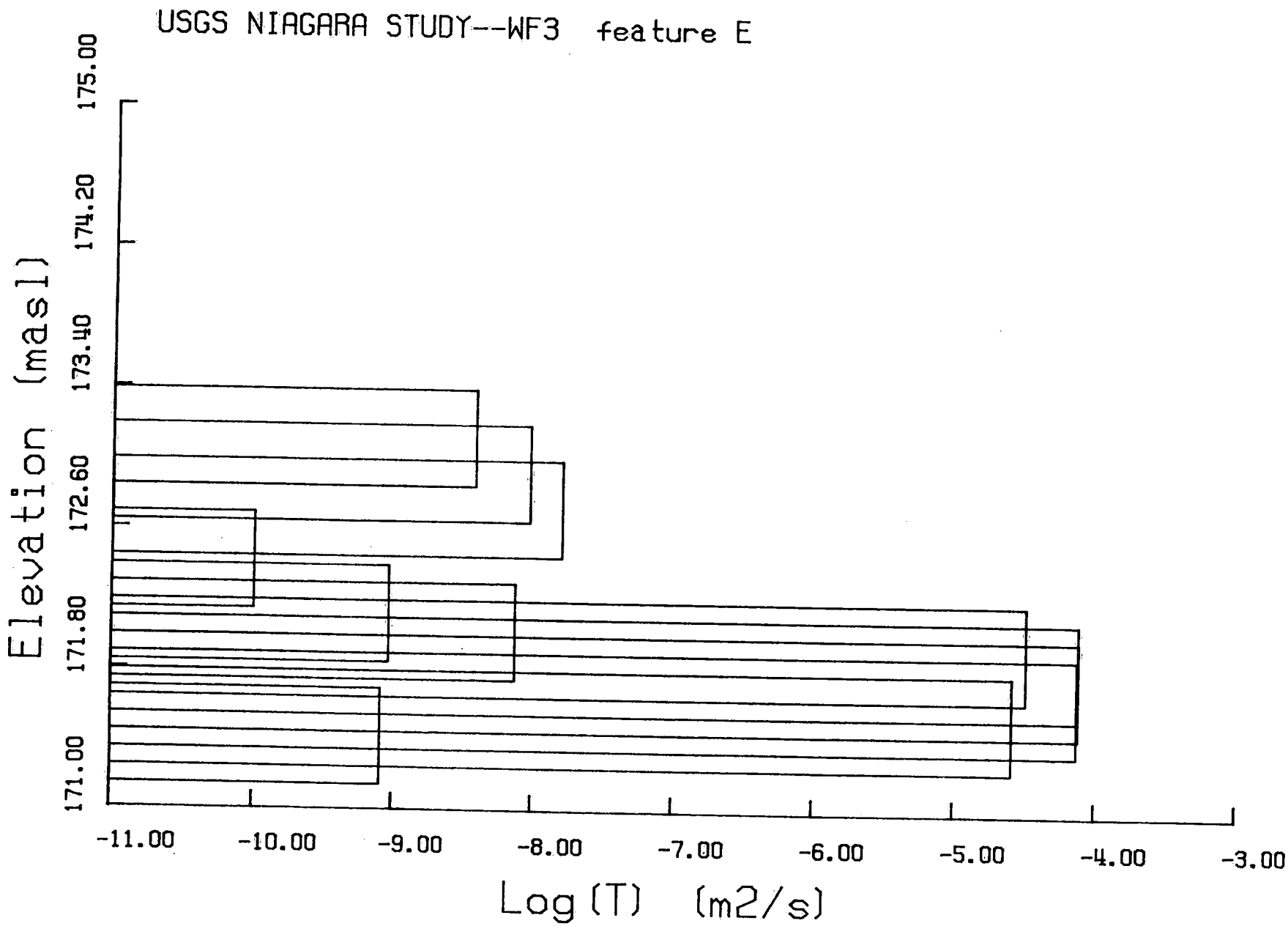
PLOTS OF SHORT INTERVAL CONSTANT HEAD INJECTION TESTS

