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H-936

WITNESS STATEMENT FOR REPLY EVIDENCE OF STANLEY FEENSTRA

In the Matter of the Consolidated Hearing for the Environmental Assessment of the Proposed Halton Landfill.

INTRODUCTION

I am a hydrogeochemist and President of Applied Groundwater Research Ltd. of Mississauga, Ontario. My involvement in the hydrogeological assessment of the candidate sites for the proposed Region of Halton Landfill began in the spring of 1986. My initial work was performed as a sub-consultant to Trow Hydrology Consultants Limited and resulted in the preparation of a report entitled "Evaluation of Groundwater Contaminant Migration at the Candidate Sites for the Proposed Region of Halton Landfill" dated July 2, 1986. This report is filed as Exhibit H-86. Prior to my testimony before the Hearing, I prepared a Witness Statement dated October 4, 1987 and filed as Exhibit H-86A. My testimony before the Hearing took place on October 14, October 15, October 19, October 20 and October 21, 1987 and is reported in Volumes 42, 43, 44, 45 and 46 of the transcripts. On behalf of the Region of Halton, I have been present at the Hearing for, or reviewed the transcripts of all of the testimony related to hydrogeology and most of testimony related to landfill design for Sites D and F.

This Witness Statement summarizes the topics related to the hydrogeological assessment of the candidate sites, Site D and Site F, which I will address in reply evidence. Included with this Witness Statement are four attachments to which I refer in the following paragraphs.

SITE D

1. The possibility of fractures extending downward through the unweathered Upper Till was discussed at length by Mr. Estrin and Mr. Petrie during cross-examination of Mr. Petrie (Transcripts v. 122, p. 29,504 to 29,606). Mr. Estrin and Mr. Petrie discussed fracturing in the Maryhill Till in Waterloo and the unweathered basal Vandalia Till in Illinois. The Vandalia Till is of Illinoian Age (>225,000 years) and has experienced a considerably different history than the late Wisconsin tills such as the Maryhill and the Halton Till (<15,000 years) in southern Ontario, and these tills are not likely comparable in terms of the nature and origin of fracturing. However, both examples do illustrate that evidence of fracturing cannot be determined from laboratory hydraulic conductivity tests and from Hvorslev (slug) tests in vertical boreholes. Mr. Petrie described that angled boreholes and

test pits are appropriate methods for investigating the presence of fractures and neither of these methods was used at Site D.

In June of 1988 I was asked by Dr. John Cherry of the University of Waterloo (UW) to review a draft of a paper which he and Wilf Ruland had prepared entitled "The Depth of Fractures and Active Groundwater Flow in a Weathered Clayey Till in Lambton County, Ontario". This paper described the results of their research which found physical evidence of chemically weathered fractures to a depth of 5.6 m and has found evidence of tritium penetration and seasonal water level fluctuations to depths of 10 to 12 m at some sites, well below the depth at which the till shows visual evidence of weathering. This paper was derived from a Masters project by Mr. Ruland (see Attachment 1). These results differ from the first studies conducted by UW at Sarnia and several other sites in Eastern North America starting in 1979 which indicated tritium only as deep as the weathered zone and it was assumed that this simply meant that open fractures did not extend deeper than the weathered zone. This finding appeared consistent from site to site but only a relatively small number of tritium profiles were developed. For the research by Ruland, more detailed tritium profiles have been developed at more sites spanning a wider range of settings. These studies have found much deeper penetration of tritium and evidence for fractures extending below the zone of weathering. These results together with the discussion of fracturing by Mr. Petrie and Mr. Estrin led me to consider the possibility and implications of fracturing in the unweathered upper till at Site D.

2. In the work done at Site D, it was assumed that the depth of fracturing and the depth of weathering coincided. The weathered zone and therefore the fractured zone extended only to a depth of approximately 4 m below ground surface. The unweathered Upper Till from a depth of 4 m to 7 or 8 m was assumed to be unfractured. If, however, the unweathered Upper Till underlying the landfill is fractured, the assessment of potential contaminant migration out of the landfill must be very different than that performed by THCL and Dr. Rowe. Though matrix diffusion may result in some degree of attenuation, the very short travel path (3 to 4 m) would result in a rapid impact on the groundwater quality in the Upper Granular Unit (UGU) in the event of failure of the hydraulic trap.

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3. The presence of fractures through the unweathered Upper Till has not been confirmed or even suggested by field data at Site D (though test pits and angled boreholes were not used) and would appear to contradict the lack of tritium in the THCL tritium nest and the lack of tritium in the UGU and Lower Granular Unit (LGU) pumping test discharge water. However, the lack of tritium in the UGU and LGU could be explained by the fact that some of

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the water supplying these zones at Site D may be older water derived from the upward gradients from the bedrock. The lack of tritium at a single nest of piezometers may be due to the fact that the vertical fractures extending through the unweathered Upper Till are widely spaced (metres or so) and were not intersected at that location. It may also be that the upper 4 m or so of the weathered till afforded a significant degree of attenuation (due to closer fracture spacing) and reduced the tritium at deeper levels.

4. The presence of vertical fractures in the unweathered Upper Till could not likely be detected by Hvorslev tests in vertical boreholes due to smearing of the surface of the borehole and/or if the fractures were not intersected because of their wide spacing, and could not be identified by laboratory hydraulic conductivity tests. There was no evidence of significant vertical leakage (ie. flattening of the log-log drawdown plots shown in the THCL Report Exhibit H-39A, Appendix 10) during pumping test PW-2 but the effects of boundary conditions may have masked any effects of minor vertical leakage.

5. Based on the hydraulic conductivity of the fractured clay till in the weathered zone at Sarnia and the possible fracture frequency at greater depths, the bulk hydraulic conductivity of sparsely fractured unweathered till at Site D might be in the range of 10^{-6} to 10^{-7} cm/s. This range is not unlike that suggested by Dr. Rowe (Rowe Report Exhibit M-442, p. 21) but he gave no indication that he expected fracturing to impart these values which exceeded those measured by TCHL by Hvorslev tests in vertical boreholes. Indeed if one considers that this hydraulic conductivity is imparted by fracturing, the travel velocities for contaminants would be much higher than suggested by Dr. Rowe and THCL because of a much lower transport porosity. Because the hydraulic conductivity of weakly fractured till is not likely to be significantly higher than the range previously suggested for this unit, the flux (flow rate) of contaminants from the landfill, and consequently the boundary concentrations, for the fractured case might not be significantly different from many of the estimates made previously. However, the travel times will be much shorter.

6. The assessment of the existence and characteristics of fractures in the unweathered Upper Till is a difficult one. Deep trenching and physical examination of the till might enable one to identify the presence or absence of fractures but cannot indicate whether the fractures are open unless groundwater flow is actually observed (possible but not very likely). In any case, the hydraulic conductivity cannot be quantified in this way. In addition, the excavation and careful examination of trenches 7 to 8 m in depth is not a trivial undertaking. Angled borings may be able to intersect fractures if the fracture spacing is not more than several metres. The presence of fractures may be evident in core samples. The hydraulic

conductivity of the fractures identified in angled borings could be determined using Hvorslev (slug) tests if piezometers were installed precisely where the fractures were located and in such a way as to remove or minimize the zone of smearing from the surface of the borehole.

7. The presence of fractures extending through the unweathered upper till has a significant effect on the nature of contaminant transport through this unit. In the event of failure of the hydraulic trap, contamination of the UGU may occur rapidly (less than a year). Though there are no site-specific data indicating the presence of fractures at Site D, at this time, it is my opinion that it is a reasonable possibility that they exist.

8. In the event that fractures extend through the upper unweathered till, a groundwater monitoring plan such as typically implemented at municipal landfills in Ontario will not be sufficient to protect the nearby groundwater users. Groundwater monitoring programs at municipal landfills in Ontario typically involve the sampling of monitoring wells on an annual or bi-annual basis. The process of sample collection, analysis in the laboratory, evaluation of the data, re-sampling and re-analysis of anomalous results, and preparation of a monitoring report can frequently take 1 to 2 months. At Site D, in the event that failure of the hydraulic trap is detected either by monitoring within the landfill itself or monitoring in the groundwater adjacent to the landfill, implementation of the primary contingency of purge wells likely would require 4 to 6 months for design, installation and testing. In the case where the unweathered upper till is unfractured and travel times are measured in years, these time requirements are not problematic. However, for the case where the unweathered upper till is fractured and travel times may be less than a year, the time required for detection of groundwater contaminants and construction of the purge wells, contaminants from the landfill may result in impacts on the nearby groundwater users.

9. Much of the time delay in the implementation of the contingency could be eliminated by design, installation and testing of the purge well system before the start of landfilling. In this way, if groundwater contaminants or a failure of the hydraulic trap are detected, capture along the site boundary can commence immediately. In addition, in selected key areas such as along the First Line, monitoring should be sufficiently frequent with respect to estimated contaminant travel times for early detection of contamination. During the installation and testing of the purge well system, information can be gathered with regard to the continuity of the granular units westward toward the First Line and beneath the site. In addition, detailed pumping tests of the type discussed by Mr. Estrin and Mr. Petrie (Transcripts v. 122, p. 29,504 to 29,560) could be conducted to assess the presence of fractures in the unweathered upper till.

This information can be used effectively to design the final groundwater monitoring program.

10. The potential impact on the nearby groundwater users could also be eliminated by connection of these residences to a piped municipal water supply. This action would not eliminate the possible impact of off-site contaminant migration on surface water surrounding the site. Such impacts must also be controlled but the time frame is longer because these receptors are generally located at greater distances from the landfill and human health and safety will not be directly effected. The effect of fractures extending through the unweathered upper till can also be eliminated by construction of a liner of re-compacted native clay silt till on the base of the landfill.

11. The THCL and CRA landfill designs for Site D call for a head difference of 0.4 m between the maximum leachate mound height and the hydraulic head in the underlying geological units (primarily the Upper Granular Unit or UGU). The head in the UGU must be greater than the head of leachate in the landfill to prevent flow of leachate downward out of the landfill into the underlying geological units. The head difference of 0.4 m can be considered a margin of safety in maintenance of the hydraulic trap. Factors which act to increase the leachate head or decrease the head in the UGU will serve to create a failure of the hydraulic trap.

12. Of concern with respect to the maintenance of the hydraulic trap are factors which could result in widespread declines in the head in the UGU. The THCL design is based on only a short period of groundwater level monitoring, for most wells less than one year from Sept. 85 to Apr. 86 (THCL Report H-39A, Appendix 8). The design does not take into account possible year to year fluctuations due to dry years (drought). The effect of drought will be twofold. Firstly, there may be less infiltration of water into the groundwater system, and secondly, drought will also result in greater groundwater usage and this increased pumping may also reduce groundwater levels. For the UGU, THCL calculated (THCL Report H-39, p. 133) that 2 purge wells pumping at a rate of 12.6 L/min. (2.8 Igpm) would create a sufficiently large zone of influence to control groundwater flow across the entire site. If private wells began pumping at significantly increased rates for lawn watering, irrigation or livestock, groundwater levels beneath the site could be affected similarly (Charlesworth Report Exhibit M-438, p. 6-6). Groundwater fluctuations of 0.4 m (the margin of safety for the hydraulic trap) are not large in the context of year to year changes in recharge and groundwater usage. Intermittent short-term (seasonal) failure of the hydraulic trap is not critical if the travel times through the unweathered upper till are measured in years (ie. no fractures)

(Testimony by Mr. Sobanski, Transcripts v. 23, p. 5,385) . However, if the unweathered upper till is fractured, even seasonal failure of the hydraulic trap could allow contaminants to enter the UGU.

13. Another factor which could act to reduce the groundwater level in the Upper Granular Unit is the reduction in the area of recharge to the UGU due to the creation of a large landfill above. Unless the UGU is continuous off-site to a significant degree, a large proportion of the water which enters the UGU likely originates as infiltration directly on Site D. When the landfill is built and hydraulic trap in operation, this recharge will be cut off .

14. A simplified calculation based on the area of the proposed landfill (53.2 ha, THCL Report H-41, p. 50) and an infiltration rate of 9.5 mm/a (THCL Report H-39, p. 66) suggests that approximately 10 L/min (2.2 Igpm) could enter the UGU from above under natural pre-landfill conditions. A reduction of the infiltration to the UGU of this order is comparable to the amount of groundwater withdrawal suggested by THCL for a purge well system in the UGU. The purge well system is expected to result in a significant reduction in water levels in the UGU and consequently it is reasonable to expect that a reduction in the recharge to the UGU from above could also reduce the groundwater levels in the UGU. The degree to which this reduced recharge will effect the groundwater levels beneath the site will depend on the relative proportion of the reduction in recharge, how readily the reduced recharge can be replaced by inducing groundwater flow from other sources, and the proportion of the flow in the UGU which is utilized by wells drawing from this unit.

15. During testimony by Dr. Charlesworth (Exhibit M-438, p. 5-4), it was indicated that there are upward gradients from the bedrock into the LGU and UGU in some areas on Site D. If this is the case, then much of the groundwater in the UGU may originate from below rather than above, and the effect that the landfill might have on the water levels in the UGU will be less. The effect of the landfill itself on the groundwater levels beneath the site is difficult to quantify without a computer model and a good understanding of the areal extent of the units, the existing recharge and discharge areas, and the groundwater flow patterns. A more detailed understanding of the groundwater flow system would be required before a rigorous evaluation of the effect of the landfill on groundwater levels beneath the landfill can be made. Groundwater level monitoring will necessarily be a part of the groundwater monitoring program at Site D, but specific emphasis should be placed on identifying and characterizing short-term and long-term groundwater level fluctuations in the units underlying the landfill because of their key role in maintenance of the hydraulic trap.

16. In the event that drought or reduced recharge due to the landfill result in significant reductions in the groundwater level in the UGU, rather than purging contaminated groundwater from the UGU, it may be possible to maintain the hydraulic trap by recharging the UGU using a series of injection wells. Water could be obtained from piped municipal supply or from bedrock or basal overburden zones to surcharge the UGU to maintain a hydraulic head above that of the leachate in the landfill. There are various potential difficulties in the operation of such a system which must first be addressed such as clogging or chemical precipitation in the injection wells, long-term changes in water quality in the UGU and a reliable source of injection water.

17. In summary, in my opinion there is a reasonable possibility that fractures extend through the unweathered upper till and these fractures may provide a rapid pathway for the movement of contaminants from the landfill into the UGU in the event of the failure of the hydraulic trap. It is also my opinion that reductions in the groundwater level in the UGU due to drought or the effect of reduced recharge due to the landfill may result in seasonal or long-term failure of the hydraulic trap. The conditions described in these opinions can be overcome by modifications to the proposed contingencies, monitoring or landfill design and Site D can be made to be suitable for landfilling but these modifications will be more involved and will likely be more costly than the original designs.

SITE F

18. The following discussion of Site F is presented in response to the opinion of Mr. Petrie that the hydrogeological conditions at Site F are unsuitable for siting a landfill because they are too complex to be understood sufficiently. Based on the available data and the performance of the Burlington and Bayview landfills, it is my opinion that there is sufficient information available to develop an understanding of the hydrogeological conditions to allow a satisfactory assessment of the suitability of Site F for landfilling.

19. Examination of rock core from the shale beneath Site F indicates the presence of many horizontal and dipping discontinuities such as fractures, bedding plane openings, sealed fractures and clay mud seams. Occasional vertical discontinuities were also observed in the core. Open fractures and bedding planes provide the pathways for groundwater flow horizontally and vertically through the shale. Examination of the rock core and correlation between boreholes indicate a zone of fractured and weathered shale in the upper several metres of the bedrock. Mr. Petrie labelled this zone as the "weathered mantle" (CRA Report Exhibit B-617, p. 151). Underlying this, is a zone which contains fewer fractures and more

sections of intact unfractured shale between the fractures. Some of these sections of intact core are up to 1.5 m in length. Underlying this zone is a zone of more frequent fracturing though many fractures are still separated by lengths of intact shale core.

20. These zones correspond to the Hydrostratigraphic Units defined by THCL: Unit 2 - the Moderately Fractured and Weathered Shale, Unit 3 - the Weakly Fractured Shale and Unit 4 - the Highly Fractured Shale. These units are not units which can be strictly characterized in terms of areal and vertical extent and hydraulic properties. For example, within the moderately fractured and weathered shale unit there will be low hydraulic conductivity zones through which there are no fractures. Similarly, within the weakly fractured shale unit there will be zones which contain fractures. The simplification of the site conditions into the hydrostratigraphic units is necessary to allow estimation of parameters such as infiltration rates and contaminant migration pathways.

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21. The key contaminant migration pathways identified by THCL were lateral migration through the Moderately Fractured and Weathered Shale, and downward through the Weakly Fractured Shale and then laterally through the Highly Fractured Shale. It was assumed that lateral flow through the Moderately Fractured and Weathered Shale would either discharge on-site or be otherwise captured in a perimeter drain system. Downward flow was considered to occur through the Weakly Fractured Shale unit having a hydraulic conductivity of 1×10^{-7} cm/s. Lateral flow through the Highly Fractured Shale was considered to occur rapidly through a zone of much higher hydraulic conductivity (1×10^{-4} cm/s or greater). Simulations of contaminant migration performed for this scenario and reported in the THCL Report Exhibit H-40 were considered to be conservative but generally consistent (given the range of uncertainty in the model input parameters) with the observations of contaminant migration made by the University of Waterloo (UW) then thought to be the case for the Bayview Landfill. That is, there were measurable levels of organic contaminants in the shallow and deep groundwater at distances of up to 800 m from the landfill which developed during the 30 years since landfilling commenced (Hewetson Thesis Exhibit E-214). At that time, there had been no attempt to assess the occurrence of high chloride concentrations in the groundwater or to reconcile the distribution of organic contaminants with the chloride concentrations in the groundwater.

22. Results of the 1986 groundwater monitoring program at the Burlington Landfill indicated that there was little if any migration of organic contaminants south of the landfill in the 15 years since landfilling commenced at the site. These, data plus some data collected by THCL south of the Bayview site were not consistent with the extent of migration of organic

contaminants observed by UW at Bayview. This inconsistency caused me to re-evaluate (Feenstra Witness Statement Exhibit H-86A) the results of the groundwater monitoring at both Bayview and Burlington. My conclusion from this re-evaluation is that the organic chemical concentrations observed south of Bayview are, most or perhaps all, the result of extraneous contamination from the piezometer installations and do not reflect actual groundwater concentrations.

23. The 1987 groundwater monitoring results from Burlington indicate that low concentrations of organic contaminants have migrated as far as 25 m south of the Burlington site in the upper several metres of the shale bedrock. The concentrations of volatile organic contaminants at this location are considerably lower than those measured in the leachate from the Burlington leachate collection system indicating a significant degree of attenuation during migration through the shale.

24. At the Bayview site, it is not possible to determine the extent of migration of organic contaminants based on the UW study because of the effect of extraneous contamination from the piezometer installations. However, the highest concentrations of chlorobenzene and 1,4-dichlorobenzene occur in the shallow shale (MB-1-2) immediately south of the landfill. Though the true concentrations in the groundwater are likely to be lower than these values due to the contribution of extraneous contaminants from the monitoring wells, these results probably indicate contaminant migration through the upper shale at this location.

25. In May 1988, Conestoga-Rovers (CRA) pumped and sampled THCL pumping well PW-3 screened in the upper 3 to 10 m of the shale and located approximately 200 m south of the Bayview site. Low concentrations (2 to 6 μg/L) of chlorobenzene and 1,1,1-trichloroethane were detected and these compounds likely represent landfill derived contaminants. Xylene and benzene were also detected at low concentrations (1 to 2 μg/L) but these compounds may occur naturally in the shale. The pumping well was constructed of steel casing which was not specifically cleaned before installation. However, because the wells was pumped at a significant rate (several litres per minute) for several hours before sampling, the effects of any extraneous contamination are expected to be minimal compared to the sampling of a monitoring well or piezometer which is only purged of its standing water several times. The results from PW-3 suggest there may be some degree of lateral migration of organic contaminants through the upper portion of the shale south of the landfill.

26. In May 1988, CRA also pumped and sampled THCL pumping well PW-1 which is screened at a depth of approximately 4 to 22 m below bedrock surface and located at a distance of 600 m

south of the landfill. Only a trace of toluene (3.7 μg/L) was detected in PW-1 and toluene can occur naturally in the shale. PW-1 is screened considerably deeper than PW-3 and these results give no indication that organic contaminants are found deeper in the shale at this location.

27. The apparent extents of contaminant migration at the Bayview and Burlington landfills are generally comparable. The migration of organic contaminants has occurred laterally through the upper portions of the shale. The rate of migration has been much less than would be expected based on the hydraulic conductivity measured in the weathered shale ($\sim 10^{-4}$ cm/s), the hydraulic gradient and the estimated transport porosity. Travel velocities of 100 m/year would be estimated. Computer simulations performed by Dr. Rowe for his reply evidence indicate that matrix diffusion and sorption processes in the weathered shale cannot account for the degree of attenuation observed. The most likely explanation for observed extent of migration is that the weathered upper shale is not a continuous zone having a horizontal hydraulic conductivity of $\sim 10^{-4}$ cm/s and some areas of the weathered upper shale have hydraulic conductivities significantly lower. This interpretation is consistent with the observed limited extent of influence during pumping tests PW-2, PW-3 and PW-4.

