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A REMEDIATION STRATEGY FOR
AN ORGANICALLY POLLUTED AQUIFER

by

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ABSTRACT

A glacial outwash aquifer underlying the Gloucester Landfill near Ottawa, Canada, has become polluted with toxic organic chemicals following the disposal of laboratory solvents in shallow trenches immediately above the aquifer. Several remedial alternatives have been considered by environmental authorities. Impermeable barrier walls were rejected as being unsuitable given the permeable nature of the underlying bedrock. It appears improbable that pools of liquid organic chemicals (DNAPLs) exist within the aquifer; therefore, much of the contaminant plume can be removed hydraulically over a period of five years by the operation of four purge wells discharging to an on-site treatment plant from which the purified water is returned to the aquifer by recharge wells. The residual contamination is anticipated to be cleaned up by in-situ bioremediation techniques presently under development.

RÉSUMÉ

Un aquifère d'alluvions glaciaires situé sous la décharge publique de Gloucester près d'Ottawa (Canada) a été pollué par des composés organiques toxiques après qu'on a déversé des solvants de laboratoire dans des fossés peu profonds creusés juste au-dessus. Les autorités responsables des questions environnementales ont envisagé diverses mesures correctives, notamment l'aménagement d'écrans imperméables, possibilité jugée inadéquate étant donné la perméabilité du socle dans le secteur. Il semble improbable qu'il se soit formé des poches de composés organiques liquides (DNAPL) dans l'aquifère; il est donc possible d'enlever en cinq ans la plus grande partie des polluants en extrayant par quatre puits de purge les eaux polluées pour les traiter sur place et les renvoyer dans l'aquifère par des puits d'alimentation. L'élimination de la fraction de polluants résiduelle se ferait sur place par des techniques de biorestauration actuellement mises au point.

EXECUTIVE SUMMARY

Ground waters beneath the Federal Special Waste Compound at the Gloucester, Ontario landfill became contaminated due to the disposal of laboratory solvents by EPS during the period 1972-80. The cost of site assessment, replacement of water supplies and aquifer remediation will cost Transport Canada M\$8.5 by 1995.

This paper describes the procedures used by DOE hydrogeologists and consultants to Transport Canada to assess the various remedial options, i.e., no action, containment or decontamination. The no action option is dismissed due to the toxicity of the contaminants in the ground water which is moving off site. Similarly, the containment option is not practical because the bedrock floor beneath the site is very permeable and concerns remain about the efficacy of slurry or grout wall curtains. Therefore, it was decided that ground water decontamination would be required, involving 4 purge wells, a waste-water treatment plant and 4 recharge wells operating for a period of 5 years.

A series of tests were undertaken to determine whether or not this would produce the required level of decontamination within 5 years. The results suggest that the method should be successful, however, some residual contamination will remain within the aquifer beneath the Compound and will likely require an in-situ bioremediation program after 1995 to complete the decontamination program.

RESUME ADMINISTRATIF

Les eaux souterraines sous l'installation d'élimination spéciale du gouvernement fédéral à la décharge de Gloucester en Ontario ont été polluées par des solvants de laboratoire que le SPE y a éliminés de 1960 à 1980. L'évaluation de l'état des lieux, l'approvisionnement en eau de remplacement et la restauration de l'aquifère auront coûté à Transport Canada 8,5 M\$ en 1995.

Dans cet article, on décrit les méthodes que les hydrogéologues du M.E. et des consultants engagés par Transport Canada ont utilisées pour évaluer les diverses mesures correctives possibles, c'est-à-dire, aucune mesure, retenue des eaux ou décontamination. La première de ces trois possibilités est éliminée, étant donné la toxicité des contaminants et le fait que les eaux souterraines s'écoulent hors du secteur. De même, la retenue n'est pas une solution pratique parce que le socle est très perméable dans le secteur et qu'il subsiste des doutes quant à l'efficacité d'un écran d'étanchéité. Il a donc été décidé de décontaminer les eaux souterraines; l'opération sera réalisée en cinq ans au moyen de quatre puits de purge, d'une installation de décontamination et de quatre puits d'alimentation.

On a fait toute une série d'épreuves pour déterminer si l'on obtiendrait le degré de décontamination voulu au bout de cinq ans. D'après les résultats de ces analyses, la méthode qu'on prévoit utiliser devrait donner l'effet voulu, mais il resterait des eaux polluées sous l'installation d'élimination et il est probable qu'il soit nécessaire de compléter l'opération de décontamination par un programme de biorestauration après 1995.