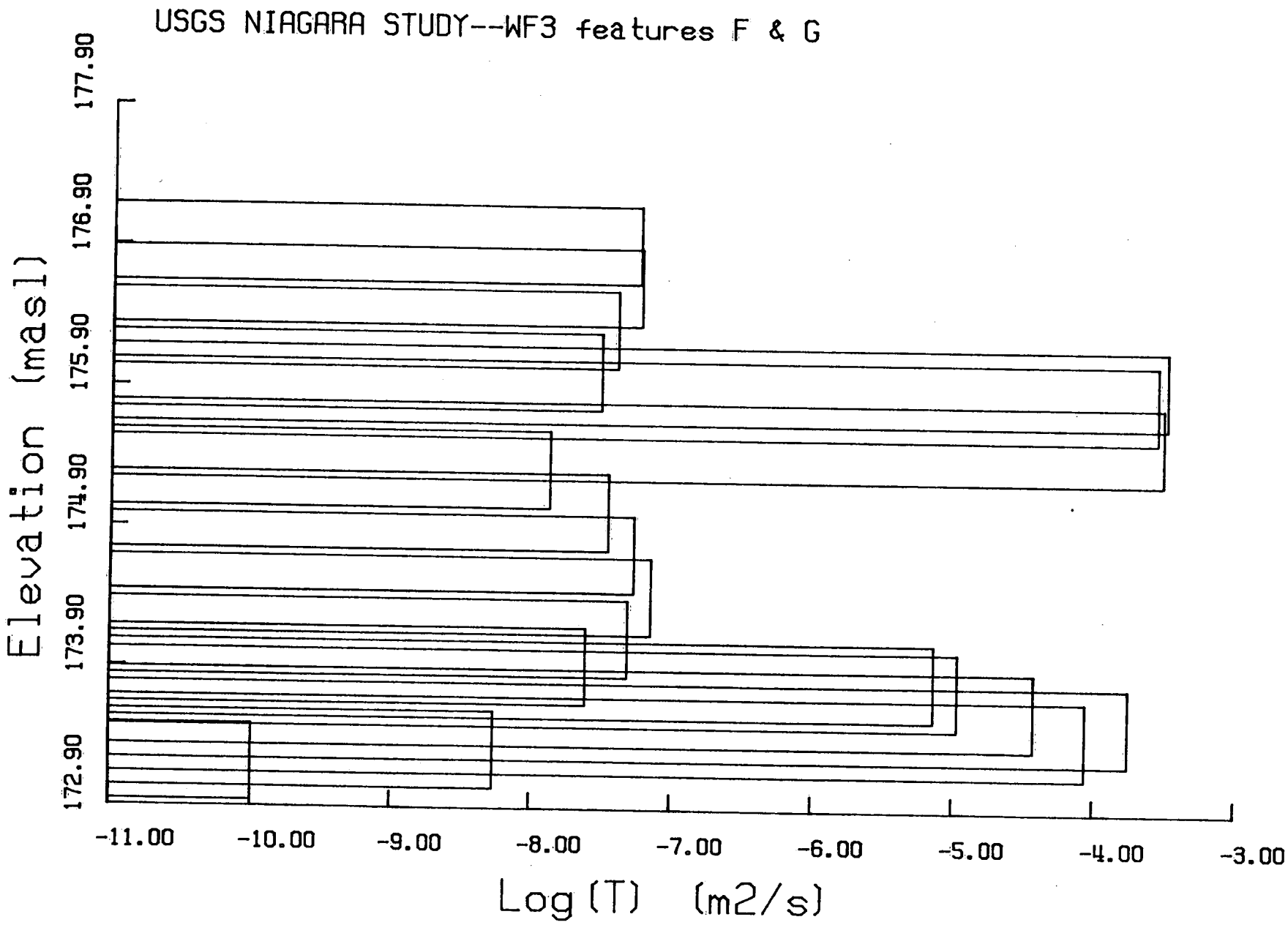

USGS NIAGARA STUDY--WF3 feature A
Elevation (masl)
161.20
160.20
159.20
158.20
157.20
156.20
-11.00
-10.00
-9.00
-8.00
-7.00
-6.00
-5.00
-4.00
-3.00
Log (T) (m2/s)