28. The potential vertical migration of contaminants is less readily evaluated because there is no reliable way to identify directly the degree of vertical fracturing and the vertical hydraulic conductivity of the shale strata. Occasional vertical fractures have been identified in the rock core but it is not possible to determine their frequency or measure their hydraulic conductivity with packer tests as can be done for horizontal fractures. The presence of significant sections of intact (unfractured) shale in the rock core indicates that there are likely zones of very low hydraulic conductivity in the shale. The hydraulic conductivity of intact shale from Site F has not been determined but is likely to be as low as 10^{-9} to 10^{-10} cm/s (Testimony by Mr. Petrie, Transcripts v. 117, p. 28,221). Horizontal hydraulic conductivities in the range of 10^{-7} to less than 10^{-8} cm/s have been measured in the shale so that vertical hydraulic conductivities could be in the range of 10^{-8} cm/s or lower provided there are no significant vertical fractures. The strong vertical downward hydraulic gradients present on-site can only be explained by zones of low vertical hydraulic conductivity within the shale strata. The limited extent of influence vertically due to the pumping tests at PW-1, PW-2 and PW-3 also supports the interpretation that zones of low hydraulic conductivity exist in the shale, even in the upper weathered portion of the shale.

29. Insight into the vertical hydraulic conductivity of the shale strata can also be gained by consideration of the chloride and tritium concentrations in the groundwater. Groundwater

containing high chloride concentrations (5,000 to 50,000 mg/L) likely represents groundwater which originated in the shale or has resided in the intergranular pore space in the shale for a very long period of time (tens of thousands of years or more). Chloride cannot be derived from the dissolution of minerals in the shale (Chloride content of shale Exhibit H-660) The high chloride groundwater generally occurs deep in the shale strata. Groundwater flow through zones of high chloride concentrations either through the intergranular pore space or through any fractures which may be present is very slow. The vertical hydraulic conductivity of the shale in these areas must be very low to prevent the movement of low chloride groundwater from above into these deeper zones.

30. Groundwater containing low chloride concentrations (<1,500 mg/L) likely represents groundwater which has originated from infiltration of meteoric water from the ground surface. Low chloride groundwaters generally occur in the upper 5 to 10 m of the shale. Groundwater flow through the upper shale will occur through fractures. High chloride groundwater originally present in the fractures will be rapidly flushed out and low chloride infiltration will enter the fractures. As the infiltrating water moves through the fractures, chloride from the high chloride porewater in the porous matrix of the shale will diffuse into the water in the fractures. In this way, the infiltrating water acquires chloride concentrations. Where groundwater flow through the fractures is high, the chloride concentrations in the fractures will be relatively low but the high flow rates will rapidly remove chloride from the matrix of the shale. Where groundwater flow through the fractures is lower, chloride concentrations in the groundwater in the fracture will be higher and the removal of chloride from the shale matrix will be slower. Low chloride concentrations indicate regions of relatively active groundwater flow.

31. Groundwaters containing moderate chloride concentrations (1,500 to 5,000 mg/L) represent a transition between the zone of active groundwater flow the zone of inactive groundwater flow. This transition does not result from physical mixing of waters but rather reflects a zone in which the fracture characteristics (spacing, aperture and interconnection) allow more flow than in the inactive flow zone but less flow than in the active flow zone.

32. The relationship between tritium concentrations and chloride concentrations in groundwater at the Bayview Site and Site F was shown in Exhibit H-664. Tritium levels corresponding to post-1950 water are found in groundwaters containing less than 1,500 mg/L chloride and pre-1950 tritium levels are found in groundwaters having higher chloride concentrations. There are only 3 exceptions to this relationship (MB-16-3, MB-12-3 and HC-5-1) for the 24 samples compared. Given the possibility for the introduction of tritiated water

from overlying strata into the boreholes for deep monitoring wells installations, these results may reflect erroneously high tritium levels for these samples. In general, low chloride concentrations can be regarded as reflecting post-1950 groundwater and moderate chloride concentrations as reflecting pre-1950 groundwater although we do not know whether these waters have been in the system for tens, hundreds or a few thousand years. The high chloride groundwater can be regarded as reflecting water which has been in the system for thousands of years.

33. The tritium results indicate that in zones where chloride concentrations are low (<1,500 mg/L), residence time of the groundwater in these zones is less than 35 years. The existing Bayview and Burlington landfills are approximately 30 and 15 years old respectively. In the context of evaluation of groundwater contamination from these sites, contaminants should only be present in groundwater which contains post-1952 levels of tritium. Similarly, it is the zone in which chloride levels are low and tritium levels are high which will include the principal pathways for contaminant migration from Site F.

34. The groundwater flow system at Site F likely began to develop toward its present configuration after the final retreat of the glaciers approximately 12,000 years ago. Stress release due to rebound of the earth's crust during the several thousand years following retreat of the glaciers could have created fracturing and opened bedding planes in the shale and allowed the infiltration of meteoric water from the ground surface. During this time, infiltrating groundwater will have begun to remove chloride for the shale matrix. The extent to which chloride is removed from the shale will depend on the groundwater flow rate through the fractures (Darcy velocity) and the period of time over which flow occurred.

35. The rate at which chloride could be removed from the shale by groundwater flow through fractures was analysed by Dr. Rowe in Exhibit M-440, Appendix C. Based on a simplified scenario of downward infiltration of meteoric water through vertical fractures, Dr. Rowe suggests that an infiltration rate of 14 mm/a downward through the shale would result in a significant degree of chloride removal in only several hundred years. An infiltration rate of 1 mm/a would result in a significant degree of chloride removal in several thousand years. With the assumption that the geochemical character of groundwater flow system has developed during the last several thousand years, this analysis gives an indication of a generally low rate of infiltration (groundwater flow) vertically down through the deeper portions of the shale.

36. The geochemical character of the groundwaters in the Queenston shale beneath Site F indicates a vertical zonation with relatively shallow zone of active groundwater flow in which groundwater resides in the subsurface for tens of years or less, and a deeper zone of very inactive flow in which groundwater resides in the subsurface for thousands of years. Separating these zones is a transition zone in which it is not possible estimate whether residence times may be many tens, hundreds or a few thousand years. The geochemical character of the groundwater in the shale indicates a relatively good hydraulic connection (ie. higher vertical hydraulic conductivity) in the upper portions of the shale. This hydraulic connection is likely due to more intensive vertical fracturing in this zone.

37. The depth of this zone of more active groundwater flow varies from 0 m below bedrock surface at HC-8, HC-15 and GL-26 to approximately 20 m at HC-4. It is my opinion that the thickness of the active zone should be largely controlled by the degree of vertical fracture connection. Mr. Petrie suggested to Dr. Kingham (Transcripts v. 133, p. 32,131) that the thickness of the active zone (zone of low chlorides) may be greater in areas where there is no till cover. If one considers a scatter plot of thickness of the active flow zone to overburden thickness for all the boreholes having chloride data, no such relationship is evident (see Attachment 2).

38. The thickness of the active zone varies without an identifiable areal pattern across the Burlington, Bayview and Site F sites. For example, in each of the three areas south of the Burlington site and the Bayview site and on Site F, there are boreholes which indicate an active zone which is very thin from 0 to 5 m and boreholes which indicate a thicker active zone ranging from 10 to 15 m (see Attachments 3a, b, c and d, Attachment 4). Of particular significance with regard to Site F is the relatively thick active zone underlying the middle portions (HC-4 and HC-5) of the site. This suggests that leachate which exfiltrates the landfill may penetrate deeper (10 to 20 m) into the shale in this area than in areas such as beneath the existing Burlington and Bayview landfills. Within this active zone leachate may move laterally off-site. However, across the southern portion (HC-8) of the site the active flow zone is non-existent. This suggests that for leachate from northern and central portions of Site F to flow off-site, the leachate might be diverted to the west and / or to the east around the area of HC-8. The thickness of the active flow zone to the west (GL-27) and to the east (MB-17) of HC-8 ranges from 5 to 10 m. With this possible scenario in mind I would recommend that groundwater monitoring sites for Site F be located along the southwest and southeast boundaries of the site as well as the southern boundary.

39. This zone of active groundwater flow will be the principal pathway for the migration of contaminants away from Site F and also for the existing Burlington and Bayview sites. Based on the performance of the leachate collection system perimeter drain at the Bayview Landfill, it is likely that most or virtually all of the groundwater contamination entering the shallow shale can be captured immediately down-gradient of Site F by the perimeter drain or a shallow purge well system.

40. Within the transition zone and the inactive flow zone, there is progressively less vertical hydraulic connection between the horizontal fractures which occur throughout the shale strata. This decline in the degree of vertical connection may be simply due to less frequent vertical fractures or may also be due to geochemical processes which may act to seal fractures with chemical precipitates such as the gypsum observed in several sections of the rock core. There is only a small likelihood that contaminants from Site F could penetrate downward into these deeper zones and then laterally away from the site during the expected contaminating life of the landfill (60 to 80 years). Should contaminants move deep into the shale, lateral migration of contaminants off-site will occur along the most significant (ie. highest hydraulic conductivity) horizontal fractures in the shale. The pumping test at PW-1 illustrated the areal continuity of such horizontal fracture zones and indicated that purge wells would be a viable contingency for the capture of contaminated groundwater in the unlikely event that contaminants enter the deeper shale strata.

41. Surface water monitoring reported by Gartner Lee Limited (Exhibit H-625, p. 1) for the Burlington Landfill indicate that there is no detectable impact on Falcon Creek due to the seepage of leachate through the shallow shale. Gartner Lee conclude that there is probably little impact of leachate on the surface water quality or the groundwater quality south of the Burlington site because most of the leachate produced is collected in the toe drain / under-drain system.

42. Similarly, surface water monitoring reported by Conestoga-Rovers (Exhibit B-624, p. 40) for the Bayview landfill indicate that there is currently no discernible impact on the water quality in the Indian Creek Basin that can be attributed to landfill leachate from Bayview. Impacts on surface water quality in previous years due to leachate seeps and shallow groundwater discharge from the shale have been reduced following installation of the leachate collection system (toe-drain) along the south side of the landfill.

43. Based on the performance of the toe-drain collection systems at the Bayview and Burlington sites, the toe-drain leachate collection system for Site F is also expected to effectively the control of leachate seeps and shallow groundwater flow from beneath the landfill.

44. There has been much discussion of the rate of exfiltration of leachate from the landfills into the shale. It is CRA's opinion (Exhibit B-617) that a clay liner is required to reduce the amount of exfiltration from Site F compared to the amount of exfiltration they expect for an unlined landfill. I consider that on the basis of the exfiltration rates calculated by THCL and the nature of the groundwater flow system in the shale, it is necessary to distinguish between the total exfiltration from the landfill, that portion of the total which infiltrates the shallow active flow system, and that portion of the total which infiltrates deeper into the shale. It is my understanding from Exhibit B-617 that CRA's estimates of exfiltration (p. 157) ranging from 50 to 100 mm/a represent total exfiltration. Similarly, the estimate of exfiltration of approximately 100 mm/a (96.3 mm/a) for the Bayview landfill made by Gartner Lee (GLL) represents total exfiltration (Transcripts v. 118, p. 28,452). In contrast, the exfiltration estimates made by THCL based on the original groundwater flow model (THCL Report Exhibit H-40, p. 63) and the "better-fit" model (Exhibit H-221) of 14 mm/a and 1.2 mm/a respectively do not reflect the total exfiltration.The size of the finite element mesh for the computer models does not allow sufficient resolution to simulate the flow of that water which penetrates less than 5 to 10 m into the subsurface. Therefore, the exfiltration estimates made by THCL more closely reflect the deep infiltration into the shale. The low values estimated by THCL are not directly comparable to the much higher values of exfiltration estimated by CRA.

45. Based on the high chloride concentrations in the groundwater deep in the shale and the possible rate of removal of this chloride by fresh infiltrating waters, the infiltration of water from above into the deeper shale is likely to be very low, approximately 1 mm/a or less. This deep infiltration rate is comparable to that estimated by THCL for a vertical hydraulic conductivity of 10^{-8} cm/s. The shallow infiltration would be expected to be higher than the deep infiltration.

46. The estimates of total exfiltration made by CRA are based on a continuous "weathered mantle" of shale 15 to 30 m in thickness having a hydraulic conductivity of 2 x 10^{-4} cm/s. Data on chloride and tritium concentrations and the results of the pumping tests conducted by THCL suggest that the "weathered mantle" of shale is considerably thinner and has a lower hydraulic conductivity in many areas in and around Site F. Such conditions would lower the estimated rate of exfiltration. Using the same assumptions as CRA (Exhibit B-617, p. 156)

with a leachate mound of 1.9 m reflecting normal operating conditions for the landfill, the total exfiltration rate calculated for a zone of active flow (ie. the "weathered mantle") of 5 to 10 m in thickness would be approximately 10 mm/a and 20 mm/a respectively (Exhibit H-649). These estimates are considerably lower than those made by CRA.

47. The estimates of total exfiltration at Bayview made by GLL in 1982 were based on the difference between the estimated infiltration of precipitation into the landfill of 165 mm/a and a visual estimate of 69 mm/a for the volume of leachate flows from the leachate seeps around the landfill. There is a good possibility that the visual estimates of the leachate seepage are underestimates because the lower flow and diffuse seepages, even if large in area, cannot be estimated. If this were the case, the estimated total exfiltration would be lower than that suggested by GLL.

48. There is additional evidence which suggests that the zone of active groundwater flow (ie. the "weathered mantle") is either relatively thin or has a relatively low vertical or horizontal hydraulic conductivity. Either of these conditions will act to reduce the total exfiltration from the landfill compared to that estimated by CRA. The observation of no impact of leachate seepage into surface water streams at the Burlington and Bayview landfills with the toe-drain leachate collection systems in operation, and the small zones of groundwater contamination in the shale south of the Burlington and Bayview sites indicate that the rate of shallow infiltration from these landfills is relatively low. Similar conditions would be anticipated at Site F.

49. The estimated total exfiltration of leachate through CRA's clay liner for Site F during normal operating conditions with a 1.9 m leachate mound is approximately 8 mm/a (Testimony by Mr. Petrie, Transcripts v. 114, p . 27,588). There is no basis for total exfiltration estimates as high as 50 to 100 mm/a and the total exfiltration at Site F would more reasonably be in the range of 10 to 20 mm/a. The construction of a liner at Site F will reduce the total exfiltration, but the cost of the liner must be weighed against the benefit of the reduced rate of exfiltration. The operation of the toe-drain leachate collection systems at Burlington and Bayview demonstrate that the bulk of the total exfiltration is already intercepted in the form of shallow groundwater flow. The addition of a liner to these systems would have only reduced the already small volume of leachate which enters the groundwater system and which is not intercepted. At the current rate of total exfiltration of leachate from the Burlington and Bayview sites (ie. with the toe-drain collection systems in operation), neither site produces a significant impact on the surrounding groundwater or surface water environments. Similar conditions would be expected for Site F. There would be no

additional benefit to the addition of a liner, consequently, it is my opinion that a liner is not required at Site F.

CONCLUSIONS

50. It is my opinion that Site F is suitable for landfilling. There should be no significant impact on the groundwater or surface water environments due to landfilling at Site F. In the event that subsurface conditions differ from my interpretation of the site and these conditions allow the migration of groundwater contaminants off-site, no water supply wells would be threatened and the would be ample time for implementation of contingencies if they were required.

51. It is my opinion that Site D can be made suitable for landfilling. For conditions when the hydraulic trap is functioning, there will be no leakage of leachate from the landfill. In the event of failure of the hydraulic trap, leachate will escape the landfill and could result in contamination of the private wells believed to draw water from the granular units underlying the landfill. If the unweathered upper till is unfractured, travel times for contaminants to reach the private wells will likely be many years. Either failure of the hydraulic trap or migration of contaminants would be detected by monitoring before the occurrence of contamination at the private wells. Within this timeframe, contingencies such as the pumping of leachate from the landfill to re-establish the hydraulic trap or the purging of contaminated groundwater from the granular units could be readily implemented.

52. If the unweathered upper till is fractured, travel times for contaminants from the landfill to the ~~private wells~~ UGU may be less than a year. In this event, it is unlikely that a typical landfill monitoring program could identify the failure of the hydraulic trap and permit timely implementation of appropriate contingencies before the private wells might be contaminated. It is my opinion that it is a reasonable possibility that fractures exist in the unweathered upper till. Given the threat to the private wells, it is my opinion that this possible eventuality should be avoided by alternatives such as design, installation and testing of the purge well system prior to landfilling, the connection of the residences to piped municipal water supply, or construction of a liner of re-compacted native clay silt till on the base on the landfill.

53. The existence of fractures in the unweathered upper till and possible rapid contamination of the UGU also magnifies the importance of even short-term (seasonal) failures of the

hydraulic trap. Because of this, a specific emphasis on the monitoring of the leachate levels in the landfill and the groundwater levels beneath the landfill should be part of the groundwater monitoring program for Site D.

54. In summary, Site D can be made to be suitable for landfilling. Because of the possibility for fracturing in the unweathered upper till, modifications to the proposed contingencies, monitoring plans or landfill design are necessary to protect the nearby private wells. These modifications will be more involved and will likely be more costly than the original design.

55. On the basis of the preceding discussion, it is my opinion as a hydrogeologist and hydrogeochemist that Site F is preferable to Site D for the proposed Region of Halton Landfill.

ATTACHMENT 1

The Depth of Fractures and Active Groundwater Flow

in a Weathered Clayey Till in Lambton County, Ontario

by

Wilfrid W. Ruland

FRACTURE DEPTHS AND ACTIVE GROUNDWATER FLOW IN A WEATHERED CLAYEY TILL IN LAMBTON COUNTY, ONTARIO

by

Wilfrid W. Ruland

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ABSTRACT

The St. Clair Plain in Lambton County, Ontario is underlain by extensive clayey till deposits of about 40 m depth. The till is vertically fractured in a thick zone near the ground surface. This study investigates the depth of active groundwater flow through the fractures. Observations in test pits show that most weathering features reach a depth of only 2.5 m to 4 m, though isolated major fractures extend past the pit bottom of 5.6 m at some sites. Water level response tests show bulk hydraulic conductivity of the fractured till ranges from $< 10^{-6}$ to 10^{-7} cm/s. Hydraulic head profiles show that fractures influence groundwater flow to depths of 5 m to more than 10 m. The water table is usually within 2 m of the surface, but piezometers went dry to depths of 2 m to 4.7 m in a dry period in 1987. Tritium levels > 0.7 T.U., indicating the presence of modern water, are found to maximum depths between 7.5 m and 12 m at all study sites. Tritium is transported by groundwater flow through deep, open fractures and also by molecular diffusion. Increasing ^{18}O depletion with depth at most sites indicates that the deeper waters are older, but two of the sites show almost no change in ^{18}O with depth. Evidence of active groundwater flow in widely spaced deeper fractures may go undetected in vertical piezometers. The maximum depth of fracture flow is variable, ranging from 5 m to more than 10 m at the 13 sites studied in Lambton County.

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INTRODUCTION

Many parts of southwestern Ontario are covered with clay-rich glacial tills, including the physiographic region known as the St. Clair clay plain (Chapman and Putnam, 1984). Lambton County and the city of Sarnia are located within this large, flat-lying region. In Lambton County clayey tills of Quaternary age extend from within a meter of ground surface to depths of 25 m to 50 m, with an average thickness of about 40 m (Desaulniers, 1986). The tills are dark grey, clay-rich, somewhat pebbly sediments which contain sporadic beds or lenses of sandy or silty material (Fitzgerald et al, 1979).

The surficial zone of the tills has undergone weathering by physical, geochemical, and biological processes (D'Astous et al, 1988). Rodvang (1987) observed fractures in drill cores as deep as 9.3 m, and Adams (1969) reported fractures at depths of more than 10 m. The deepest root is that observed by Hanna (1966) at 9 m depth. The fractures and root holes are ubiquitous near the surface, but the frequency of these features diminishes sharply below a few meters depth.

Chemical weathering has caused a colour change in the tills from grey to brown due to oxidation of chlorite in the clay (Ogunbadejo and Quigley, 1973). This process is most active within 2.5 m of the surface and along fractures. The fractures and root holes in the tills are easily distinguished due to colour changes associated with precipitates or chemical alteration haloes.

Based on piezometer test data, Harding (1986) believed that fractures in the clay tills of Lambton County are usually closed and are rarely significant pathways for groundwater flow. D'Astous et al (1988) showed that borehole smearing caused by augering prevented piezometers from responding with hydraulic conductivities governed by open fractures. When the smeared clay was removed from boreholes, hydraulic conductivities of 10^{-8} to 10^{-6} cm/s were commonly obtained for the fractured tills. These values are one to three orders of magnitude higher than those measured in the underlying and unfractured tills. D'Astous et al (1988) concluded that the fractures and fossil root holes are pathways for 'active' groundwater flow.