INTRODUCTION

The Gloucester Landfill is located on the property of Ottawa International Airport (75°38'W, 45°18'N), south of downtown Ottawa, Ontario, Canada (see Figure 1). Between 1969 and 1980, various government agencies disposed liquid wastes in a "Special Waste Compound" (SWC) at the southwest corner of the Gloucester municipal landfill (see Figure 2). The wastes were predominantly organic solvents in glass containers from various laboratories in the nearby city of Ottawa. The bottles were placed in trenches and partially combusted by detonation of explosives set within the wastes. By 1982, it was apparent that this method of waste disposal was causing the pollution of the underlying outwash aquifer.

The Gloucester Landfill is situated above a sequence of Quaternary fluvioglacial outwash, marine and littoral deposits which overlie Paleozoic limestone bedrock (Figure 3). Two aquifers occur in the unconsolidated deposits. The principal aquifer is the thick (65-82 ft or 20-25 m) sequence of interstratified silts, sands and gravels (Unit C) believed to have been deposited as coalescing and overlapping subaqueous esker fans that formed beneath standing water adjacent to a glacial ice front. It is confined over most of the site by marine silts which form a discontinuous aquitard (Unit D). In areas where the aquitard occurs, an overlying unconfined sand aquifer (Unit E) is present (Jackson et al., 1985).

The outwash aquifer (Unit C) has an average hydraulic conductivity of 140 ft/day (5×10^{-4} m/s), a mean transmissivity of 70,000 gpd/ft (10^{-2} m²/s) and a storativity on the order of 2×10^{-3} . The average ground water velocity in the aquifer is approximately 0.2 ft/day (7 cm/day, $\sigma = 5$ cm/day) as measured by borehole dilution techniques (Jackson et al., 1985) and by tritium measurements (Michel et al., 1984). The organic carbon content of the outwash aquifer materials varies from 0.1% to 0.6% by weight, with a mean of 0.35% (Jackson et al., 1985). Aquifer materials are principally quartz and feldspar with minor amounts (i.e. <10% each) of mica, calcite, dolomite, hornblende and garnet.

CONTAMINANT MIGRATION AND FATE

The patterns of ground water contamination in the outwash aquifer resulting from disposals in the SWC suggest that the organic solvents have undergone chromatographic dispersion, i.e., aqueous-phase solute transport concurrent with sorption of the contaminants, principally by organic carbon particles within the aquifer sediments (Patterson et al., 1985). As shown in Figure 4, the organic contaminants have been transported distances that are inversely proportional to their respective octanol-water partition coefficients. Because the octanol-water partition coefficient (K_{ow}) provides a measure of a compound's

propensity to become sorbed by organic matter (i.e., hydrophobic partitioning), it follows that the observed transport of the organic solvents by ground water is in accord with the hydrophobic sorption theory of Schwarzenbach and Westall (1981) and others.

Following the 1982 survey of the Gloucester Landfill, further multilevel samplers of the type shown in Figure 5 were installed. All available multilevels were sampled and analysed for volatile organics in 1984. Plan-view plumes from this sampling are shown in Figure 6; these figures are based on analytical results for approximately 100 samples.

In the most heavily contaminated zones of the aquifer, such as the zone of >100 μg total organo-chlorine compounds (TOH)/L shown in Figure 7, the pH varies between 7 and 8, the $E_H < 200$ mV and dissolved oxygen is not detectable (Jackson *et al.*, 1985). Cross-section plumes from the 1984 sampling are shown in Figure 8. The 1983 chloride plume is also included to demonstrate that the organic contaminants have been retarded.

AQUIFER REMEDIATION

The initial phase of site remediation involved excavation of heavily contaminated soils and solid wastes (MacLaren Engineers, 1988). Simultaneously, hydrogeologists addressed the

more complex problem of ground water contamination. Several remedial alternatives, e.g., no action, containment and decontamination, were evaluated and ranked. The no action alternative was deemed unacceptable on the basis of the results of an endangerment assessment. Containment alternatives included the installation of impermeable slurry walls or grout curtains around the zone of highest contamination. These techniques were rejected principally because the limestone bedrock underlying the plume is very permeable and is hydraulically connected to the overlying outwash aquifer (Jackson et al., 1985). In similar conditions at the Sylvester site in Nashua, N.H., the remedial slurry wall and cap system was "much less effective than anticipated" (OTA, 1985) due to leakage through the bedrock. Consequently complete isolation could not be assumed at the Gloucester Landfill. Furthermore, there remain uncertainties pertaining to the viability and integrity of engineered barriers in the presence of hydrocarbons, which have been shown to increase the hydraulic conductivity of natural clays (e.g., Fernandez and Quigley, 1985).