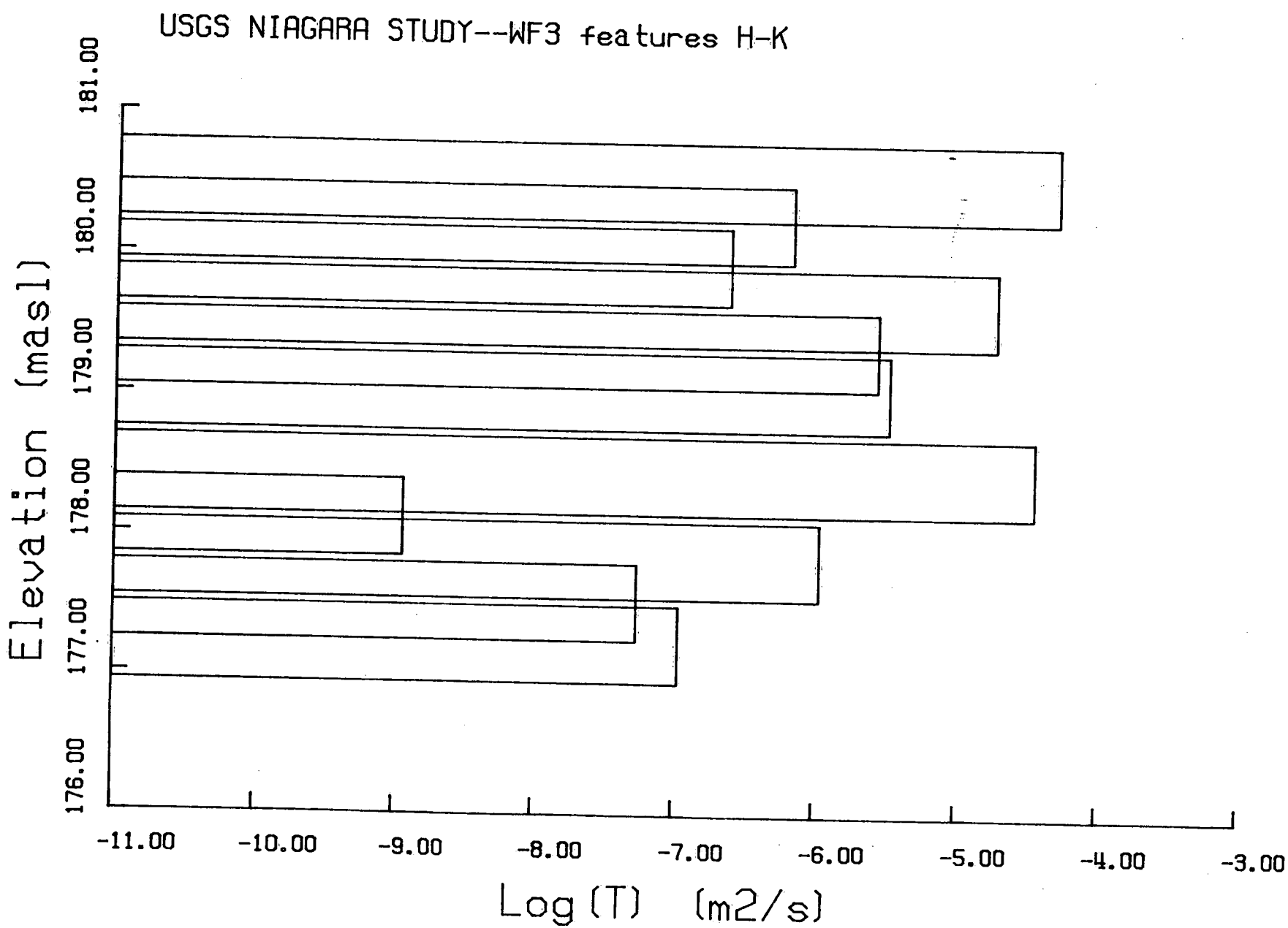

USGS NIAGARA STUDY--WF3 feature B
Elevation (masl)
164.00
163.20
162.40
161.60
160.80
160.00
-11.00
-10.00
-9.00
-8.00
-7.00
-6.00
-5.00
-4.00
-3.00
Log (T) (m2/s)