The goal of this study is to determine the depth to which fractures cause active groundwater flow in the clayey tills. Information was obtained from 13 sites across Lambton county (Figure 1). One part of the study involves the aquisition of visual evidence about fractures from test pits. In the other part of the study the depth of fracture flow is investigated using isotopes of hydrogen and oxygen to determine groundwater age, and using hydraulic evidence from water level response tests and from monitoring of water level fluctuations over time in piezometers.

Information pertaining to the depth of active groundwater flow is relevant to many types of land use in the clay plains of Lambton County and other parts of southwestern Ontario. Such information is important to rural residents for installation of agricultural drainage or development of water supplies. Knowledge about fractures and fracture flow is also required when trying to determine or predict the extent of groundwater contamination from sources such as landfills or spills of industrial chemicals or petroleum products. Finally, the depth of active groundwater flow through fractures must be accounted for in the design and monitoring of waste disposal facilities such as landfills and lagoons.

METHODS OF INVESTIGATION

Six test pits were excavated by backhoe at four sites, three at Tricil in 1986 and one each at the Dow, Union Carbide and Esso sites in 1987. D'Astous et al (1988) used two pits at the Tricil site for a tracer test and used the third pit, located about 20 m away, for more detailed investigation of the tills. The test pits at all sites were located near previously installed piezometer nests and were about 2 m wide, 4 m long, and 5 m to 6 m deep.

A backhoe provides a quick and safe method of pit excavation and is required for installation of the hydraulic safety supports in the open pits. Smearing of clay on the test pit walls during backhoe excavation is unavoidable. Trowels and paint scrapers were used for prying the smeared clay from the pit walls to expose fractures and other features. Fracture spacings (the number of fractures intersecting the pit wall per horizontal meter) were recorded at half-meter depth intervals. Fracture strike, dip and length were recorded for the 3 pits at the Tricil site. Coatings of the fractures, till colour and consistency, and the maximum depth of fracturing and root penetration were also recorded.

Nests of the Shelby-hole type of standpipe piezometers were installed at 10 of the 13 study sites in 1985. The ten piezometers in each nest ranged in depth from 0.9 to 16 m.

The piezometer tips and standpipes had a diameter of 5 cm. To install a Shelby-hole piezometer a hole is augered to about 0.5 m above the target depth, and a 70 mm diameter Shelby tube is pushed through the base of the augered hole to the target depth. The piezometer tip is installed in the hole created by the Shelby tube, thus avoiding the clay smearing caused by the augering process (D'Astous et al, 1988).

Water levels have been measured monthly in all Shelby-hole piezometers since installation. The piezometers were pumped dry immediately after installation, and water levels recovered for 10 months. The piezometers were then sampled for analyses of major ions, ^{18}O, deuterium and tritium. The water-level recoveries of the piezometers after installation and sampling were analyzed for hydraulic conductivity using the method of Hvorslev (1951).

Auger-hole piezometers at the Lambton and Sarnia sites used by Desaulniers (1986), and Shelby-hole piezometers at the Tricil site used by D'Astous et al (1988) were also sampled for tritium. All tritium analyses from were done at the University of Waterloo Isotope Laboratory using the enrichment method.

Tritium, a radioactive isotope of hydrogen, is often used as an indicator of groundwater age (Payne, 1972). Background atmospheric levels of tritium in Ontario were low, about 3 to 5 tritium units until the early 1950's (Robertson and Cherry, 1988). Subsequent aboveground nuclear tests caused atmospheric levels of many radioactive isotopes to increase dramatically. Measured tritium concentrations in precipitation reached several thousand tritium units (T.U.'s) by 1963, when most above-ground testing ended. Tritium has a half-life of 12.3 years. Groundwater recharged by precipitation prior to 1952 has tritium levels < 0.7 T.U. today. If water samples have higher tritium levels then mixing with at least some 'modern' precipitation has taken place.

Deuterium and ^{18}O are isotopes of hydrogen and oxygen which are used for determining groundwater origin directly, and groundwater age indirectly. Their relationship is described by the 'meteoric water line', the line of the equation which best fits the relative concentrations of these isotopes in precipitation. This line varies around the globe but is quite stable for any one region. Groundwater samples falling on or near the local meteoric water line have recharged directly from precipitation, with little or no evaporation having taken place. The concentrations of both ^{18}O and deuterium in precipitation decrease with decreasing air temperature. Desaulniers (1986) used plots of ^{18}O vs depth to determine the relative age of groundwaters in Sarnia-area clays. The older waters at depth, recharged in the colder climate prevalent after the last glaciation, were more depleted in ^{18}O than modern near-surface groundwaters.

RESULTS

Observations From Test Pits:

The following features were observed in each of the six test pits (Figure 2):

1) A soil zone extends from the surface to depths of up to 1 m. The soil is composed of a reddish-brown, aggregated, highly oxidized and organic-rich clay. The base of the soil zone is marked by a colour change from reddish-brown above to brown below.

2) Underlying the soil zone is a zone of oxidized, brown or mottled-brown clay which reaches depths of 2.2 m to 2.5 m. The boundary to the soil zone above is also marked by the appearance of carbonate minerals leached from the soil zone, which are present as secondary coatings or areas of alteration around fractures.

3) A gradual colour change occurs over the next 0.3 m to 1.3 m. Below depths of 2.5 m to 3.5 m the clay then has the grey colour characteristic of the unweathered tills. Quigley and Ogunbadejo (1976) attributed this colour change from grey below to brown above to oxidation of illite and chlorite to form swelling clays near the surface of the Lambton County clay tills.

4) Fractures extend from the soil zone through the brown

clay and into the underlying, unweathered grey clay zone. Fractures reach depths of at least 4.5 m at all sites.

5) The fractures have red, black, or grey-white coatings or reddish-brown oxidation zones, giving them a different colour from the surrounding matrix of grey or brown clay. Red coatings are likely iron hydroxides (Quigley and Ogunbadejo, 1973) and the black fracture coatings have the appearance of manganese. The grey-white coatings reacted strongly with acid and are apparently calcareous. Chemically weathered fractures extend past the bottom of the 5.6 m deep test pits at the Esso and Tricil sites, but were not observed below 5 m depth at the Dow and Novacor sites.

6) Below the oxidized brown clay zone some fractures are the same colour as the surrounding grey clay matrix. These fractures were only discovered by chance when the clay, which is otherwise very stiff, parted more easily along the relatively smooth planar fracture surfaces.

7) Most fracture dips are vertical or near-vertical. There are no apparent preferred directions of strike (D'Astous et al, 1988).

8) Fracture spacing steadily increases, from one fracture every 1 cm near the surface to one fracture every 50 cm to 2 m at 4.5 m depth (Figure 3). Fractures are closely spaced and obviously interconnected near the surface. Just below

the oxidized zone there are often criss-crossing systems of sub-parallel and closely spaced fractures (one fracture every 2 cm to 6 cm), separated by blocks of unweathered clay. These fracture systems decrease in number with depth and the blocks of unweathered clay become larger. The systems eventually reduce to single isolated fractures, which at depths of about 4.5 m to 5.5 m often become indistinguishable from the surrounding grey clay till matrix. The fractures without visible weathering features detected below the oxidized zone were not counted for fracture spacing determinations.

9) The vertical length of the fractures varies widely. There are many small fractures (2 cm to 20 cm long) generally found near the ground surface. Longer fractures up to 1 m in length are usually found between depths of 2 m and 4 m. Very long fractures, which can extend from near the ground surface to 5 m depth or more, are infrequent but were observed at all sites.

10) Roots or fossil roots were observed to depths of 3.9 m. The roots develop preferentially along fracture surfaces, though isolated root channels with visible weathering features such as oxidation haloes were observed in otherwise unweathered clay from drill cores at depths of 2.5 m to 4 m.

11) The clay becomes increasingly moist and plastic as the depth below ground surface increases.

The following observations were made in test pits at one or more, but not all of the sites:

1) Water was observed flowing from fractures after rainfall events at the Tricil and Novacor sites. Test pits were excavated at the Tricil site during a very wet summer (1986), and flow rates of up to 90 L/hour into the open pits were observed (D'Astous et al, 1988). The test pit at the Novacor site was excavated 12 hours after brief showers had occurred, and fracture surfaces were moist near the surface and dripping water at the trench bottom. Trenches at the other sites were excavated during a long drought (in 1987), and fractures ranged from dry near the surface to moist at the trench bottom.

2) Fossil root channels acting as macropores for vertical groundwater flow were observed dripping water at the Tricil site. Further evidence of roots acting as macropores are the alteration or oxidation zones in the clay matrix around root channels.

3) Gypsum crystals were observed in fractures, and also in the clay matrix unassociated with fractures, near the surface of the Novacor site. Smaller amounts of gypsum occur around fractures at the Esso site, Dow site and in one but not the other two test pits at the Tricil site.

Water Level Response Tests and Hydraulic Head Profiles:

Hydraulic conductivities based on water level response tests show significant variation (Table 1). Piezometers in the upper 3 m of the tills commonly have hydraulic conductivities greater than 10^{-6} cm/s. Below 3 m, values usually range from between 10^{-6} cm/s to 10^{-7} cm/s. Though there are exceptions, values tend to decrease with increasing depth below the ground surface.

Many of the deeper piezometers took until the spring of 1987 (even longer in a few cases) to recover to equilibrium levels following installation in 1985 and sampling in 1986. The piezometers had 'fully recovered' once water levels, which climbed steadily after installation and sampling, levelled-off or fell.

In the spring of 1987 there was an almost uniform downward hydraulic gradient throughout the profiles (Figures 4a to 4e). Soil frost prevented groundwater-surface interactions during the previous winter and a downward hydraulic gradient developed. The water table was close to the surface because of the heavy precipitation of the preceding year.

The summer profiles (recorded during a period of below-normal precipitation) show the downward hydraulic gradients observed in spring being replaced by an upward gradient near the ground surface. This was caused by evapotranspiration and may have been influenced by lateral gradients caused by small-scale local topographic irregularities. Several of the near-surface piezometers were completely dry.

By the fall of 1987 (the dry conditions persisted through this period) a strong upward gradient developed. Piezometers were dry to depths of up to 4.7 m at some sites.

^{18}O and ^{2}H Results:

A plot of $\delta^{2}H$ vs $\delta^{18}O$ was prepared for all data from the 10 sites (Figure 5). The meteoric water line for Simcoe, Ontario (Fritz et al, 1987), which is the closest location for which this information is available, is included for comparison. The data points fall on or slightly below the Simcoe meteoric water line, indicating that there has been little or no change in the isotopic composition of these waters since they fell as precipitation.

Profiles of $\delta^{18}O$ vs depth are presented in Figure 6, and fall into two distinct groups. Near the ground surface, $\delta^{18}O$ values of -8 to -10 ‰ are common. As depth below surface increases, the groundwater at six of the sites becomes increasingly depleted of ^{18}O. Samples from 15 m depth at these sites have values around -13 ‰. The other four sites show much less of a depletion of ^{18}O with depth, with values at 15 m depth of about -10 ‰.

Distribution of Tritium with Depth:

Tritium vs depth profiles (Figures 7a, 7b) generally show maximum tritium concentrations of 30 to 80 T.U. at depths of less than 3 m. There is then an abrupt drop to about 10 T.U over the depth interval of 3 m to 5 m. There are anomalously long 'tails' on the tritium profiles, with levels gradually dropping to below detection limits of the enrichment method (of 0.7 T.U.) at depths of about 7.5 m to 12 m. The occasional increases in tritium levels below 3 m are not commonly seen on such profiles.

DISCUSSION

Visual Evidence of Fractures:

An air photograph of the Tricil site (Richards et al, 1984) shows wet and dry areas indicative of a well defined sub-surface lateral flow system influenced by very small local topographic irregularities. Similar flow systems have been observed in other clay plains by several researchers (Keller et al, 1986 and Gartner Lee Limited, 1987), and are believed to be caused by groundwater flow through fractures.

The depth of visible fractures varies across Lambton County. Most (>90 %) of the fractures with visible weathering features such as coatings or oxidation haloes do not extend below 5 m depth (Figure 3). Significant numbers of these fractures do, however, extend well beyond 5 m depth.

There is evidence in the literature that fractures have been observed in drill cores beyond 10 m depth in places in Lambton County (Figure 8). Most researchers determined the maximum depth of fractures from observations of drill cores, except Harding (1986) and Vorauer et al (1986) who also used shallow test pits like those used in this study.

Though the number of fractures decreases steadily with depth, there is no easy way to determine whether or where there is an absolute cut-off depth below which there are no fractures. Figure 9 is a theoretical graph of the probability of encountering equally spaced vertical fractures of specified spacing in vertical drill holes of different diameters. Combining the average fracture spacings vs depth recorded in the 6 test pits (Figure 3) with Figure 9, yields a plot showing the probability with depth of encountering vertical fractures with drill holes of different diameters (Figure 10).

Below 5 m depth there is less than a 10 % chance of encountering fractures with the vertical holes used in conventional drilling programs, though there are still significant numbers of fractures present (eg. an average of 5 fractures every 10 m at a depth of 5.5 m). Vertical drill holes will miss vertical fractures which lie directly beside but do not intersect those holes. If fractures are not encountered with vertically drilled holes beyond a given depth, this does not necessarily mean that there are no fractures present beyond that depth.

Fractures without weathering features, discernible only because the clay parted easily along well-defined and smooth planar surfaces, were encountered near the bottom of all test pits. It is not clear whether groundwater flow is occurring through these fractures.

Groundwater flow is definitely occurring in at least some of the visible fractures. This was proven by the observations in test pits at the Tricil site, where water flowed through fractures into test pits at rates of up to 90 L/hour.

Hydraulic Evidence of Active Groundwater Flow in Fractures:

The water-level response tests show that piezometers near the ground surface, where the probability of intersecting fractures is greatest, have hydraulic conductivities significantly higher than deeper piezometers (Table 1). The presence of a surficial fractured zone of higher hydraulic conductivity means that only a minimal amount of (downward) flow through the unfractured, unweathered clay below this zone is to be expected (Richards et al, 1984 and Desaulniers, 1986).

The hydraulic conductivities obtained from Shelby-hole piezometers in this study represent an increase of one to three orders of magnitude over the values obtained by Desaulniers (1986) and Harding (1986), who used piezometers installed in augered holes. The Shelby-hole piezometers give measured hydraulic conductivity values more representative of fracture flow in the clayey tills than those obtained from conventional auger-hole piezometers. Other types of installations may, however, be required if truly representative measurements of the hydraulic conductivity of the fractured tills are to be achieved.

A comparison of water level fluctuations over time can assist in determining the depth to which fracture flow is occurring in clayey deposits. Significant water level fluctuations occur to depths of 5 m to 10 m across Lambton County, and provide strong evidence of an active zone of groundwater flow through fractures.

Water level fluctuations exceeding half a meter over the 6 months from spring to fall 1987 must be caused by fracture flow. Such fluctuations take place to depths of between 5 m and 10 m at most sites, and are observed throughout the profile at the Allen site (Figures 4a to 4e). At most sites water levels are virtually constant below a depth of 5 m to 10 m, indicating that below these depths the fractures are not significantly contributing to groundwater flow or are so widely spaced that their influence is not felt by piezometers.

In a related, detailed study at the Tricil Ltd. site of water level fluctuations using piezometers and tensiometers equipped with pressure transducers, Adomait (1988) reported a 5 m deep zone of rapid piezometric response to rainfall events overlying a deeper unresponsive zone.

The drying out of shallow piezometers in the fall of 1987 provides another indication of groundwater flow through fractures. In unfractured clays, strong negative hydraulic heads can develop without an appreciable amount of water being drawn from the clay. The pore spaces in the clay are so small that capillary effects hold water in the pores against significant negative hydraulic head. Fractures in clays drain more quickly in dry periods than the unfractured blocks of clay matrix because the water in the fractures is more readily available. When piezometers go dry to depths of more than 4 m as in the fall of 1987, this implies that water is being removed through fractures at that depth.

Isotopic Evidence of Active Groundwater Flow:

The depth profiles of ^{18}O in this study are similar to the upper part of Desaulniers' 35 m to 45 m profiles (Figure 11). Desaulniers (1986) found that porewaters from the unfractured zone of the Sarnia tills became increasingly depleted in ^{18}O with depth. He attributed depleted ^{18}O values in the deeper waters to their being composed of precipitation or meltwater from local ice sheets of the much colder late Pleistocene or early Holocene time periods. Groundwater closer to the surface has higher ^{18}O levels because of mixing with less depleted modern waters.

Six of ten ^{18}O profiles from this study are similar to the typical ^{18}O profiles of Desaulniers (1986), for which he hypothesized a downward flow velocity of 0 below the active zone. Four other site profiles (Allen, Dupont, Tiernay, & CIL) are similar to Desaulnier's profile from the Lambton II site, which had a large hydraulic gradient (0.4) and an estimated downward flow velocity of 0.25 cm/year. The high ^{18}O levels at Lambton II and at 3 of the study sites are likely due to high rates of recharge of modern water. Water level fluctuations show that fractures are deepest at the Allen and Dupont study sites, while the Tiernay and Dupont sites have the largest hydraulic gradients (0.3) observed in the study. The CIL profile starts with very enriched ^{18}O levels but then shows a more typical depletion of ^{18}O with depth. Since the site is located in a bog, isotopic fractionation during evaporation may have caused the recharging groundwater to become enriched in ^{18}O.

Further evidence of fracture flow was provided by groundwater tritium levels, which exceeded detection limits to maximum depths of 7.5 m to more than 12 m.

A one-dimensional analytical model was used to generate theoretical profiles of tritium vs. depth, which were then compared to measured tritium profiles from the study sites. The model features an analytical solution to the one-dimensional advection-dispersion equation given by Cleary (1978). An effective diffusion coefficient value of 6×10^{-6} cm^2/s, similar to values obtained from laboratory tests by Desaulniers (1986), was used to represent Lambton county clays. Longitudinal dispersivity and average flow velocity were varied to obtain a theoretical profile with the best possible fit to the field profiles.

The Ottawa, Ontario tritium vs time relation was used in the model to represent precipitation input conditions (Robertson and Cherry, 1988). Levels recorded for Ottawa are the world's only continuous record dating back to 1952 of tritium in precipitation. Tritium values before 1952 are assumed to be 3 T.U.

The best fit of a theoretical profile of tritium vs depth was obtained using an average linear velocity of 2 cm/year and a longitudinal dispersivity of 3 m (Figure 12). The general shape of the simulated profile, with highest tritium levels near the surface and a steady decline to below detection limits as depth increases, is observed in most profiles (Figure 12). There are however anomalous increases in tritium concentrations at various depths in 8 of the profiles, and long 'tails' on the tritium profiles before they drop below detection limits of 0.7 T.U.

The 'tails' of tritium could be indicative of a significant downward flow velocity in the Lambton County tills. Previous modelling by Desaulniers (1986) indicates, however, that field profiles of ^{18}O and Cl^- over the entire till sequence can best be fitted by simulated curves with a zero downward flow velocity below the fractured zone. The 'best fit' average flow velocity from the model used in this study is also insignificant over the tritium timescale of 35 years. Another explanation must be found for the significant tritium levels at depths of 8 m or more.

The likelihood of sample contamination is remote, as is the possibility of contamination of the piezometers. Tritium values eventually do drop to below detection limits at the bottom of the profiles. It is unlikely that only samples from near-surface piezometers are contaminated, with deeper samples being unaffected.

One explanation for the observed profiles is that the zone of fracture flow does not have an abrupt lower boundary, and instead that the density of fractures and the degree of their interconnectedness decreases slowly with depth. Flow through isolated, exceptionally deep and open fractures could be the cause of the anomalous features in the tritium profiles. This is consistent with the modelling results, in which the high downward flow velocity and longitudinal dispersivity can be interpreted as representing groundwater flow through fractures.

Most of the fracture flow in the Lambton County tills should be lateral however, with only a minor downward component in the areas of topographic highs. In the summer, significant rates of upward flow could even be expected. In such a flow system, molecular diffusion to the matrix as described by Day (1977) should be reducing concentrations of tritium in fractures to very low levels even if fracture flow at depth is occurring.

The observation that piezometers went dry to depths of up to 4.7 m during the dry period in 1987 helps explain the unexpectedly high tritium levels at depth. A major rainfall event after such a dry period will rapidly flood the relatively dry, open fractures. The high flow velocities during fracture flooding can be expected to carry the tritiated rain water to the base of the dry part of the fractures with little molecular diffusion having time to take place. Molecular diffusion will then steadily reduce the tritium levels present in the deep fractures over time, while increasing tritium levels in the matrix surrounding the fractures.

The driest summer in Sarnia since 1952, when nuclear testing began, was in 1963 with less than 20 cm of total precipitation recorded from June through November (Monthly Record, 1952 - 1988). Tritium levels in Ontario precipitation reached their peak of 2000 to 3000 T.U. in 1963.

Tritium reaches maximum depths of about 7.5 m to 12 m. All other evidence from this study indicates that the fracture flow zone is about 5 m to 10 m deep (Table 2). Tritiated water reaching the base of the active flow zone in 1963 has had 25 years to move into the unweathered clay around fractures by molecular diffusion. Diffusion transports tritium about 2 m in 25 years, accounting for the presence of tritium 2 m below the base of the fractured zone.