Aquifer decontamination has been selected as the most appropriate alternative. The recommended option is a "pump and treat" scheme which, it is estimated, will need to operate five years (A.J. Graham Engineering Consultants, 1985) and involve four purge wells situated along the axis of the plume. Discharge will be treated by lime addition, air stripping and

granular activated carbon adsorption. Treated water will be returned to the aquifer by four recharge wells. The four purge wells are planned to operate at a total rate of 120 gpm (655 m³/day) beginning in 1990. The cost of this operation is estimated to be of the order of C\$6 million (US\$5 million) in current dollars.

In a pump and treat operation, it is first essential to remove any immiscible organic liquids from the aquifer. Such dense, non-aqueous phase liquids (DNAPLs) released by waste disposal operations or by spills tend to migrate to depth leaving residual droplets of liquid within the unsaturated and saturated zones. If DNAPLs are present in sufficient volume, pools may form on relatively impermeable strata within the aquifer or at its base (see Schwille, 1984 and 1988 and Feenstra and Cherry, 1988). Residual droplets and pools are a long-term source of aquifer contamination. If they remain in an aquifer, decontamination will not be achieved by pump and treat operations or recontamination of a supposedly decontaminated aquifer will occur once the "pump and treat" operation is suspended.

There has been no unequivocal evidence of DNAPLs in the Gloucester outwash aquifer. Inspection of shallow cores and soils removed by backhoe during waste excavation failed to indicate any separate organic phases. In addition, chemical results from multilevel monitors situated within one hundred

feet (30 m) of the disposal pits, indicate (see Figure 9) that maximum concentrations of individual contaminants have never exceeded 4% of their solubility. Those compounds disposed in relatively large quantities in 1978, e.g., chloroform, benzene and carbon tetrachloride, have not been measured in concentrations in excess of 1% of their solubility. Furthermore, Figure 9 shows that concentrations of contaminants have decreased substantially since 1984, suggesting an absence of DNAPL pools. Finally, the vertical distribution of contamination, as depicted in Figure 10 for the multilevel samplers in the SWC area, shows no evidence of an increase in contamination with depth, again suggesting the absence of deep pools of DNAPL within the aquifer. It should be noted, however, that emulsified DNAPL residues may still be present within the unconfined and the outwash aquifers.

In order to demonstrate the effectiveness of decontaminating the outwash aquifer by purge wells (i.e., the "pump and treat" option), a field test was conducted (Whiffin and Bahr, 1985; Bahr, in submission) at a site near the centre of the contaminant plume (Fig. 2). The test involved the introduction of uncontaminated ground water into the contaminated aquifer via an injection well and the withdrawal of a similar volume of contaminated ground water from another well 15 feet (5 m) away (Figure 11). A multilevel sampler, M1, situated between the two wells was used to take samples throughout the 6-day period of

the test. The samples were analysed for two injected, nonreactive tracers and for three organic solvents present in the aquifer at the test site -- 1,4-dioxane, tetrahydrofuran (THF) and diethyl ether (DEE).

The behavior of the organic contaminants during purging is shown in Figure 11, in which the time axis is replaced by the number of pore volumes pumped through the test section of the aquifer. A pore volume is defined by Whiffin and Bahr (1985) as "the volume of water required per unit aquifer thickness to displace the interstitial ground waters located between the injection and monitoring points as defined by the breakthrough of the 50% concentration level for the non-reactive tracer". Although 1,4-dioxane disappears quite readily from the test section of the aquifer, THF and DEE display pronounced tailing. This is most probably a result of the relatively slow rate of solute desorption compared to the rates of change of solute concentration due to advection (10 ft/day or 3 m/day at the multilevel sampler) and dispersion. That is, local chemical equilibrium was not attained everywhere during the course of the purge-well test (Bahr, in submission). A second test of this type was conducted in a shallow plume of organic contaminants in the unconfined aquifer (see Figure 2) with similar results (Water and Earth Science Associates Ltd., 1988).