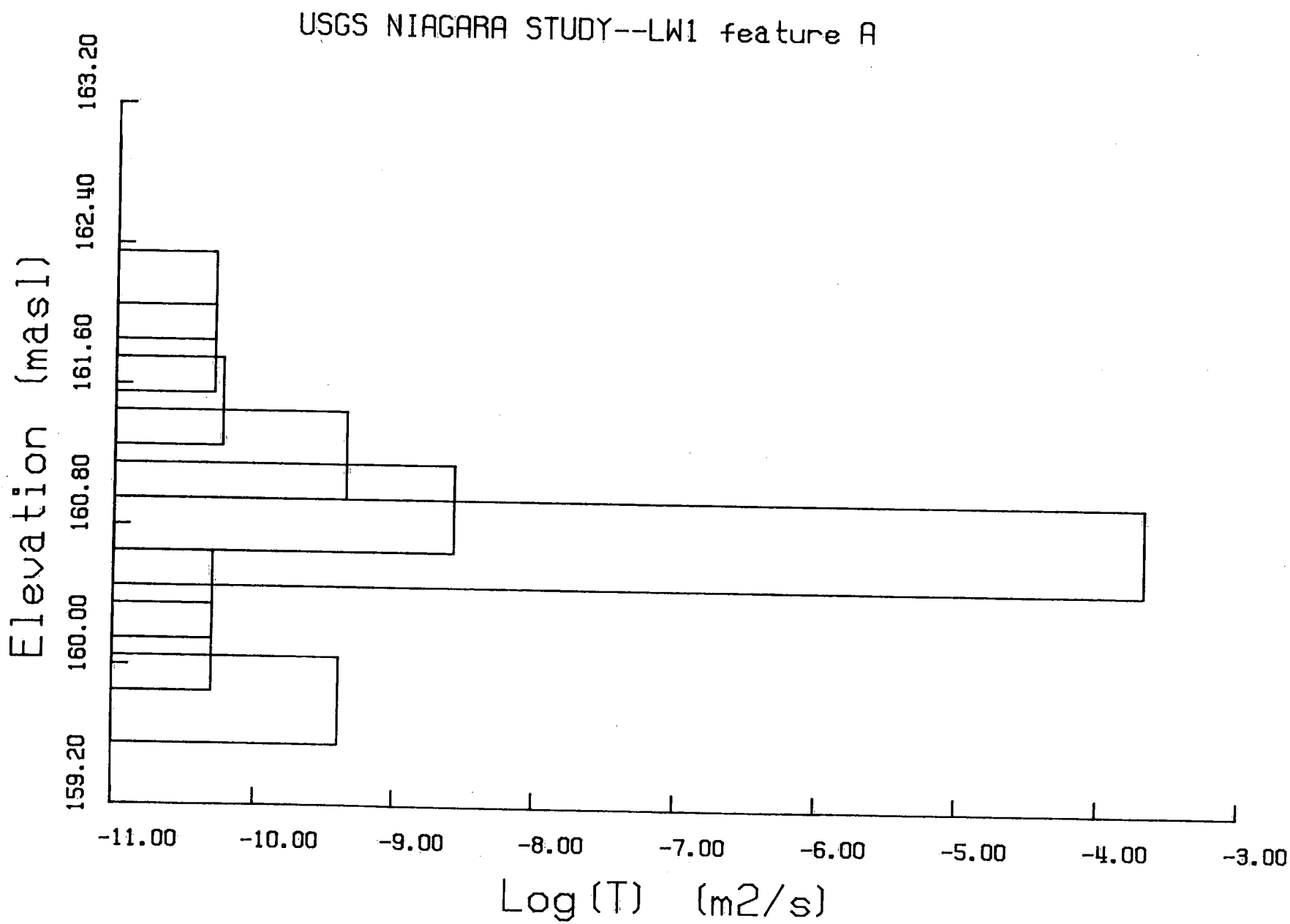

USGS NIAGARA STUDY--WF3 feature C
Elevation (masl)
168.00
167.20
166.40
165.60
164.80
164.00
-11.00
-10.00
-9.00
-8.00
-7.00
-6.00
-5.00
-4.00
-3.00
Log (T) (m2/s)