There is an expectation that tritium found in a piezometer below a few meters depth in clays has been carried there by a fracture which the piezometer intersects. Diffusion from the fracture to the matrix is in fact expected to reduce tritium levels to below detection limits well above the base of a deep, open fracture due to the slow flow rates involved. If sudden flooding (after a drought) carries tritiated waters to the bottom of the dry part of a fracture, then a piezometer located within the clay matrix but close (eg. 50 cm away) to the fracture will have significant levels of tritium due to molecular diffusion within a few years. This piezometer will not, however, show the rapid changes in water levels or have the high hydraulic conductivity expected for a piezometer with significant tritium levels.

Implications:

Vertical drilling is ineffective for determining the maximum depth of fractures in Lambton County tills. The use of test pits excavated by backhoe is more useful, because these allow a more representative count of the fractures at a given depth. However, for accurate determination of maximum fracture depths, the pits must be considerably deeper than those used in this study.

Using piezometers to determine the maximum depth of active fracture flow can be misleading because of the increase with depth of fracture spacing. If the fracture spacing at some depth is only one fracture every 4 m and a piezometer is located midway between two such fractures, then there will be no hydraulic indication of the fractures even if very active flow through them is occurring. Tritium provides a more accurate indication of the depth of the active flow zone because molecular diffusion will spread tritium several meters beyond the fractures in which it is found. A piezometer has a much greater chance of detecting the tritium envelope around a fracture than it does of detecting the fracture itself.

This study indicates that in Lambton County fractures are present and contributing to groundwater flow to maximum depths of 5 m to more than 10 m (Table 2) - considerably deeper than reported by previous researchers.

Virtually all landfilling in Lambton County has resulted in municipal, industrial and hazardous waste being deposited in the fractured zone of the clay tills. Future studies must address the question of whether dissolved contaminants are escaping from these landfills at significant lateral velocities via the same fractures which have been shown to provide pathways for groundwater flow.

CONCLUSIONS

The maximum depths of fractures in Lambton County clay tills appear to be quite variable and were very difficult to determine. Direct observation indicated that there were no fractures below 5 m in test pits at two study sites, but fractures extended past the bottom of test pits (at 5.6 m depth) at the other two sites.

The increase in spacing with depth of fractures which are primarily vertical, means that vertical drill cores will not provide accurate visual evidence of the maximum depth of fracturing in Lambton County. Test pits of the type described in this paper should be a part of any investigation in which accurate determination of the maximum depth of fracturing is an issue.

Hydraulic conductivities measured in water level response tests in piezometers are often greater than 10^{-6} cm/s in the upper 3 m of the tills, and generally range from 10^{-6} to 10^{-7} cm/s below 3 m depth. Hydraulic head profiles in the same piezometers generally show downward hydraulic gradients, but strong seasonal water level fluctuations indicative of fracture flow occur in the upper 5 m to 10 m of the tills.

Field profiles show tritium levels above 0.7 T.U. occur to depths of 7.5 m to more than 12 m. Tritium transport has occurred in fractures to depths of 5 m to more than 10 m, with subsequent molecular diffusion carrying tritium about 2 meters into the underlying unweathered clay.

The maximum depth of the fractured zone in Lambton County clay tills ranges from 5 m to more than 10 m, and groundwater flow occurs in at least some fractures throughout that zone at all study sites. Future studies must address the question of what depth the fractures without visible weathering features extend to, and whether the lack of weathering features necessarily implies that those fractures do not contribute to groundwater flow.

The increase in fracture spacing with depth results in considerable uncertainty in determinations of the maximum depth of fracture flow using hydraulic, isotopic or other evidence from piezometers. The results of this study should be viewed as a conservative estimate of the actual maximum depth of active groundwater flow in fractures in Lambton County.

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TABLE 1: Hydraulic Conductivity (x 10^{-7} cm/s) vs Depth for 10 Lambton County Study Sites

	Lambton County Study Sites									
Approx. Depth	Roy	Dow	Ess	Dup	PC	UC	RP	CIL	T	Allen
1.0 m	>10	>10	>10	>10	>10	>10	>10	>10	>10	>10
2.0 m	3	>10	>10	>10	>10	>10	3	>10	>10	>10
3.0 m	4	2	>10	>10	>10	>10	3	2	3	>10
4.0 m	2	5	3	4	2	1	2	2	2	>10
5.0 m	3	4	1	2	3	3	2	1	3	3
6.5 m	2	3	2	2	2	2	2	2	2	2
8.0 m	2	2	2	1	3	2	1	1	1	6
9.5 m	3	2	1	1	3	2	2	2	0.9	3
12.6 m	2	3	1	1	1	2	6	1	0.9	4
15.7 m	1	3	1	1	1	2	1	2	1	4

TABLE 2: Indicators of Maximum Depth of Fracturing in Lambton County

	Lambton County Study Sites									
Indicator	Roy	Dow	Ess	Dup	PC	UC	RP	CIL	T	Allen
tritium	6.1	8.1	12.9	8.0	13.0	8.1	8.1	9.6	7.7	7.8
w.levels	4.8	6.5	9.6	9.6	9.8	5.0	6.6	5.0	3.9	15.6
test pits		4.5	>5.6			4.5				
cores			5.0			9.3	9.2	2.1		

The maximum depth of fracturing should be seen as a conservative estimate based on the line of evidence indicated

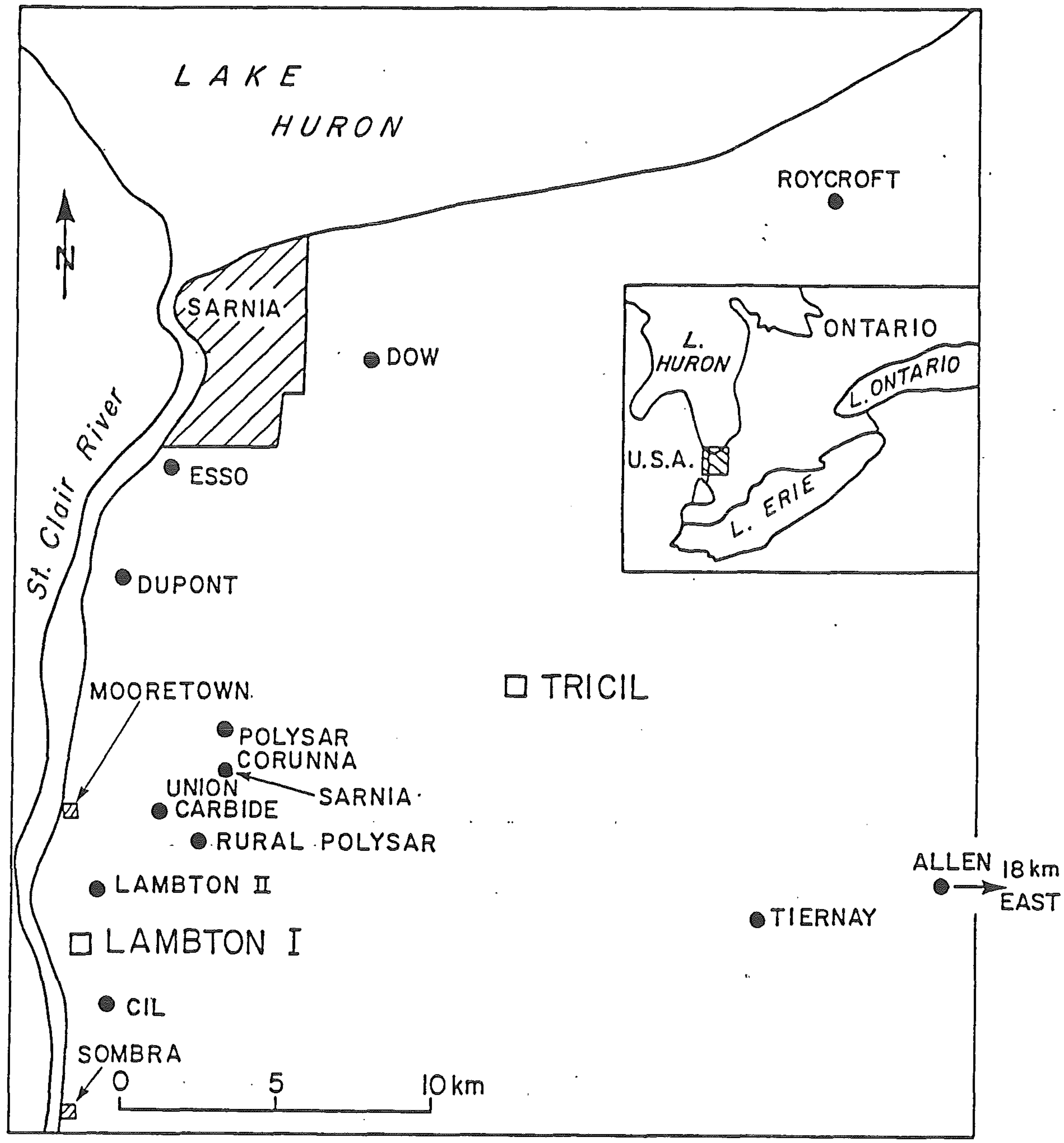


Figure 1: Location of study sites

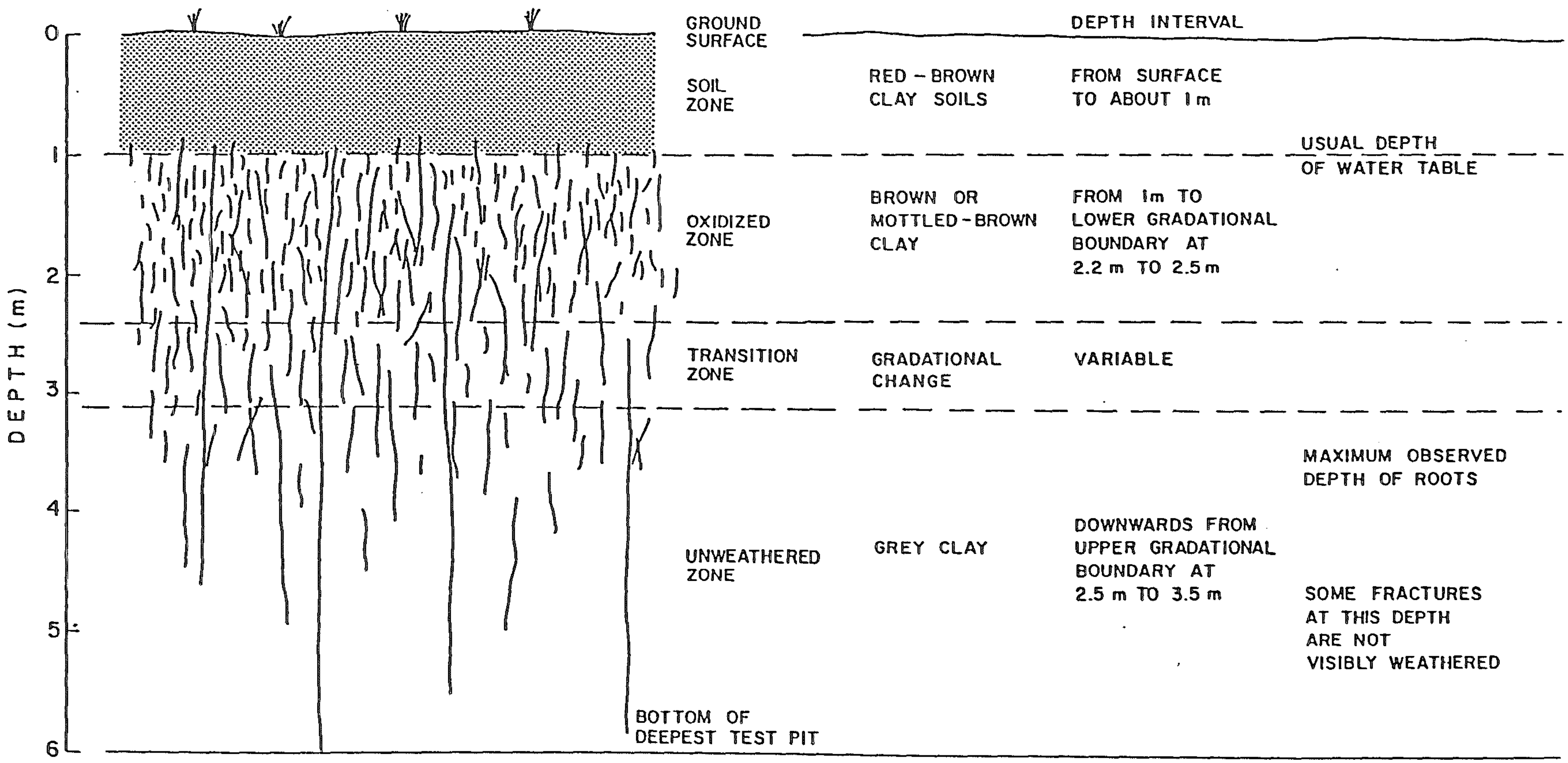


Figure 2: Typical test pit cross-section

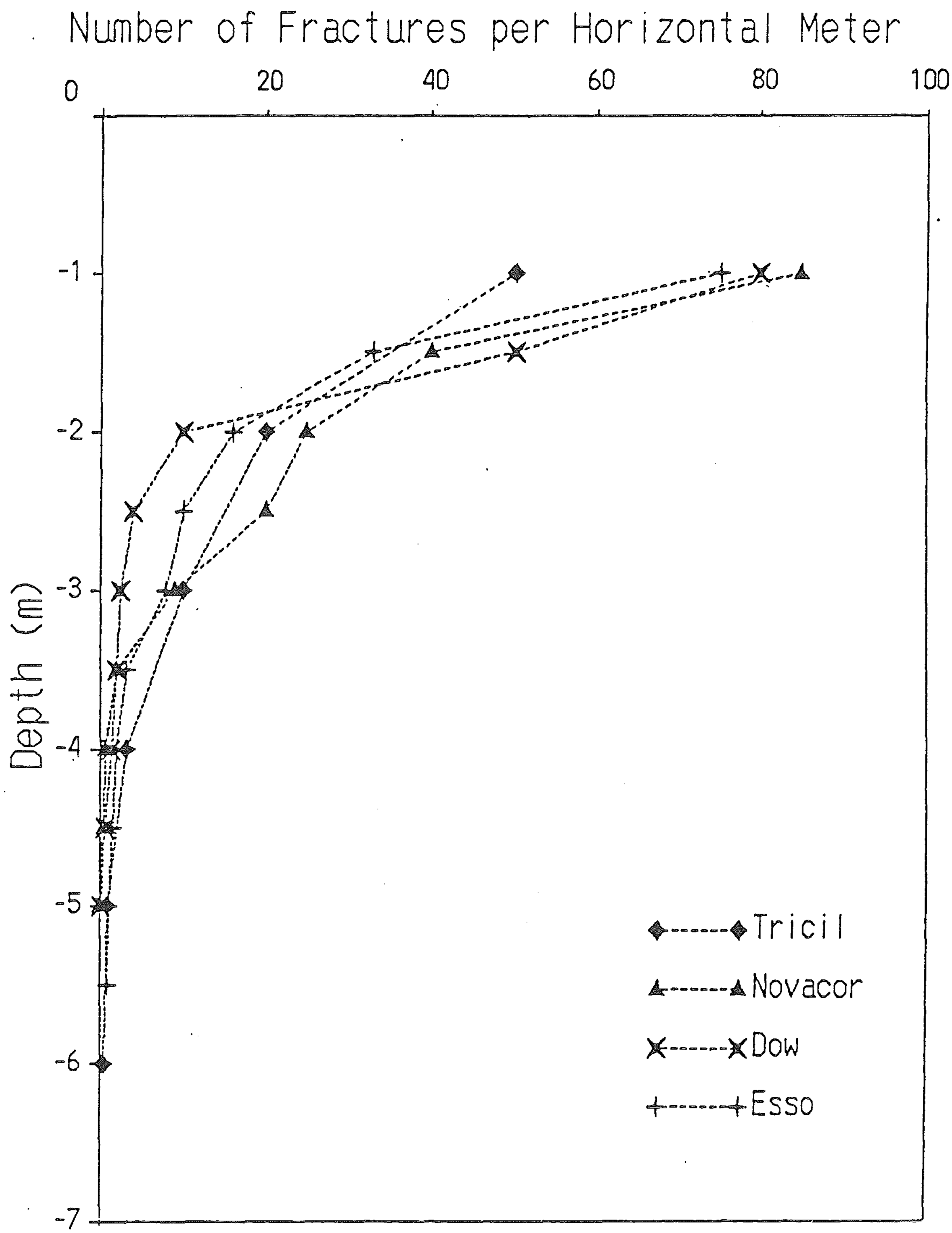


Figure 3: Fracture spacing vs depth in test pits at four Lambton County study sites