Analysis of the disappearance curves in Figure 11 indicates that there is a log-linear relationship (Figure 12) between the

number of pore volumes withdrawn from the aquifer to obtain 90% apparent decontamination of each of the organics and their respective K_{ow} values. This site specific relationship can be extrapolated (i.e., beyond ten pore volumes) to obtain an estimate of the number of pore volumes required to decontaminate parts of the aquifer containing contaminants not found in the test area. It must be noted that the values in Figure 12 are minimum estimates of the number of pore volumes required to decontaminate the aquifer under the hydraulic conditions of the test. Because local chemical equilibrium was not attained everywhere during the test, large volumes of relatively dilute ground water were pumped from the aquifer. Bahr has concluded "that pumping may be more efficient, in terms of volumes of clean water required for injection and volumes of contaminated water removed for treatment, if lower flow rates are used". By so doing, more time is available to allow the relatively slow desorption of the organic chemicals.

An important step in the design of the pump and treat system is optimization of purge well placement so as to minimize the amount of uncontaminated ground water pumped and sent for treatment. This is being accomplished by developing a three-dimensional (3-D) ground water flow model of the aquifer that provides reliable information for the development of simpler and less costly 2-D models of ground water flow and solute transport. The 2-D ground water flow code is embedded in

the USGS code AQMAN (Lefkoff and Gorelick, 1987), which combines the flow simulation with mathematical optimization to evaluate purge and recharge well siting. AQMAN prepares a data file that defines the objective and all constraint functions plus other information required; the file is then used in a mathematical programming code such as MINOS (Murtagh and Saunders, 1983). The 2-D code is also used to prepare input files for the simulation of contaminant transport by the USGS code MOC (Konikow and Bredehoeft, 1978), which uses the method of characteristics to solve the solute transport equation.

Because of the high cost of "pump and treat" operations, there is much interest in developing lower cost alternatives. The most promising of these is in-situ biological remediation. This technique, generally known as bioremediation, involves the prior removal of DNAPL pools and the subsequent injection of oxygen and nutrients into a plume of dissolved toxic organic chemicals to stimulate the native microbial populations to metabolize or cometabolize the organic contaminants (Wilson et al., 1986; Lee et al., 1988). Because in-situ bioremediation is still under development, it was not considered as a remedial option for the Gloucester aquifer. However, it is anticipated, that at the end of the five years of purging the contaminated aquifer, in-situ bioremediation will be available to clean up the residual contamination that will undoubtedly remain. The biological techniques are potentially cost

effective methods for reducing residual contamination to compliance levels.

CONCLUSIONS

An exhaustive assessment has been conducted of the organically-polluted outwash aquifer beneath the Gloucester Landfill and potentially applicable alternative strategies for remediation have been evaluated. It is concluded that:

1. the installation of a slurry wall system to contain the organic pollutants is unsuitable because of the very permeable nature of the bedrock;
2. pools of DNAPL chemicals are unlikely to be present within the ground water flow system although emulsified DNAPL chemicals may exist;
3. a "pump and treat" operation should be successful in removing the dissolved and sorbed organic chemicals provided that the purge and recharge wells are placed in the optimal locations; and
4. in-situ bioremediation will likely be required to complete the decontamination of the aquifer following the "pump and treat" operations.

ACKNOWLEDGEMENTS

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FIGURES

- Figure 1. Location of the Gloucester Landfill.
- Figure 2. The Gloucester Landfill and Special Waste Compound near Ottawa, Ontario, Canada
- Figure 3. Hydrostratigraphy.
- Figure 4. Plan view of three plumes of volatile organic chemicals in 1982 illustrating chromatographic dispersion (from Patterson et al., 1985).
- Figure 5. A bundle-type multilevel sampler of the kind used at the Gloucester Landfill.
- Figure 6. Plan view of plumes of chloroform (above) and 1,1,1-trichloroethane (below) in 1984 showing preferential migration from the south end of the Special Waste Compound.
- Figure 7. Cross-sectional view of chloride and total organic halogen plumes in 1987/88.
- Figure 8. Cross-sectional view of plumes of chloroform (above) and 1,1,1-trichloroethane (below) in 1984.
- Figure 9. Time series data from two multilevel monitoring points within or adjacent to the Special Waste Compound showing that concentrations of volatile organic chemicals have always been a small percentage of the solubility of any compound present in the ground water.