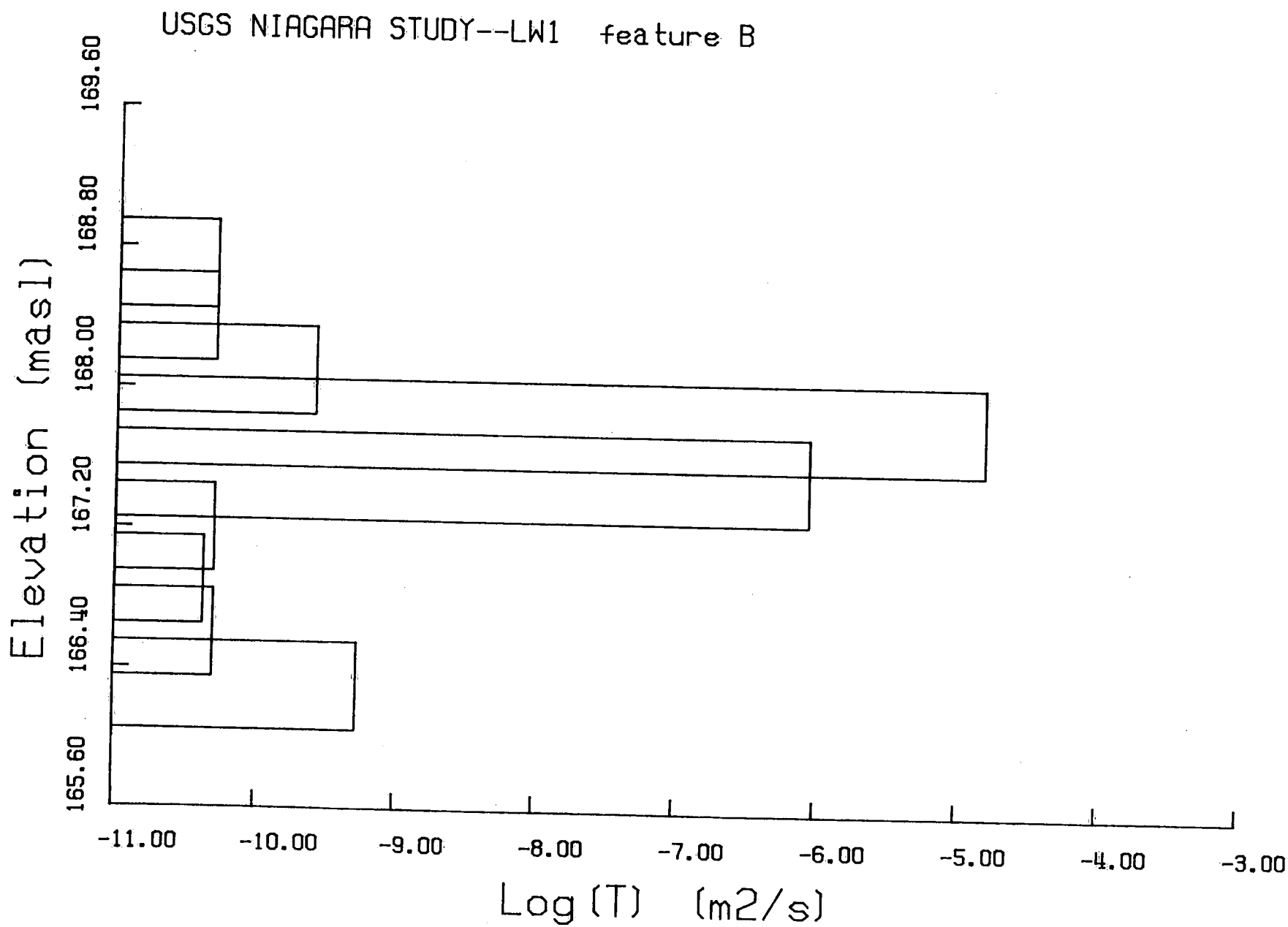

USGS NIAGARA STUDY--WF3 feature D
Elevation (masl)
172.00
171.00
170.00
169.00
168.00
167.00
-11.00
-10.00
-9.00
-8.00
-7.00
-6.00
-5.00
-4.00
-3.00
Log (T) (m2/s)