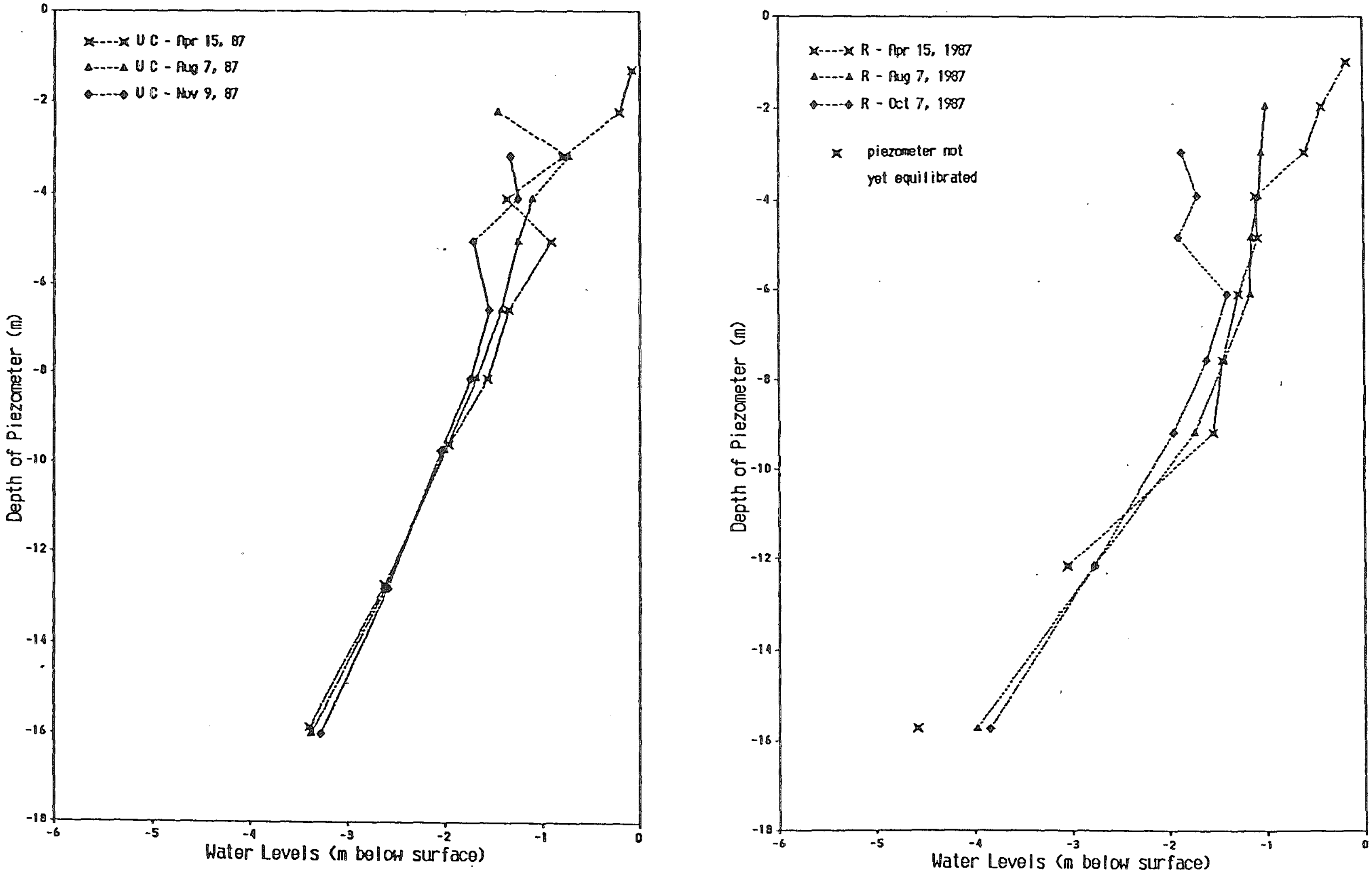


Figure 4a: Water level variations - Union Carbide (Novacor) and Roycroft sites

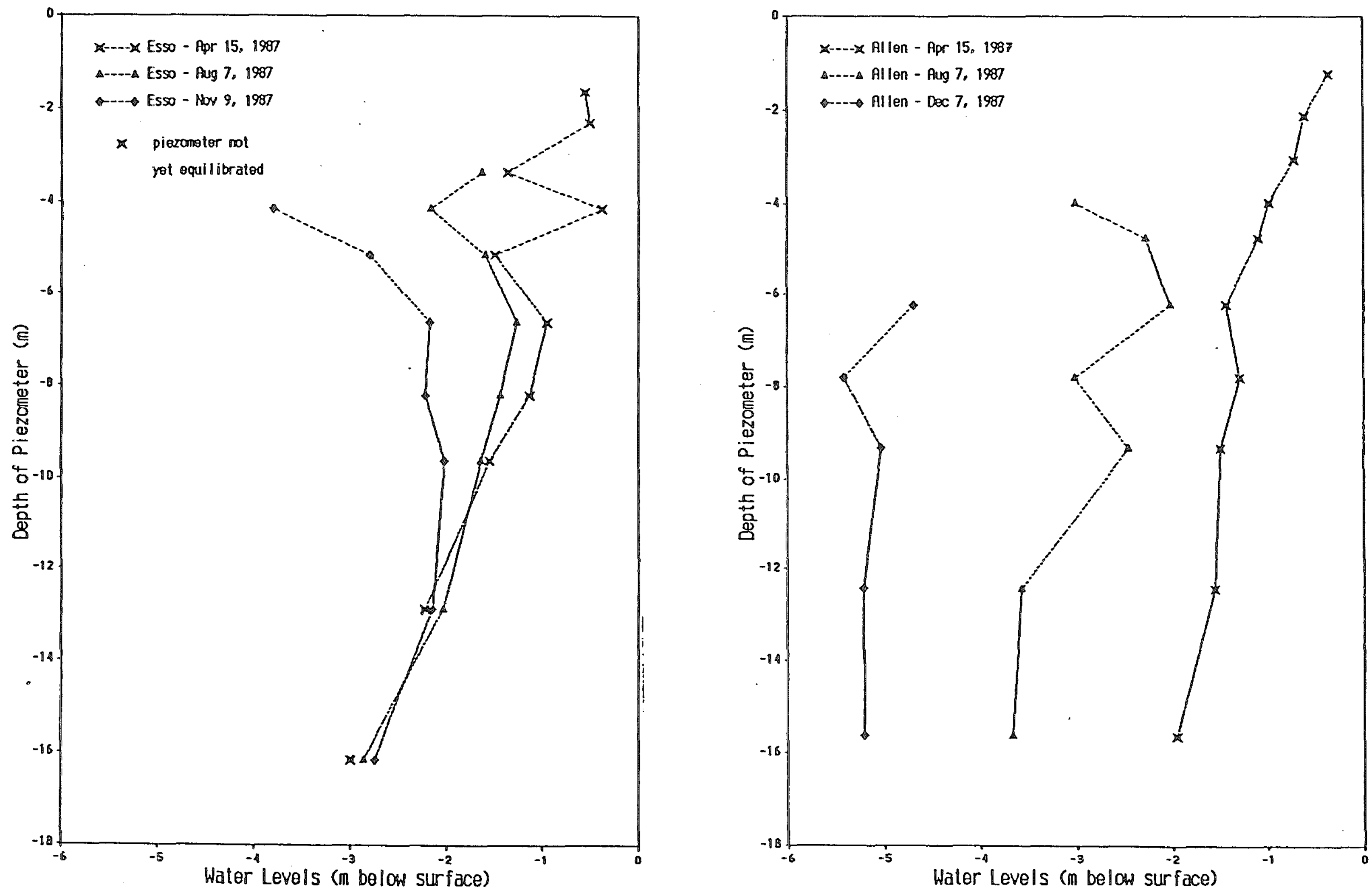


Figure 4b: Water level variations - Esso and Allen sites

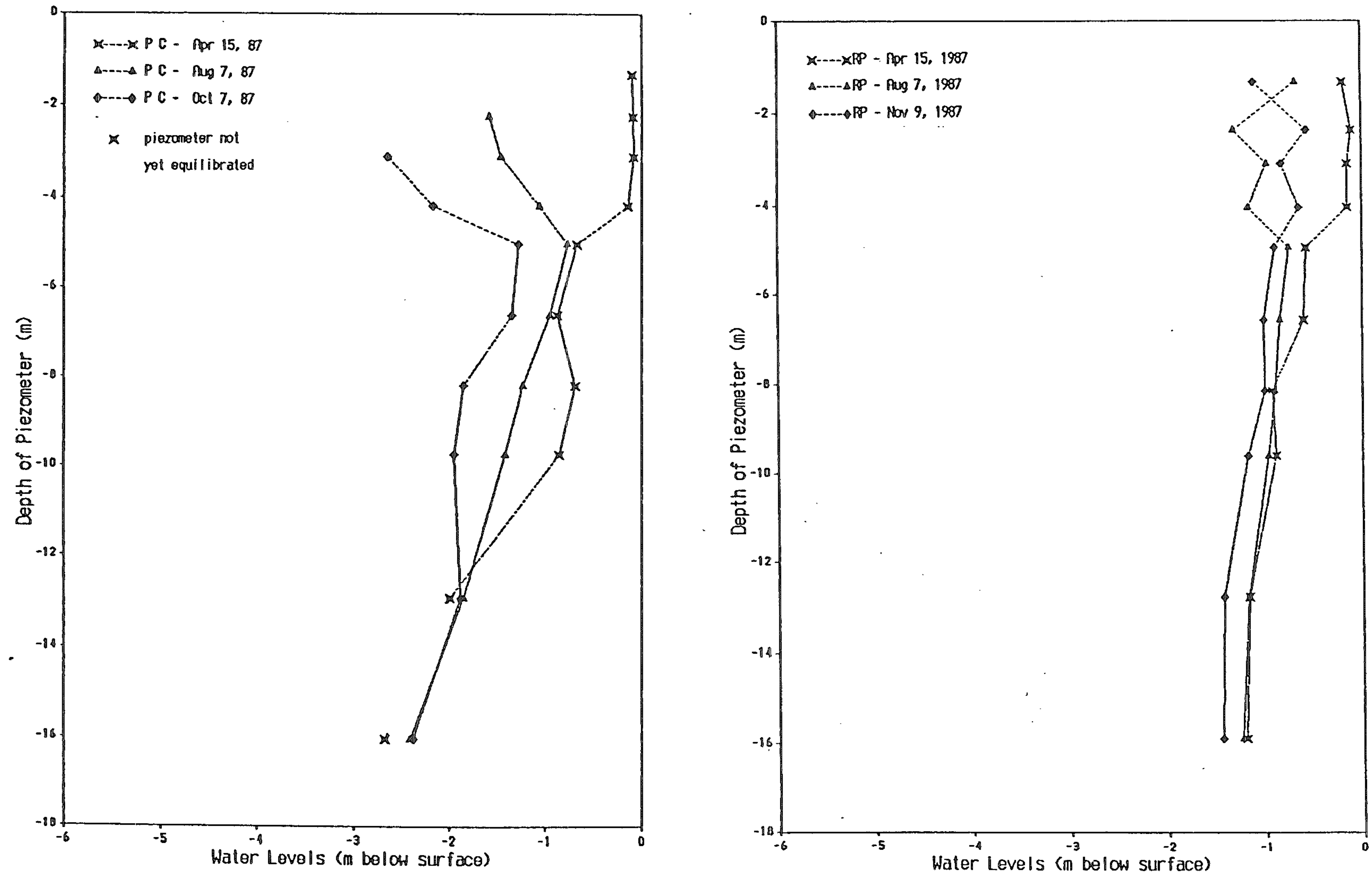


Figure 4c: Water level variations -

Polysar Corunna and Rural Polysar sites

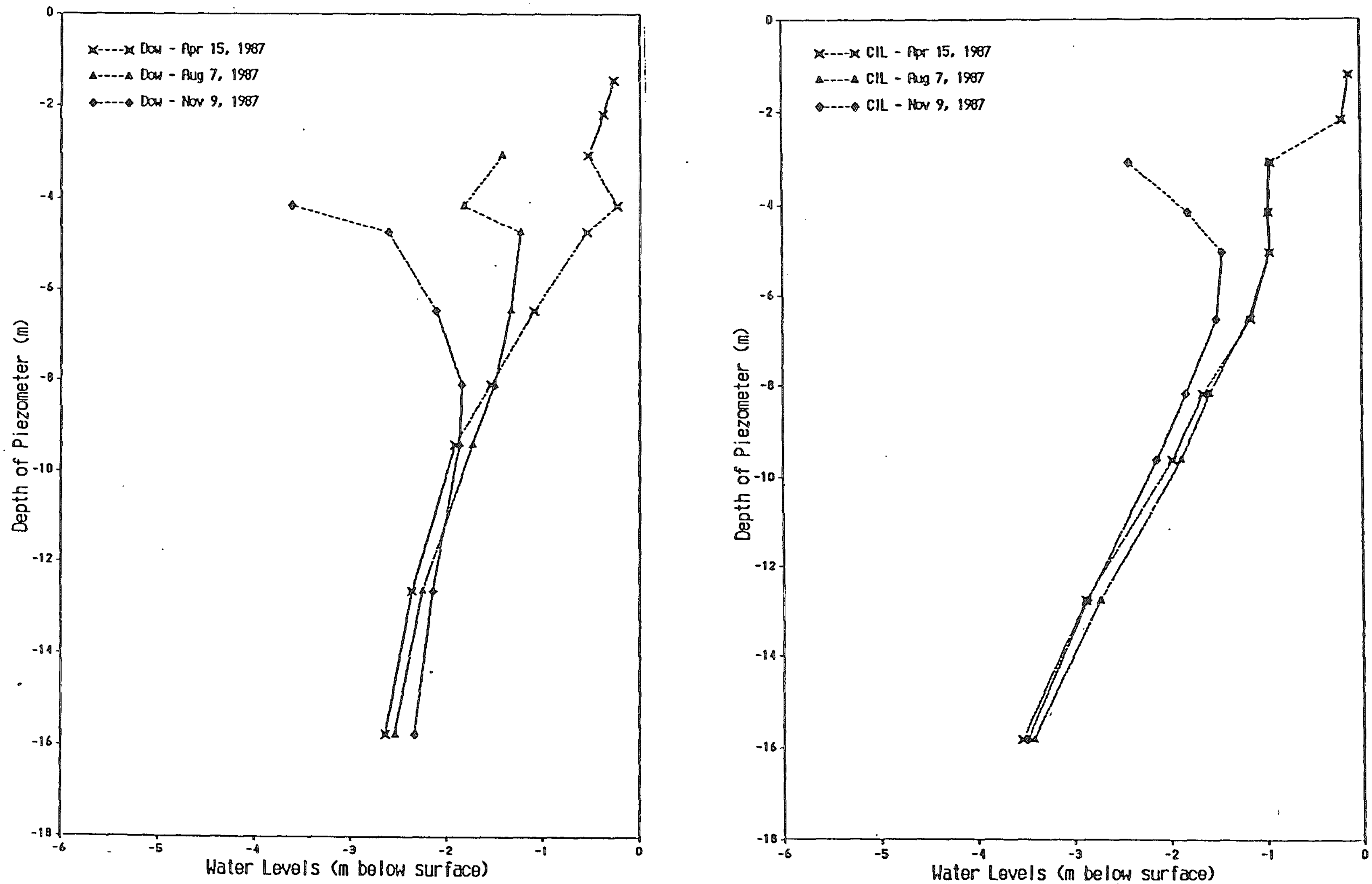


Figure 4d: Water level variations - Dow and CIL sites

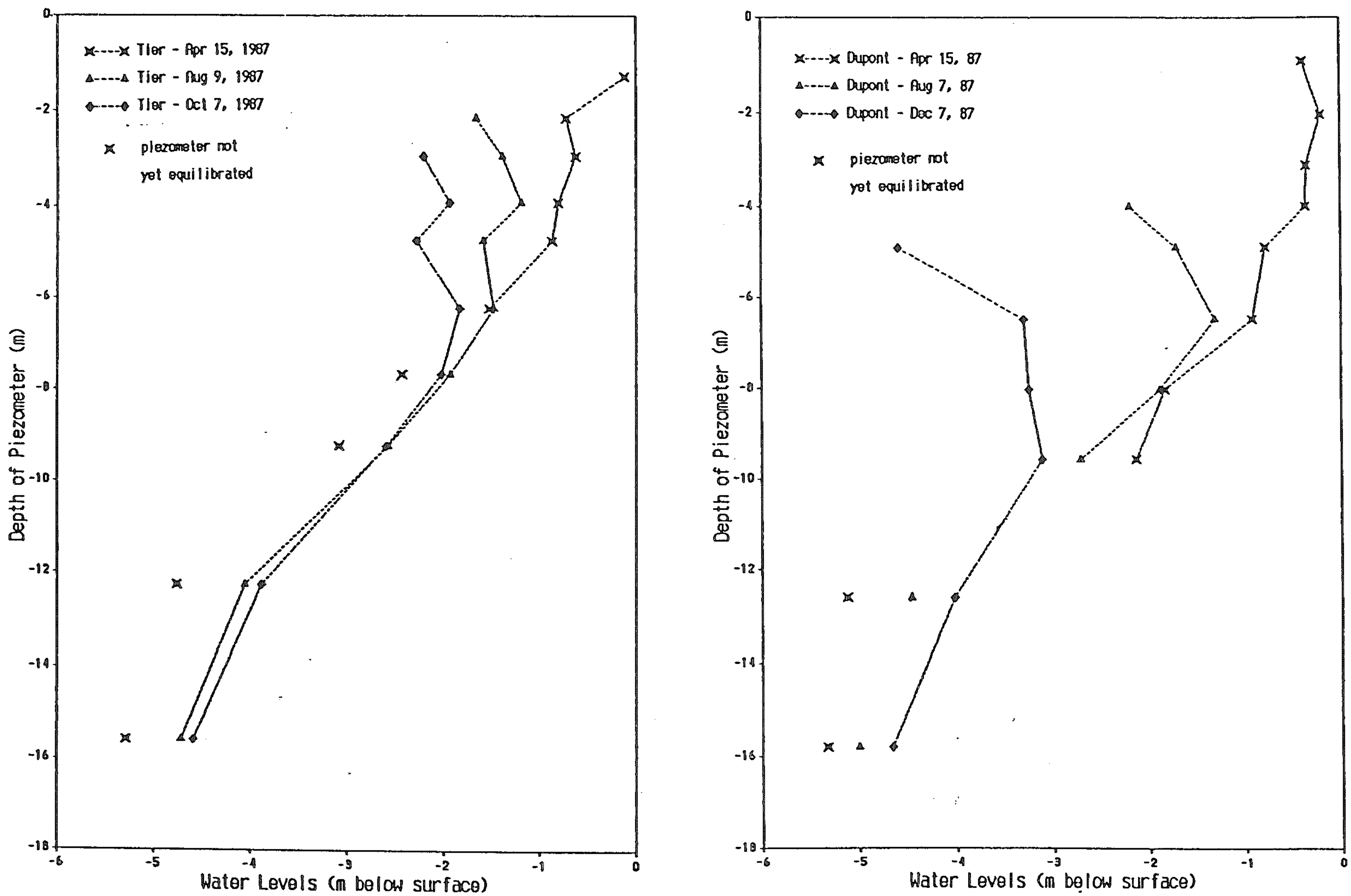


Figure 4e: Water level variations - Tiernay and Dupont sites

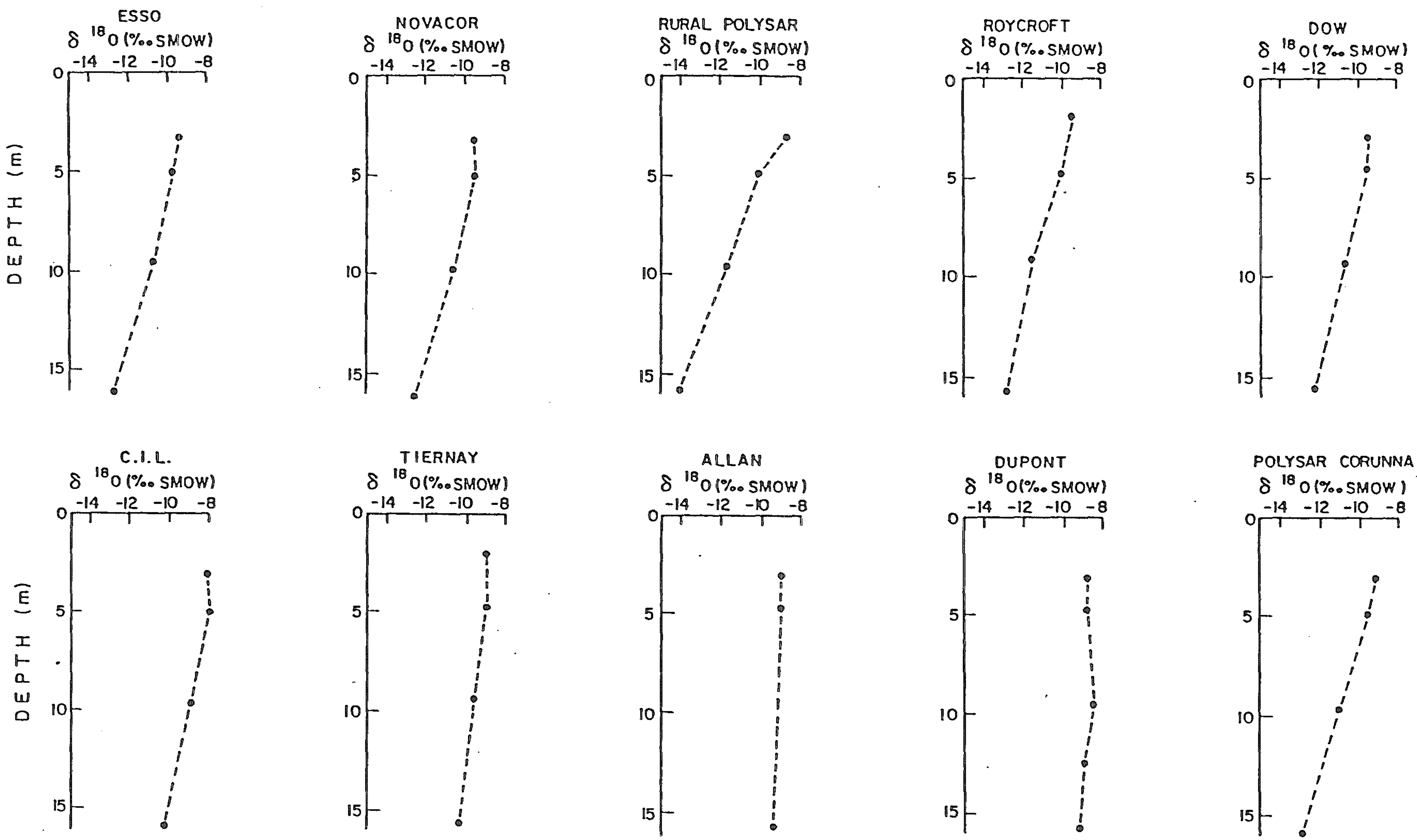
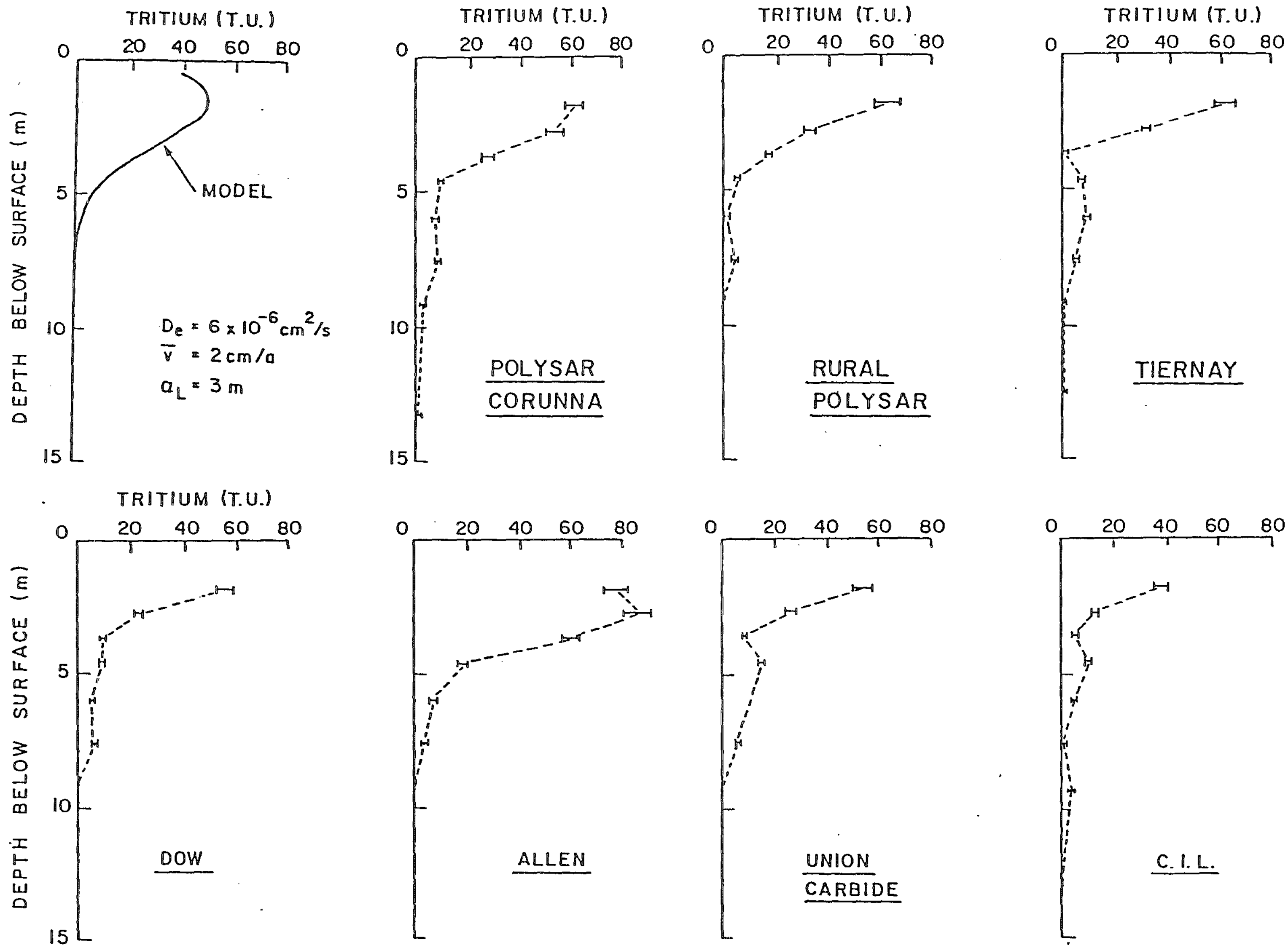
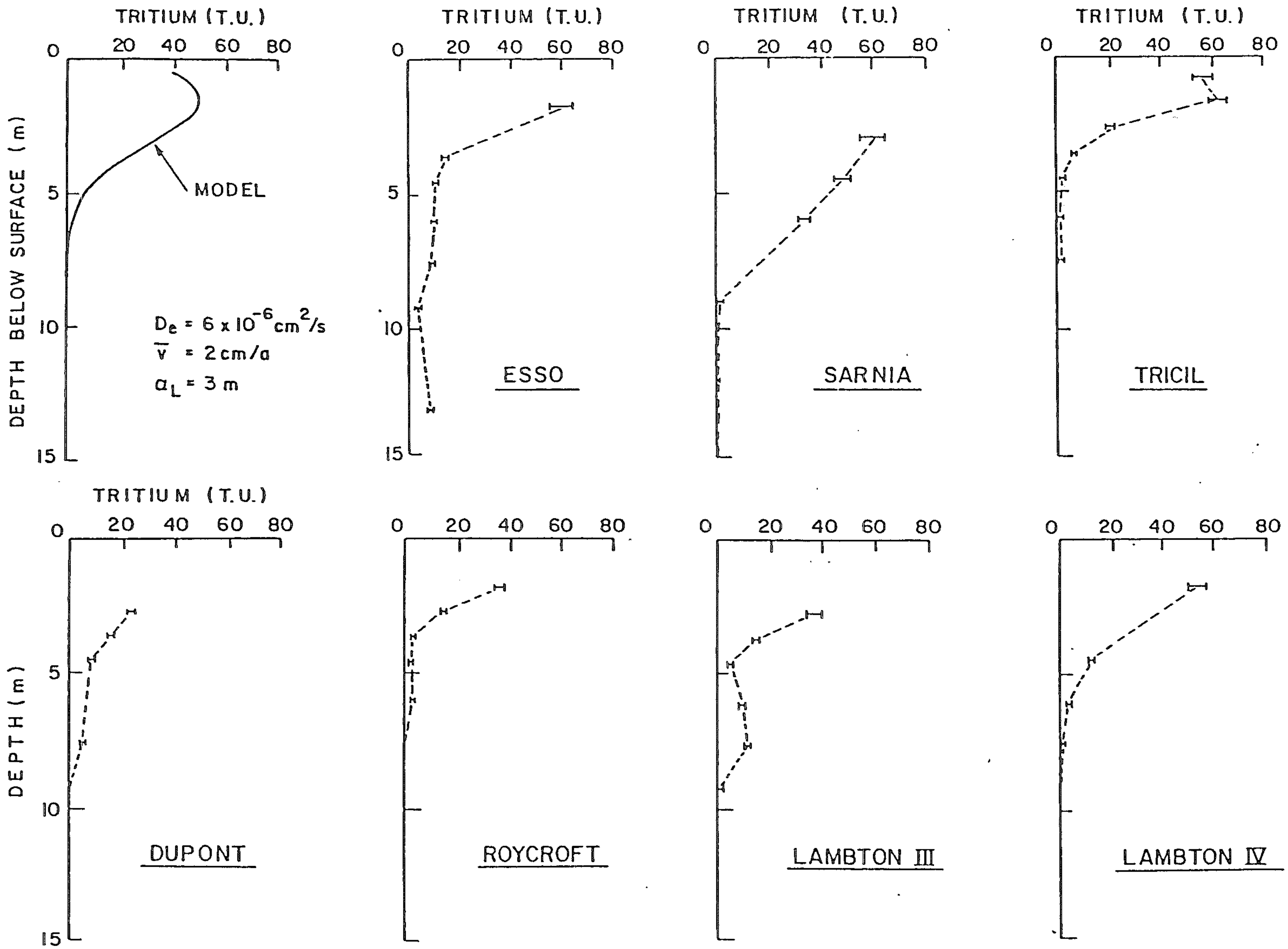


Figure 6: ^{18}O vs. depth profiles for Lambton County



Figures 7a: Field and model tritium vs. depth profiles



Figures 7b: Field and model tritium vs. depth profiles

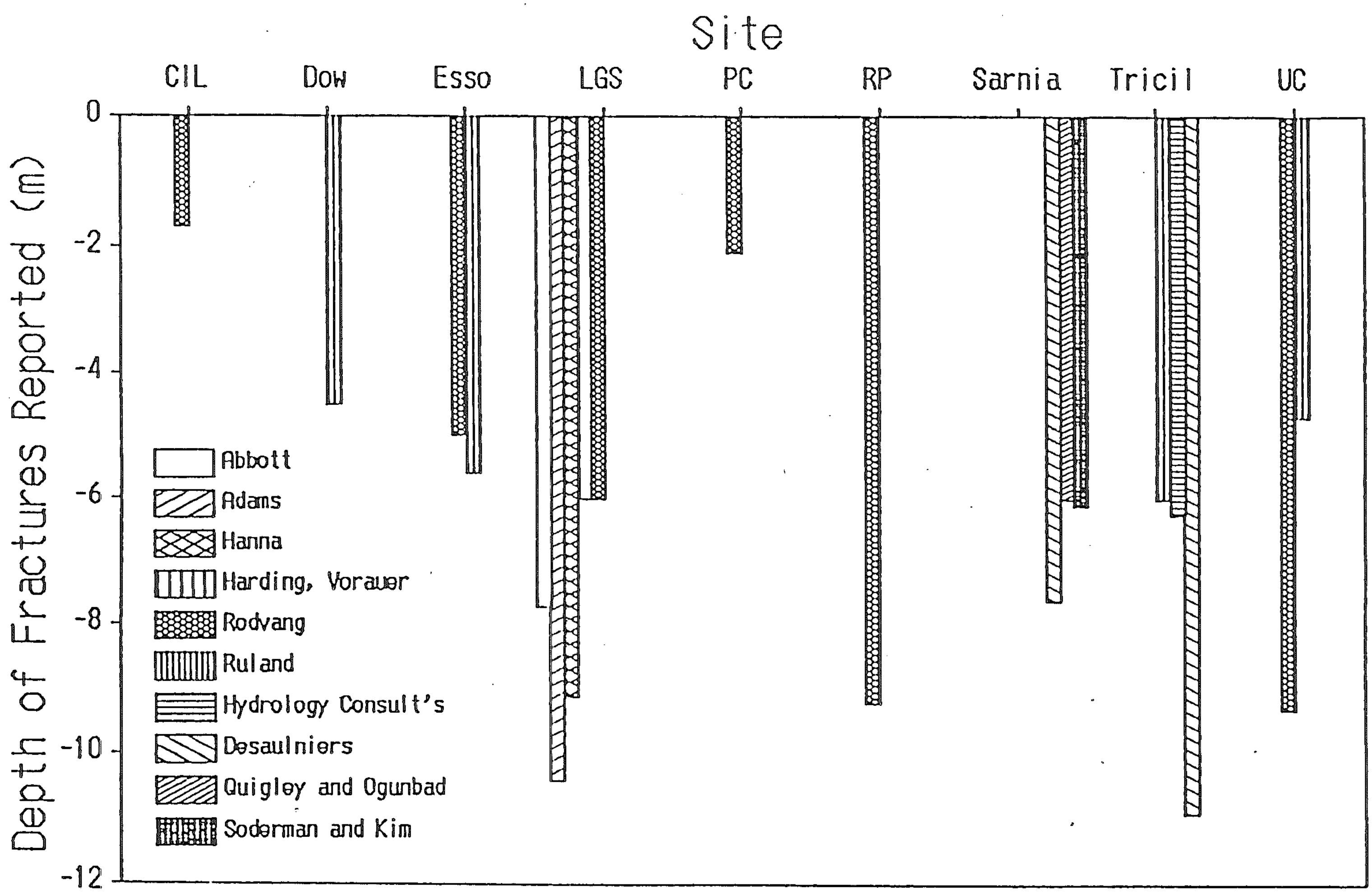


Figure 8: Maximum depth of fractures from drill cores or excavations in Lambton County

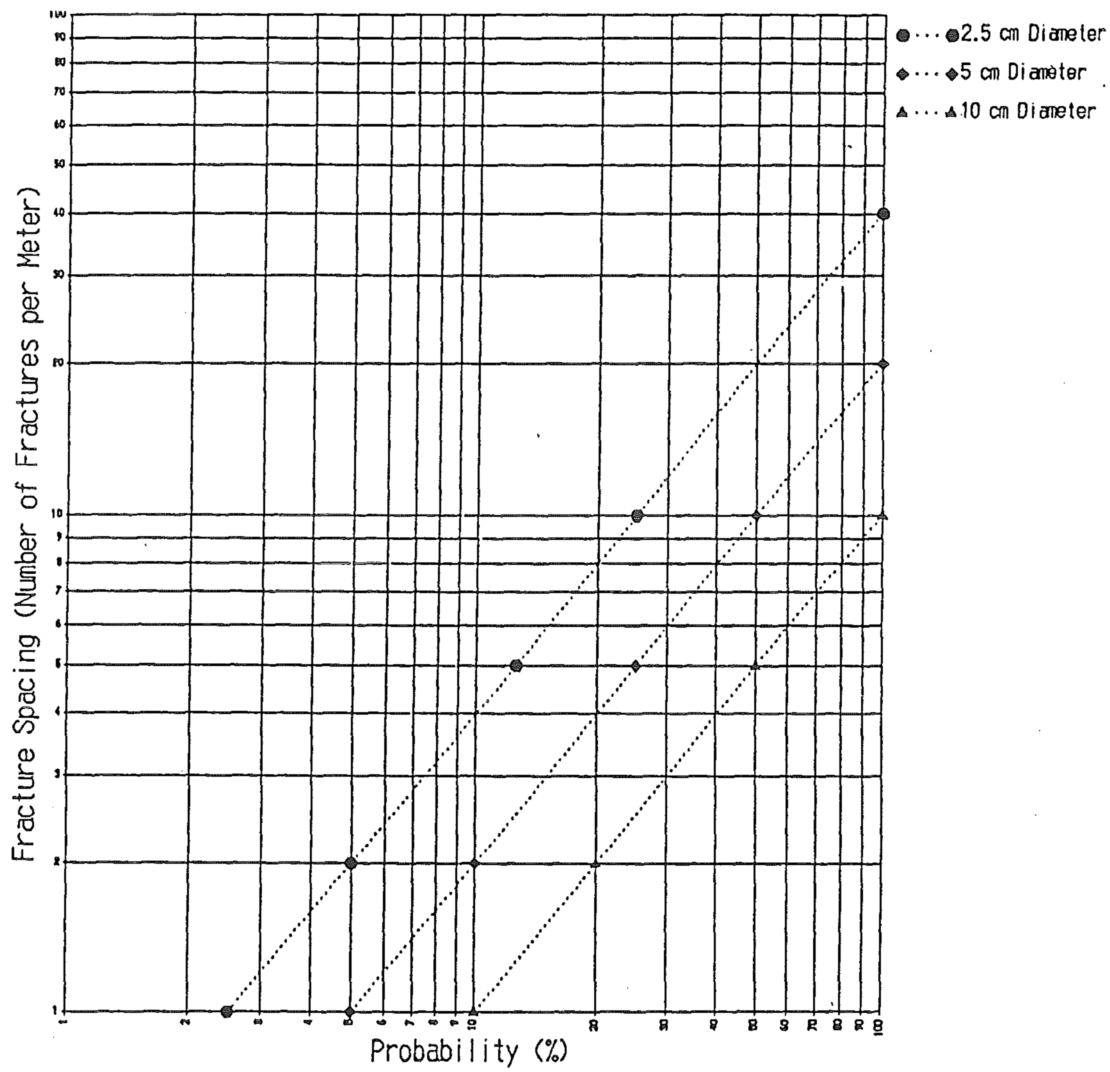


Figure 9: Fracture Spacing vs Probability of Encountering Fractures with Various Diameter Cores

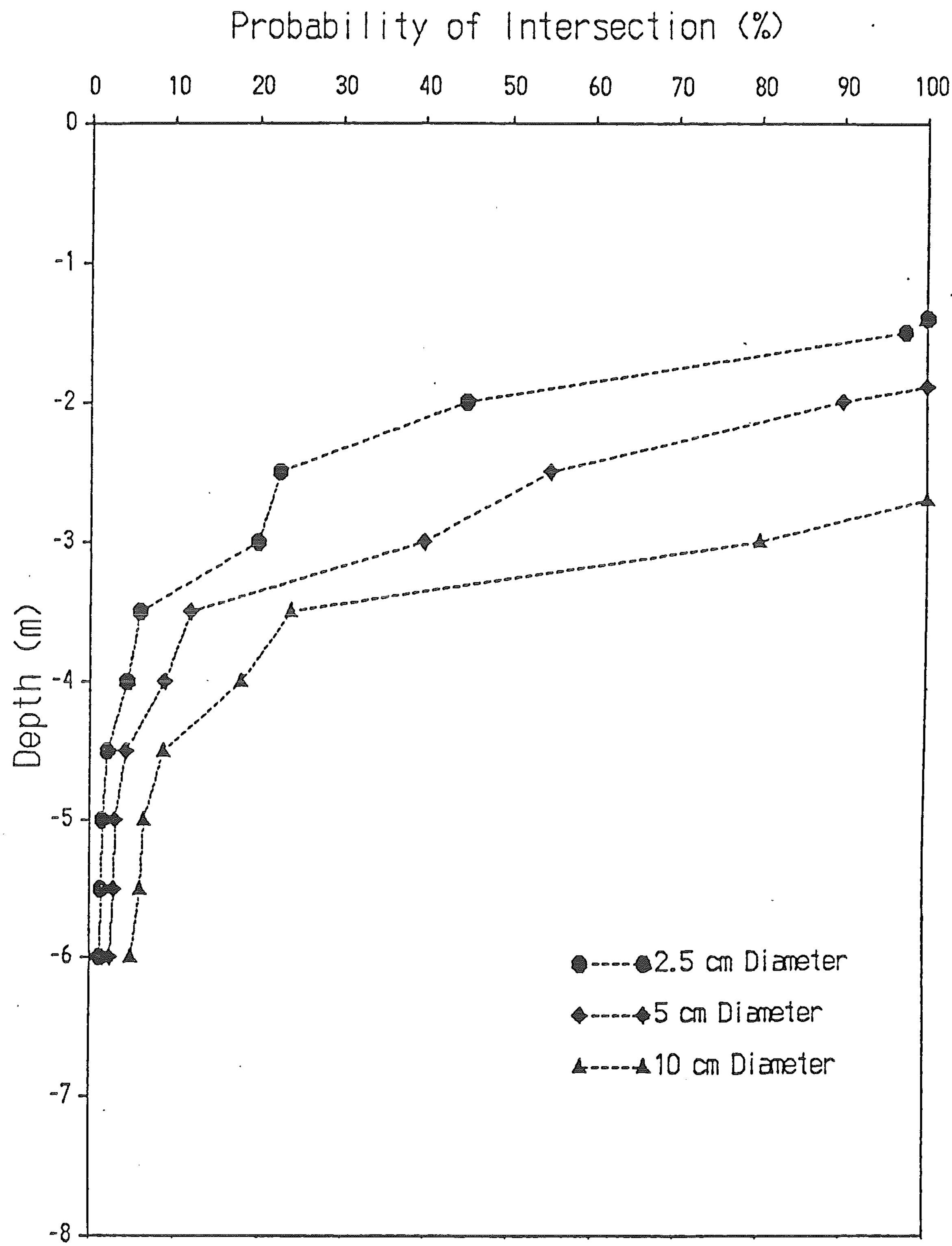
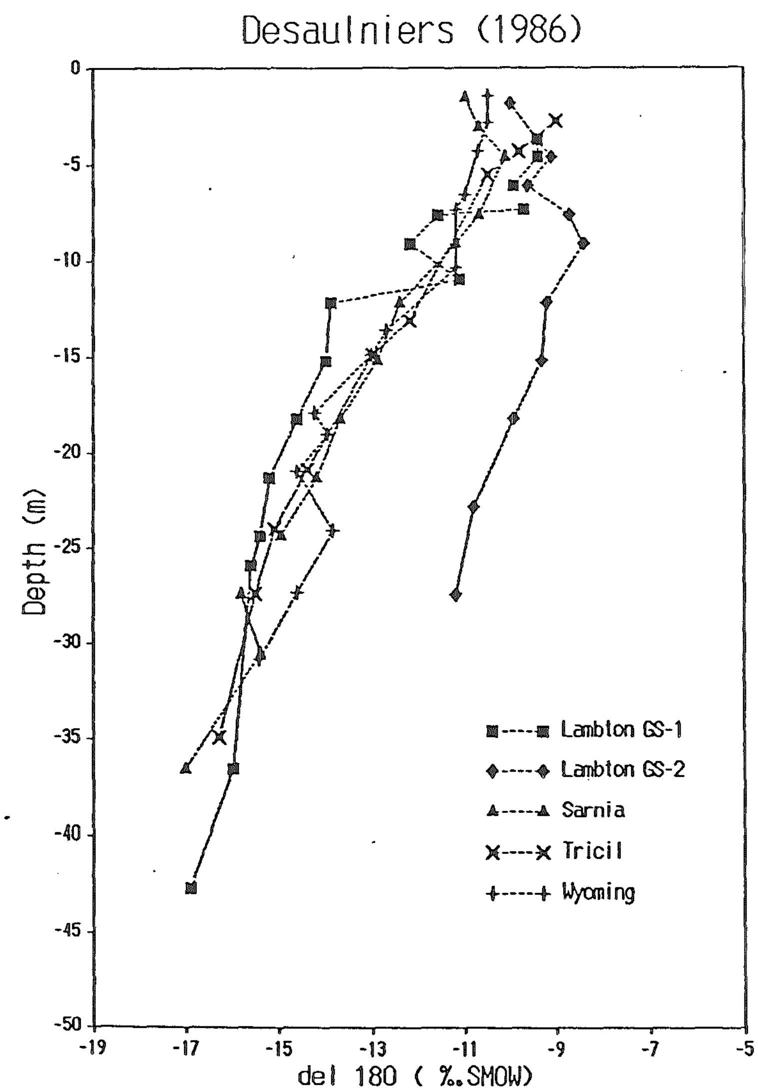


Figure 10: Probability of encountering fractures at various depths with drill cores of different diameters