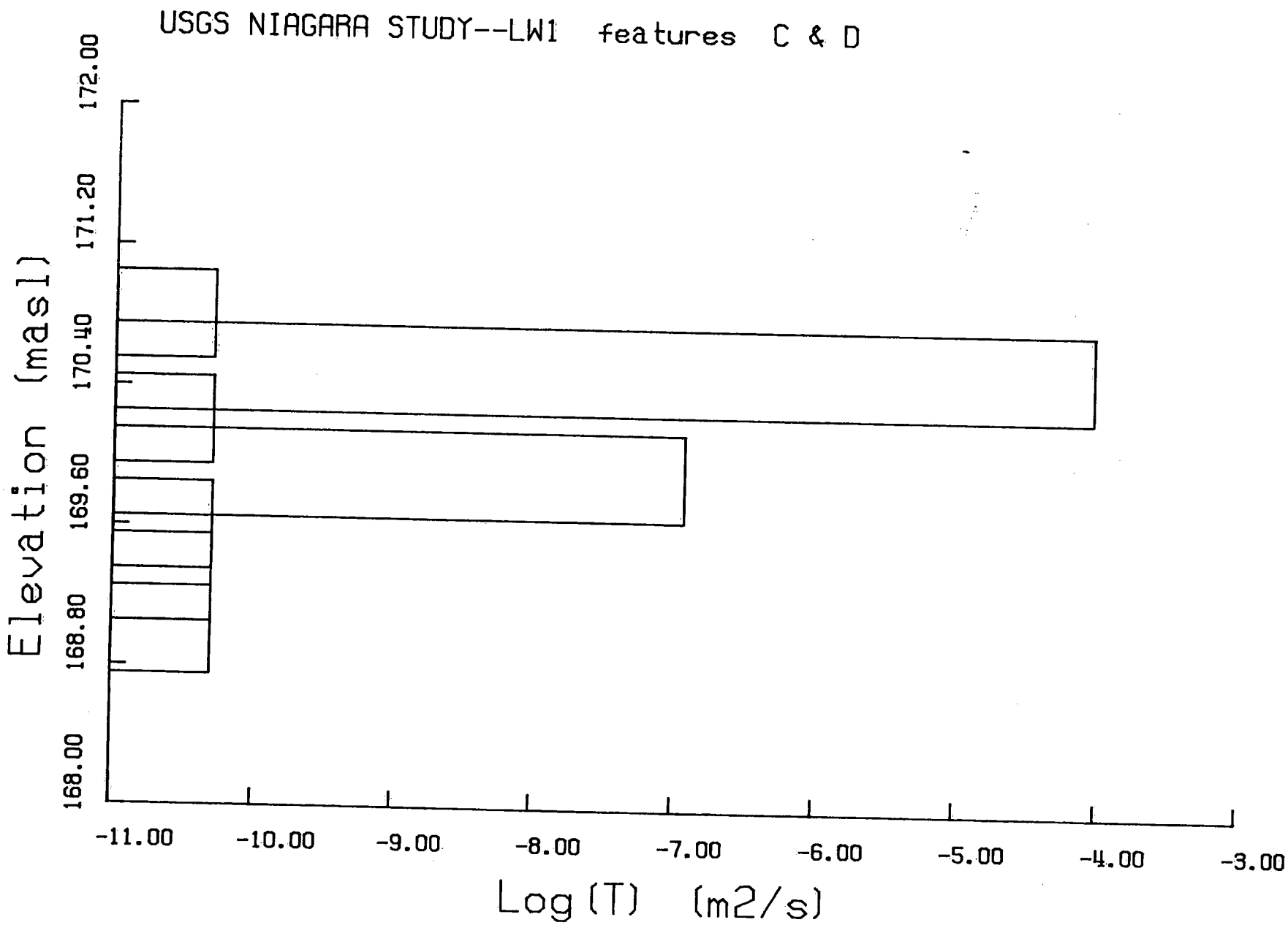

USGS NIAGARA STUDY--WF3 feature E
Elevation (masl)
175.00
174.20
173.40
172.60
171.80
171.00
-11.00
-10.00
-9.00
-8.00
-7.00
-6.00
-5.00
-4.00
-3.00
Log (T) (m2/s)


USGS NIAGARA STUDY--WF3 features F & G
Elevation (masl)
177.90
176.90
175.90
174.90
173.90
172.90
-11.00
-10.00
-9.00
-8.00
-7.00
-6.00
-5.00
-4.00
-3.00
Log (T) (m2/s)


USGS NIAGARA STUDY--WF3 features H-K
Elevation (masl)
181.00
180.00
179.00
178.00
177.00
176.00
-11.00
-10.00
-9.00
-8.00
-7.00
-6.00
-5.00
-4.00
-3.00
Log (T) (m2/s)


USGS NIAGARA STUDY--LW1 feature A
Elevation (masl)
163.20
162.40
161.60
160.80
160.00
159.20
-11.00
-10.00
-9.00
-8.00
-7.00
-6.00
-5.00
-4.00
-3.00
Log(T) (m2/s)


USGS NIAGARA STUDY--LW1 feature B
Elevation (masl)
169.60
168.80
168.00
167.20
166.40
165.60
-11.00
-10.00
-9.00
-8.00
-7.00
-6.00
-5.00
-4.00
-3.00
Log (T) (m2/s)


USGS NIAGARA STUDY--LW1 features C & D
Elevation (masl)
172.00
171.20
170.40
169.60
168.80
168.00
-11.00
-10.00
-9.00
-8.00
-7.00
-6.00
-5.00
-4.00
-3.00
Log (T) (m2/s)