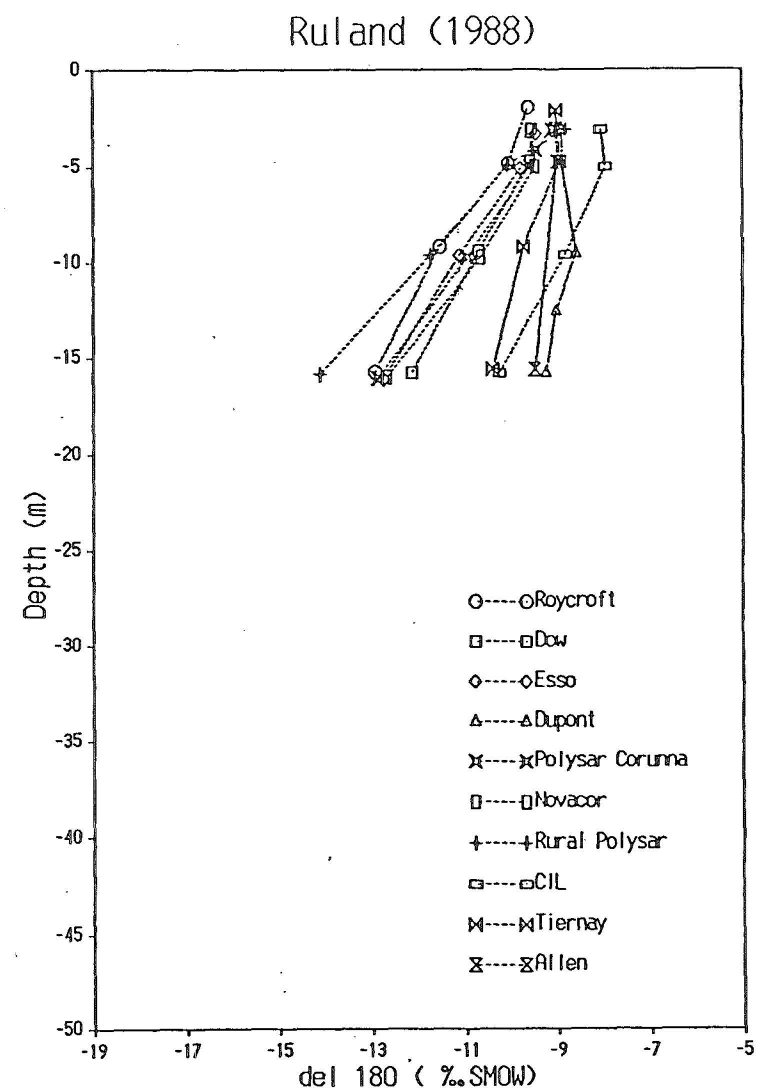


Figure 11: Comparison of ^{18}O vs depth profiles

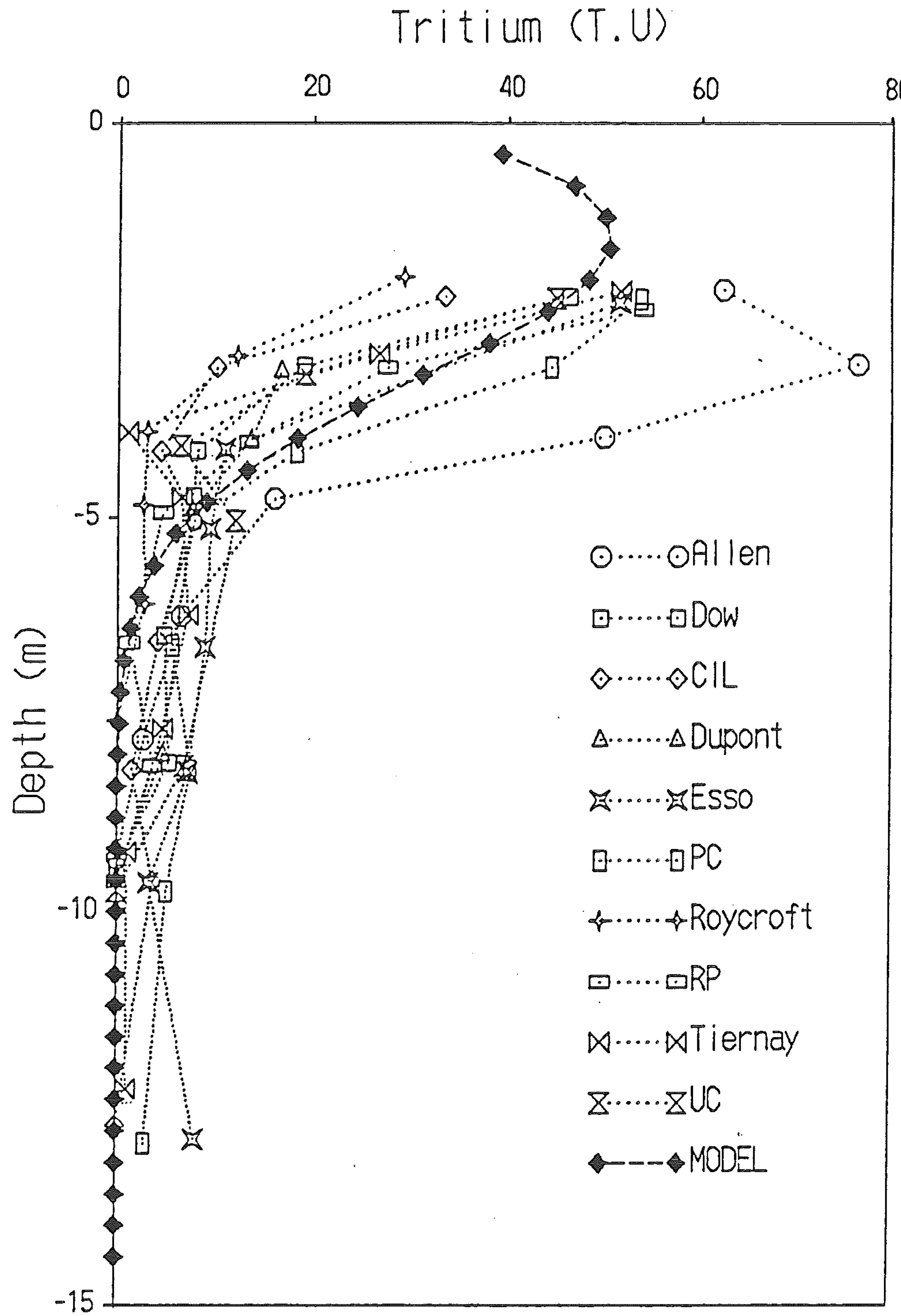


Figure 12: Profiles of tritium vs depth with the best fit theoretical profile

APPENDIX OF DATA

The data used in preparing this project is presented on the following pages. Data on fracture dips, fracture spacing, and ^{18}O, deuterium, and tritium analyses and water level measurements have been transcribed directly from the original field notes or laboratory reports.

TABLE OF CONTENTS

Fracture Dips - Tricil Site

The results are from three test pits excavated at the Tricil Ltd. site in 1986.

Fracture Dip:	0-10°	10-20°	20-30°	30-40°	40-50°	50-60°	60-70°	70-80°	80-90°
No. of Observ's:	0	0	0	0	1	1	11	26	139

Fracture Spacings

These results are from observations in 3 test pits excavated at the Tricil site in 1986, and from one test pit each at the Esso, Dow and Union Carbide (now Novacor) sites in 1987.

	Fracture Spacing (no. of fractures per horizontal m)			
Depth (m)	Tricil	Esso	Dow	Union Carbide
1	50	75	80	85
1.5		33	50	40
2.0	20	16	10	25
2.5		10	4	20
3.0	10	8	2.5	9
3.5		3.3	2	2
4.0	3.3	2	1.4	0.7
4.5		1.5	0.6	0.5
5.0	1.0	1.2	0	0
5.5		1.0	0	0
6.0	0.5	-	-	-

Results of ^{18}O and ^{2}H Analyses

Information about ^{18}O and ^{2}H analysis results for 10 Lambton County sites is presented as follows (eg. Roycroft site, piezometer depth approx 6 ft) :

-9.6 - sample $\delta^{18}O$ (‰ SMOW)
-68.4 - sample $\delta^{2}H$ (‰ SMOW)
A dash (-) indicates no sample submitted for that depth

Lambton County Study Sites

Approx. Piez. Depth (ft)	Roy	Dow	Ess	Dup	PC	UC	RP	CIL	Tie	All
3	-	-	-	-	-	-	-	-	-	-
6	-9.6 -68.4	-	-	-	-	-	-	-	-9.0 -65.0	-
9	-	-9.5 -67.5	-9.5 -70.7	-8.9 -62.5	-9.1 -63.6	-9.6 -70.4	-8.8 -61.8	-8.0 -58.2	-	-9.0 -71.7
12	-	-	-	-	-9.5 -72.2	-	-	-	-	-
15	-10.1 -71.2	-9.6 -71.1	-9.8 -70.8	-8.9 -62.9	-9.6 -70.2	-9.5 -71.7	-10.1 -74.3	-7.9 -58.3	-8.9 -63.3	-9.0 -59.8
20	-	-	-	-	-	-	-	-	-	-
25	-	-	-	-	-	-	-	-	-	-
30	-11.6 -80.0	-10.7 -79.0	-11.1 -78.8	-8.6 -68.2	-9.5 -72.2	-10.7 -77.0	-11.7 -89.2	-8.8 -65.5	-9.7 -71.7	-
40	-	-	-	-	-	-	-	-	-	-
50	-12.9 -96.2	-12.1 -85.6	-12.7 -91.8	-9.2 -64.3	-12.8 -87.4	-12.7 -91.3	-14.1 -98.1	-10.3 -77.8	-10.4 -74.2	-9.5 -68.3

Results of Tritium Analyses

Information about tritium analysis results for 10 Lambton County sites is presented as follows (eg. Roycroft site, piezometer depth approx 6 ft) :

29.5 - tritium concentration in sample (in T.U.)
2.1 - error margin (+/- ___ T.U.)
A dash (-) indicates no sample submitted for that depth

Lambton County Study Sites

Approx. Piez. Depth (ft)	Roy	Dow	Ess	Dup	PC	UC	RP	CIL	Tie	All
3	-	-	-	-	-	-	-	-	-	-
6	29.5	46.5	51.6	-	53.8	45.2	54.1	33.7	51.7	62.5
	2.1	3.2	3.5		3.6	3.1	3.7	2.4	3.5	4.2
9	12.2	19.2	-	16.8	44.6	19.3	27.7	10.1	26.8	76.6
	1.1	1.5		1.3	3.1	1.5	2.0	1.0	1.9	5.1
12	3.0	8.1	11.0	13.6	18.4	6.3	13.5	4.4	1.0	50.1
	0.7	0.8	1.1	1.2	1.5	0.8	1.2	0.7	0.6	3.4
15	2.6	7.7	9.4	7.6	7.8	12.1	4.6	7.9	6.5	16.2
	0.5	0.7	0.8	0.8	0.8	1.0	0.6	0.8	0.7	0.9
20	2.7	4.7	9.0	-	5.6	-	1.2	4.1	7.3	6.5
	1.0	0.7	0.9		0.8		0.6	0.7	0.9	0.8
25	<0.8	5.2	7.3	4.6	7.5	6.8	3.6	1.5	4.6	2.6
		0.8	0.9	0.7	0.9	0.9	0.8	0.7	0.7	0.7
30	<0.8	<0.8	3.2	<0.8	5.0	<0.8	<0.8	3.6	1.0	<0.8
			0.9		0.8			0.7		
40	-	-	8.0	-	2.9	-	-	<0.8	1.1	-
			0.6		0.8				0.7	
50	-	-	-	-	-	-	-	-	-	-

Water Level Measurements

Information regarding piezometers at 10 Lambton County sites is presented as follows (eg. Roycroft site, piezometer depth approx 3 ft):

1.01 - true depth of piezometer tip below ground surface (m)
0.93 - height above ground of casing (must be subtracted from water levels on the following pages to give the actual water level in m below surface)

Lambton County Study Sites

Approx. Piez. Depth (ft)	Roy	Dow	Ess	Dup	PC	UC	RP	CIL	Tie	All
3	1.01 0.93	1.46 0.85	1.63 0.80	0.92 0.65	1.33 0.78	1.31 0.84	1.35 0.95	1.22 0.78	1.27 0.87	1.23 0.79
6	1.96 0.90	2.20 0.85	2.29 0.81	2.05 0.70	2.24 0.80	2.23 0.80	2.37 0.90	2.21 0.77	2.14 0.87	2.12 0.77
9	2.96 0.88	3.09 0.90	3.35 0.79	3.15 0.70	3.11 0.82	3.19 0.79	3.11 0.89	3.11 0.75	2.94 0.88	3.07 0.70
12	3.91 0.85	4.15 1.05	4.13 0.80	4.01 0.65	4.17 0.78	4.09 0.80	4.04 0.94	4.16 0.77	3.92 0.86	3.98 0.71
15	4.83 0.81	4.72 1.00	5.14 0.79	4.89 0.69	5.01 0.79	5.04 0.80	4.94 0.93	5.04 0.73	4.74 0.84	4.76 0.70
20	6.09 0.90	6.48 0.85	6.64 0.80	6.47 0.71	6.62 0.83	6.59 0.86	6.58 0.88	6.56 0.74	6.23 0.80	6.24 0.76
25	7.56 0.91	8.10 0.87	8.23 0.77	8.00 0.68	8.20 0.80	8.14 0.82	8.14 0.86	8.19 0.69	7.67 0.95	7.81 0.78
30	9.18 0.92	9.43 0.92	9.64 0.78	9.55 0.71	9.75 0.80	9.74 0.81	9.62 0.83	9.62 0.70	9.24 0.84	9.32 0.83
40	12.17 0.93	12.67 0.85	12.91 0.74	12.59 0.69	12.96 0.74	12.82 0.80	12.74 0.84	12.73 0.69	12.27 0.84	12.41 0.86
50	15.79 0.96	15.78 0.92	16.16 0.64	15.80 0.70	16.05 0.71	16.01 0.71	15.86 0.86	15.79 0.79	15.58 0.86	15.61 0.88

WATER LEVEL MEASUREMENTS - ROYCROFT SITE

Water levels for the Roycroft site are presented below, all values are in meters below casing. Note the sampling event on July 18, '86 and the effects of sampling the 5 shallowest wells in Dec. '86, and note the following symbols:

dry - piezometer is dry
n/a - no measurement possible (due to ice, breakage or obstruction)

Approximate Piezometer Depth (ft)

Date	50	40	30	25	20	15	12	09	06	03
1985										
O 29	16.70	dry	dry	8.50	6.99	5.11	4.64	3.59	2.70	1.91
N 27	14.98	12.61	9.11	8.08	6.70	3.39	3.76	2.82	2.13	1.54
D 22	13.82	11.62	7.88	7.39	6.08	2.65	3.12	2.20	1.76	1.30
1986										
J 19	12.66	10.51	6.78	6.63	5.39	2.14	2.68	1.86	1.57	1.28
M 14	10.56	8.47	5.12	5.36	4.30	1.61	2.03	1.37	1.25	1.07
A 14	9.62	7.57	4.48	4.77	3.82	1.42	1.75	1.21	1.13	1.01
M 16	8.81	6.63	4.00	4.29	3.44	1.38	1.63	1.23	1.18	1.13
J 13	8.22	6.34	3.72	3.97	3.18	1.42	1.58	1.28	1.23	1.24
J 18	7.62	5.83	3.49	3.66	2.92	1.46	1.54	1.34	1.30	1.30
18	9.41	7.50	5.53	5.40	5.35	3.70	3.82	2.85	2.70	1.30
A 22	8.52	6.62	4.62	4.72	4.60	2.91	2.98	2.26	2.22	1.38
S 24	7.86	6.04	4.07	4.17	4.05	2.40	2.45	1.91	1.88	1.32
O 23	7.37	5.60	3.59	3.70	3.56	1.92	1.96	1.53	1.50	1.13
N 19	6.95	5.21	3.23	3.30	3.17	1.69	1.68	1.35	1.32	1.09
D 17	6.57	4.86	2.93	2.97	2.83	1.57	1.58	1.29	1.25	1.07
1987										
J 15	6.25	4.55	2.70	2.71	2.58	4.03	3.26	2.35	1.87	1.22
F 07	6.00	4.35	2.58	2.56	2.42	3.02	2.75	1.99	1.65	1.18
M 02	5.78	4.16	2.51	2.46	2.32	2.45	2.38	1.76	1.51	1.18
A 15	5.52	3.97	2.46	2.36	2.18	1.89	1.96	1.48	1.32	1.09
M 01	5.33	3.84	2.43	2.30	2.07	1.65	1.73	1.37	1.26	1.12
J 06	5.14	3.75	2.49	2.29	2.02	1.63	1.67	1.44	1.38	1.38
J 07	5.02	3.71	2.58	2.30	2.02	1.71	1.71	1.59	1.54	1.73
A 07	4.92	3.70	2.66	2.34	2.06	1.96	1.92	1.93	1.91	dry
S 04	4.86	3.70	2.76	2.43	2.16	2.30	2.19	2.31	2.01	dry
O 07	4.79	3.70	2.87	2.52	2.30	2.71	2.55	2.75	dry	dry
N 09	4.76	3.72	2.92	2.60	2.38	2.62	2.56	2.64	2.82	2.00
D 07	4.75	3.71	2.78	2.50	2.26	2.12	2.22	2.16	2.39	1.76

WATER LEVEL MEASUREMENTS - DOW SITE

Water levels for the Dow site are presented below, all values are in meters below casing. Note the sampling event on July 18, '86 and note the following symbols:

dry - piezometer is dry
n/a - no measurement possible (due to ice, breakage or obstruction)

Approximate Piezometer Depth (ft)

Date	50	40	30	25	20	15	12	09	06	03
1985										
O 29	13.48	12.78	10.15	8.62	7.01	5.15	3.16	3.53	2.70	1.46
N 27	8.61	10.18	9.56	7.72	6.03	3.90	1.50	2.83	1.92	1.18
D 22	6.48	9.41	8.65	6.62	5.12	3.18	1.41	2.40	1.56	1.27
1986										
J 19	5.21	6.92	7.70	5.95	4.34	2.71	1.49	2.11	1.52	1.43
M 14	4.14	5.07	5.96	4.56	3.25	2.03	1.28	1.61	1.23	1.11
A 14	3.93	4.51	5.23	4.00	2.85	1.81	1.22	1.45	1.18	1.16
M 16	3.83	4.13	4.66	3.57	2.56	1.71	1.36	1.42	1.32	1.23
J 13	3.75	3.91	4.29	3.30	2.42	1.71	1.51	1.49	1.51	1.69
J 18	3.71	3.74	3.91	3.10	2.33	1.80	1.87	1.67	1.88	2.13
18	5.71	5.76	5.90	5.25	4.64	4.08	4.18	3.22	2.48	2.13
A 22	4.36	4.72	5.06	4.46	3.83	3.42	2.75	3.02	2.90	dry
S 24	3.84	4.13	4.51	3.98	3.42	3.25	2.02	3.12	3.11	dry
O 23	3.70	3.88	4.13	3.63	3.08	2.77	1.88	2.72	2.41	1.45
N 19	3.68	3.72	3.81	3.31	2.73	2.35	1.58	2.30	1.76	1.46
D 17	3.66	3.60	3.53	3.02	2.45	2.05	1.40	1.99	1.42	1.29
1987										
J 15	3.63	3.49	3.27	2.78	2.21	1.80	1.30	1.72	1.25	1.21
F 07	3.59	3.41	3.10	2.62	2.09	1.71	1.32	1.62	1.30	1.31
M 02	3.57	3.35	2.96	2.50	2.01	1.62	1.31	1.53	1.26	1.01
A 15	3.55	3.31	2.83	2.40	1.94	1.54	1.28	1.43	1.23	1.12
M 01	3.54	3.29	2.74	2.32	1.88	1.49	1.27	1.38	1.25	1.50
J 06	3.52	3.26	2.68	2.29	1.91	1.60	1.59	1.52	1.69	dry
J 07	3.48	3.22	2.64	2.30	2.00	1.83	2.11	1.82	2.41	dry
A 07	3.45	3.20	2.65	2.37	2.18	2.23	2.87	2.32	dry	dry
S 04	3.44	3.20	2.69	2.48	2.45	2.71	3.63	3.07	dry	dry
O 07	3.36	3.16	2.75	2.60	2.71	3.23	4.26	dry	dry	dry
N 09	3.25	3.09	2.79	2.71	2.95	3.60	4.65	dry	dry	dry
D 07	3.30	3.14	2.87	2.84	3.10	3.65	4.19	3.90	2.47	1.30

WATER LEVEL MEASUREMENTS - ESSO SITE

Water levels for the Esso site are presented below, all values are in meters below casing. Note the sampling event on July 18, '86 and the results of sampling in Dec. '86 in the 5 shallowest wells, and note the following symbols:

dry - piezometer is dry
n/a - no measurement possible (due to ice, breakage or obstruction)

Approximate Piezometer Depth (ft)

Date	50	40	30	25	20	15	12	09	06	03
1985										
O 29	9.88	8.14	6.25	5.00	4.81	3.25	1.83	3.06	1.13	1.13
N 27	8.82	7.16	5.48	4.32	4.22	2.54	1.26	2.49	0.95	0.94
D 22	8.08	6.48	4.91	3.80	3.74	2.12	1.15	2.13	1.15	1.28
1986										
J 19	7.36	5.81	4.38	3.40	3.36	1.89	1.22	1.92	1.17	1.09
M 14	6.20	4.77	3.58	2.76	2.70	1.50	1.15	1.54	0.97	0.91
A 14	5.70	4.34	3.28	2.54	2.43	1.37	1.10	1.40	1.15	1.12
M 16	5.27	3.97	3.02	2.35	2.36	1.36	1.20	1.36	1.69	1.76
J 13	5.02	3.71	2.88	2.31	2.17	1.43	1.42	1.41	1.51	1.08
J 18	4.75	3.52	2.77	2.26	2.08	1.50	1.43	1.44	2.01	2.03
18	6.50	5.20	5.07	3.91	4.42	3.89	3.75	3.13	2.97	2.03
A 22	5.78	4.59	4.29	3.31	3.77	3.19	2.31	2.80	2.40	dry
S 24	5.30	4.17	3.84	3.07	3.40	2.87	1.99	2.73	1.34	1.05
O 23	4.95	3.92	3.52	2.76	3.02	2.25	1.11	2.26	1.02	1.06
N 19	4.72	3.70	3.25	2.52	2.68	1.87	1.06	1.94	1.05	1.12
D 17	4.65	3.63	3.12	2.42	2.55	1.73	1.02	1.83	0.94	0.95
1987										
J 15	4.32	3.28	2.75	2.11	2.17	n/a	n/a	n/a	n/a	n/a
F 07	4.21	3.16	2.60	2.02	2.04	n/a	n/a	n/a	n/a	n/a
M 02	4.14	3.05	2.50	1.96	1.94	3.79	1.84	3.08	0.91	0.92
A 15	3.92	2.93	2.39	1.92	1.81	2.81	0.95	2.50	0.92	0.93
M 01	3.82	2.86	2.32	1.90	1.75	1.98	1.18	1.94	1.32	1.35
J 06	3.72	2.80	2.31	1.94	1.78	2.10	1.92	2.00	2.08	dry
J 07	3.66	2.78	2.32	2.04	1.88	2.16	2.40	2.08	2.60	dry
A 07	3.60	2.77	2.41	2.20	2.06	2.39	2.96	2.41	dry	dry
S 04	3.53	2.80	2.49	2.41	2.28	2.72	3.57	3.12	dry	dry
O 07	3.46	2.83	2.62	2.67	2.62	3.22	4.34	dry	dry	dry
N 09	3.38	2.88	2.79	2.98	2.97	3.58	4.59	dry	dry	dry
D 07	3.42	3.00	2.98	3.12	3.01	3.10	2.22	3.89	1.02	0.98

WATER LEVEL MEASUREMENTS - DUPONT SITE

Water levels for the Dupont site are presented below, all values are in meters below casing. Note the sampling event on July 18, '86 and the result of sampling in the 9' and 15' deep wells in Dec. '86, and note the following symbols:

dry - piezometer is dry
n/a - no measurement possible (due to ice, breakage or obstruction)

Approximate Piezometer Depth (ft)

Date	50	40	30	25	20	15	12	09	06	03
1985										
O 29	15.41	13.06	10.12	8.44	6.80	5.15	4.44	dry	dry	dry
N 27	13.05	12.79	9.85	7.99	5.87	3.89	3.01	3.30	1.52	0.98
D 22	11.45	12.15	9.27	7.17	5.03	2.95	1.80	2.18	1.16	1.30
1986										
J 19	10.13	11.34	8.53	6.29	4.28	2.39	1.52	1.72	1.11	0.85
M 14	8.32	9.82	7.08	4.86	3.18	1.70	1.07	1.17	0.82	0.83
A 14	7.71	9.11	6.44	4.29	2.74	1.48	1.02	1.05	0.95	1.01
M 16	6.99	8.48	5.89	3.83	2.41	1.39	1.14	1.10	1.42	1.56
J 13	6.95	7.99	5.49	3.56	2.26	1.44	1.47	1.37	1.47	1.14
J 18	6.67	7.51	5.10	3.31	2.13	1.53	1.74	1.72	2.70	0.95
18	8.46	9.22	7.07	5.12	4.42	3.78	3.91	3.31	2.72	0.95
A 22	7.52	8.41	6.28	4.41	3.74	3.20	2.28	3.48	dry	dry
S 24	6.97	7.81	5.73	3.98	3.35	2.93	2.46	dry	dry	dry
O 23	6.69	7.39	5.33	3.68	2.96	2.53	1.72	3.31	1.39	1.36
N 19	6.51	7.06	5.05	3.40	2.60	2.17	1.31	2.36	1.23	1.26
D 17	6.50	6.93	4.92	3.29	2.48	2.03	1.20	2.03	0.89	0.85
1987										
J 15	6.25	6.45	4.42	2.88	2.02	4.26	1.25	2.54	n/a	n/a
F 07	6.17	6.23	4.20	2.73	1.88	3.47	1.11	1.60	n/a	n/a
M 02	6.09	6.03	4.04	2.62	1.76	2.89	1.05	1.21	n/a	n/a
A 15	6.02	5.81	3.84	2.51	1.64	2.32	1.02	1.06	n/a	n/a
M 01	5.96	5.64	3.70	2.45	1.55	1.99	1.03	1.05	n/a	n/a
J 06	5.90	5.46	3.58	2.42	1.58	1.85	1.28	1.55	n/a	n/a
J 07	5.81	5.30	3.49	2.45	1.71	1.98	1.94	2.50	n/a	n/a
A 07	5.70	5.15	3.42	2.56	2.03	2.40	2.84	dry	n/a	n/a
S 04	5.59	5.03	3.46	2.85	2.45	3.02	3.88	dry	n/a	n/a
O 07	5.47	4.91	3.55	3.24	3.12	3.88	dry	dry	n/a	n/a
N 09	5.39	4.84	3.68	3.62	3.71	4.87	dry	dry	n/a	n/a
D 07	5.36	4.71	3.81	3.92	4.00	5.28	dry	dry	n/a	n/a

WATER LEVEL MEASUREMENTS - POLYSAR CORUNNA (PETROSAR) SITE

Water levels for the Polysar Corunna site are presented below, all values are in meters below casing. Note the sampling event on July 18, '86 and note the following symbols:

dry - piezometer is dry
n/a - no measurement possible (due to ice, breakage or obstruction)

Approximate Piezometer Depth (ft)

Date	50	40	30	25	20	15	12	09	06	03
1985										
O 29	9.32	7.86	3.11	3.22	4.65	3.78	2.21	1.69	1.69	1.70
N 27	8.10	6.88	2.53	2.51	3.92	3.19	1.49	0.94	0.91	0.90
D 22	7.27	6.17	2.18	2.10	3.41	2.78	1.22	0.91	1.12	1.08
1986										
J 19	6.49	5.46	2.00	1.86	2.98	2.43	1.08	0.98	0.86	0.83
M 14	5.38	4.45	1.86	1.77	2.40	1.95	0.94	0.90	0.86	0.86
A 14	4.90	4.06	1.88	1.66	2.18	1.75	0.91	0.95	0.97	0.99
M 16	4.52	3.76	1.90	1.66	2.01	1.61	1.01	1.21	1.32	1.37
J 13	4.28	3.55	1.96	1.72	1.92	1.54	1.13	1.29	0.96	0.97
J 18	4.02	3.36	2.02	1.79	1.88	1.50	1.31	1.57	1.66	1.69
18	5.91	5.06	4.05	3.56	4.33	4.04	3.74	3.04	2.78	1.69
A 22	5.15	4.48	2.75	2.64	3.67	3.46	2.39	1.89	1.92	1.92
S 24	4.80	4.11	2.48	2.40	3.27	3.09	2.10	1.70	2.27	1.28
O 23	4.43	3.80	2.12	2.03	2.88	2.63	1.38	1.01	1.05	1.05
N 19	4.18	3.55	1.91	1.86	2.54	2.30	1.15	1.07	1.09	1.10
D 17	3.96	3.32	1.71	1.56	2.25	2.03	1.00	0.95	0.98	0.98
1987										
J 15	3.76	3.12	1.63	1.47	2.02	1.82	0.94	0.94	0.94	0.89
F 07	3.64	2.99	1.62	1.45	1.91	1.70	0.95	0.98	0.97	0.98
M 02	3.51	2.86	1.62	1.46	1.80	1.59	0.96	0.96	0.87	0.86
A 15	3.38	2.73	1.66	1.49	1.70	1.46	0.92	0.90	0.89	0.88
M 01	3.25	2.64	1.68	1.51	1.63	1.36	0.93	1.07	1.10	1.12
J 06	3.18	2.58	1.80	1.60	1.61	1.34	1.15	1.46	1.53	1.56
J 07	3.15	2.57	1.99	1.80	1.68	1.42	1.53	1.92	1.98	1.97
A 07	3.12	2.59	2.22	2.03	1.78	1.56	1.88	2.28	2.39	dry
S 04	3.11	2.60	2.49	2.31	1.92	1.74	2.33	2.86	dry	dry
O 07	3.08	2.62	2.75	2.65	2.18	2.07	2.95	3.46	dry	dry
N 09	3.05	2.65	2.98	2.97	2.46	2.38	3.22	3.02	2.80	dry
D 07	3.03	2.69	3.08	3.10	2.58	2.35	2.57	1.34	1.26	1.28

WATER LEVEL MEASUREMENTS - UNION CARBIDE (NOVACOR) SITE

Water levels for the Union Carbide site are presented below, all values are in meters below casing. Note the sampling event on July 18, '86 and note the following symbols:

dry - piezometer is dry
n/a - no measurement possible (due to ice, breakage or obstruction)

Approximate Piezometer Depth (ft)

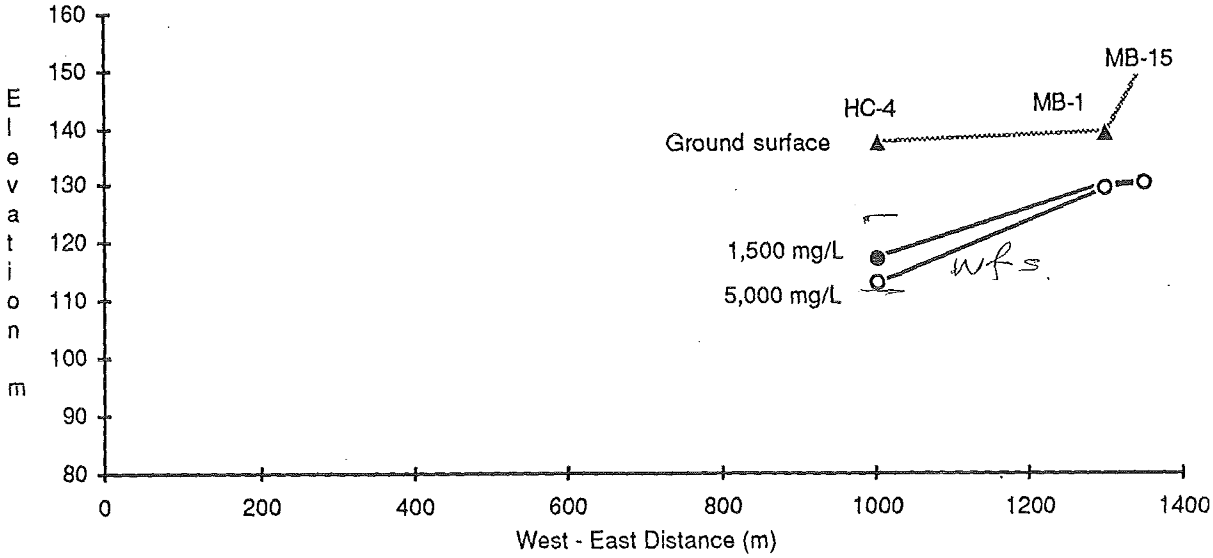
Date	50	40	30	25	20	15	12	09	06	03
1985										
O 29	7.04	7.33	6.82	5.86	5.39	2.99	3.99	3.56	2.61	1.50
N 27	6.18	6.46	6.01	5.16	4.81	2.55	3.68	3.24	1.53	0.95
D 22	5.68	5.79	5.38	4.67	4.34	2.23	3.40	2.96	1.28	1.36
1986										
J 19	5.27	5.25	4.81	4.19	3.89	2.12	3.16	2.74	1.36	1.01
M 14	4.74	4.46	3.96	3.45	3.24	2.03	2.76	2.35	1.17	0.91
A 14	4.55	4.19	3.67	3.19	2.97	1.96	2.56	2.13	1.09	1.17
M 16	4.43	3.99	3.44	2.98	2.79	1.89	2.36	1.91	1.05	1.11
J 13	4.39	3.89	3.32	2.90	2.70	1.90	2.25	1.79	1.56	1.15
J 18	4.35	3.81	3.22	2.86	2.70	1.92	2.15	1.71	1.67	2.08
18	6.19	5.79	5.12	4.78	4.98	4.22	4.50	3.31	2.71	2.08
A 22	5.37	4.94	4.41	4.03	4.19	2.81	3.94	2.85	2.58	dry
S 24	4.93	4.47	4.00	3.59	3.72	2.43	3.58	2.64	1.72	dry
O 23	4.66	4.15	3.70	3.26	3.32	2.13	3.28	2.39	1.12	1.19
N 19	4.50	3.97	3.60	3.02	3.01	1.89	2.99	2.18	1.22	1.30
D 17	4.36	3.79	3.23	2.78	2.73	1.73	2.75	2.01	1.04	1.11
1987										
J 15	4.26	3.66	3.06	2.62	2.52	1.68	2.56	1.87	0.95	0.93
F 07	4.20	3.57	2.94	2.53	2.40	1.69	2.42	1.72	1.06	0.90
M 02	4.16	3.51	2.85	2.44	2.30	1.71	2.30	1.61	0.99	dry
A 15	4.10	3.42	2.77	2.38	2.20	1.71	2.16	1.58	1.00	0.91
M 01	4.08	3.38	2.73	2.32	2.15	1.70	2.04	1.48	1.17	1.47
J 06	4.04	3.36	2.71	2.35	2.17	1.80	1.95	1.45	1.63	1.96
J 07	4.07	3.39	2.75	2.42	2.22	1.92	1.91	1.50	1.96	dry
A 07	4.08	3.41	2.82	2.49	2.28	2.05	1.90	1.52	2.26	dry
S 04	4.07	3.44	2.85	2.54	2.32	2.16	1.92	1.65	2.63	dry
O 07	4.62	3.41	2.86	2.55	2.36	2.30	1.95	1.82	dry	dry
N 09	3.99	3.38	2.85	2.56	2.40	2.51	2.05	2.11	dry	dry
D 07	3.96	3.37	2.86	2.55	2.42	2.62	2.15	2.33	1.62	1.11

ATTACHMENT 3.

THE ELEVATION OF THE 1,500 mg/L and 5,000 mg/L CHLORIDE CONTOURS ALONG WEST - EAST CROSS-SECTIONS THROUGH SITE F.

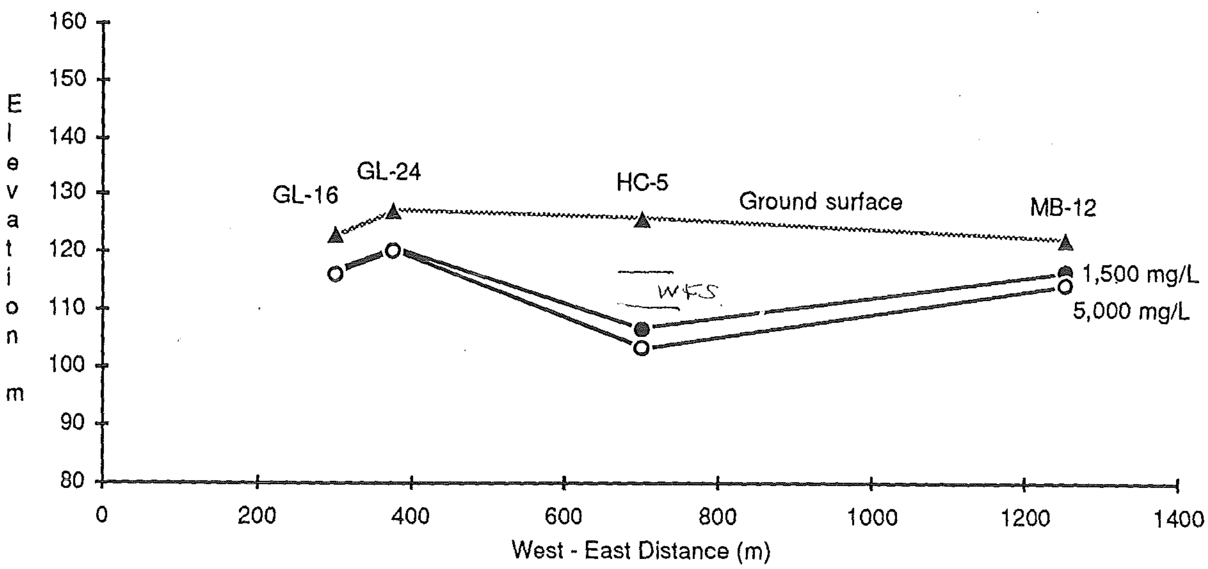
ATTACHMENT 3a

CHLORIDE CONTOURS - SITE F NORTH

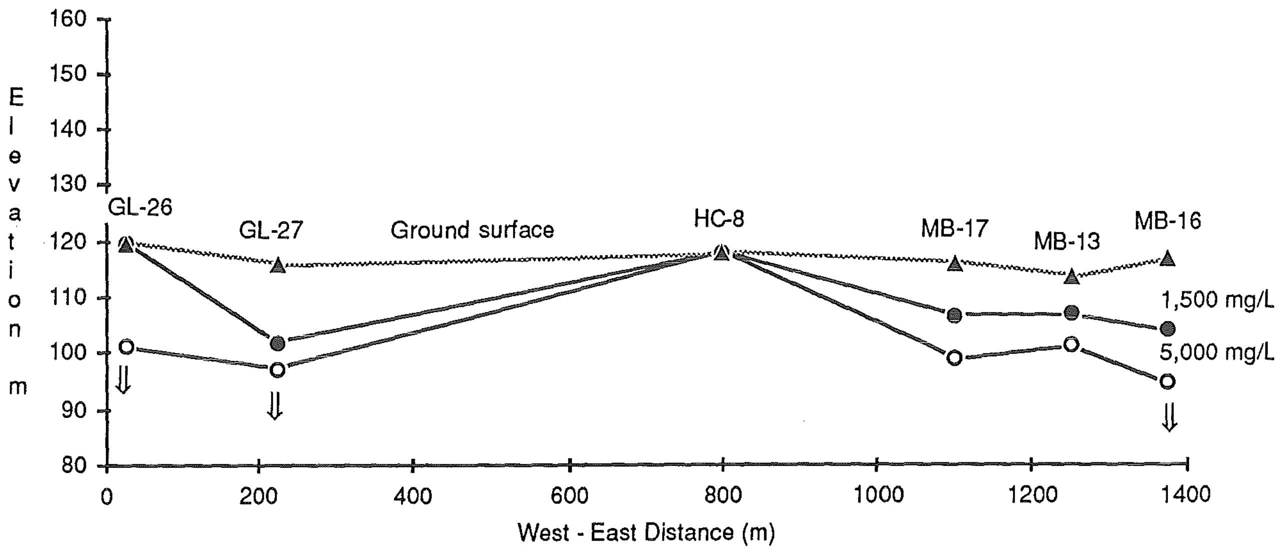


ATTACHMENT 3b

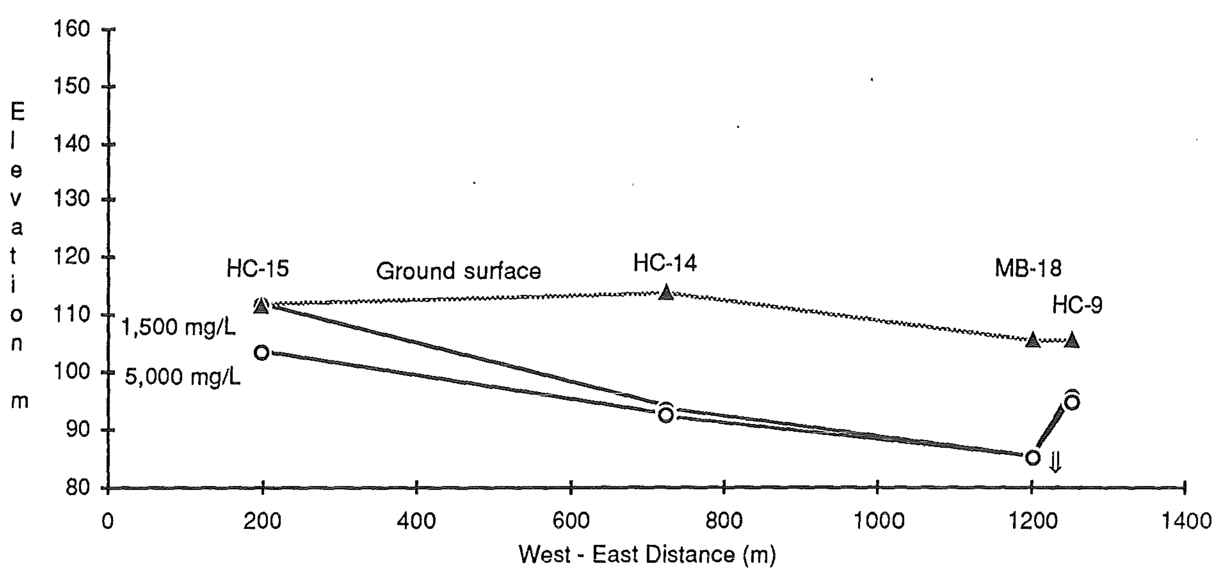
CHLORIDE CONTOURS - SITE F CENTRAL



ATTACHMENT 3c
CHLORIDE CONTOURS - SITE F SOUTH



ATTACHMENT 3d
CHLORIDE CONTOURS - SOUTH OF 403



ATTACHMENT 4

THE THICKNESS OF THE ACTIVE GROUNDWATER FLOW ZONE (m) DEFINED BY CHLORIDE CONCENTRATIONS LESS THAN 1,500 mg/L AT BOREHOLES ON SITE F AND SOUTH OF THE BURLINGTON AND BAYVIEW LANDFILLS.