Figure 10. Vertical distribution of selected volatile organic chemicals at multilevel samplers within 100 feet (30 metres) of the disposal trenches.

Figure 11. Rate of reduction of contaminant concentrations (diethyl ether (DEE), tetrahydrofuran (THE) and 1,4-dioxane) during the purge well test.

Figure 12. Estimation of the number of pore volumes that must be purged from the outwash aquifer to achieve 90% decontamination. Pore volume values for diethyl ether, tetrahydrofuran and 1,4-dioxane only are obtained from Figure 11. Other values are extrapolated.

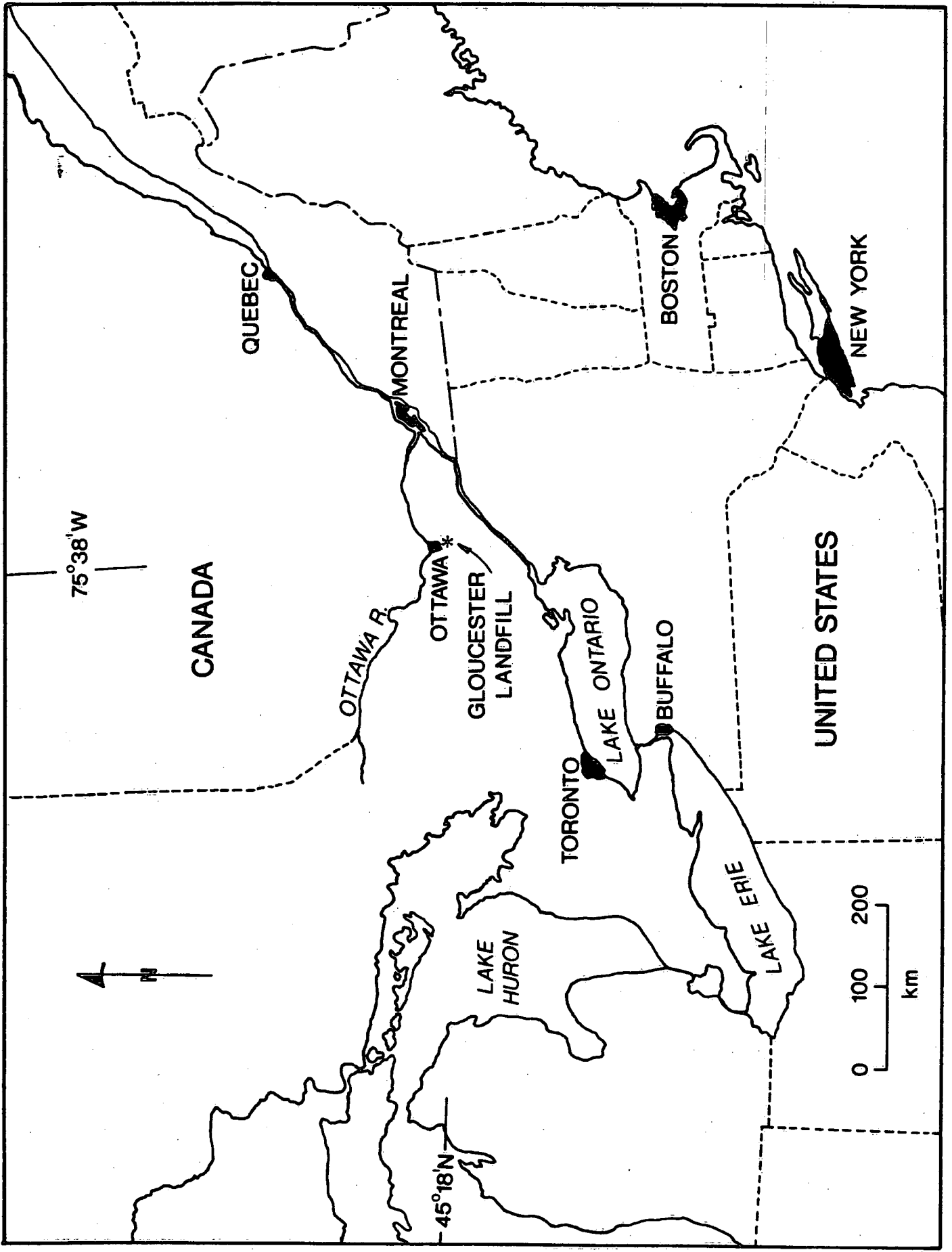


FIGURE 1

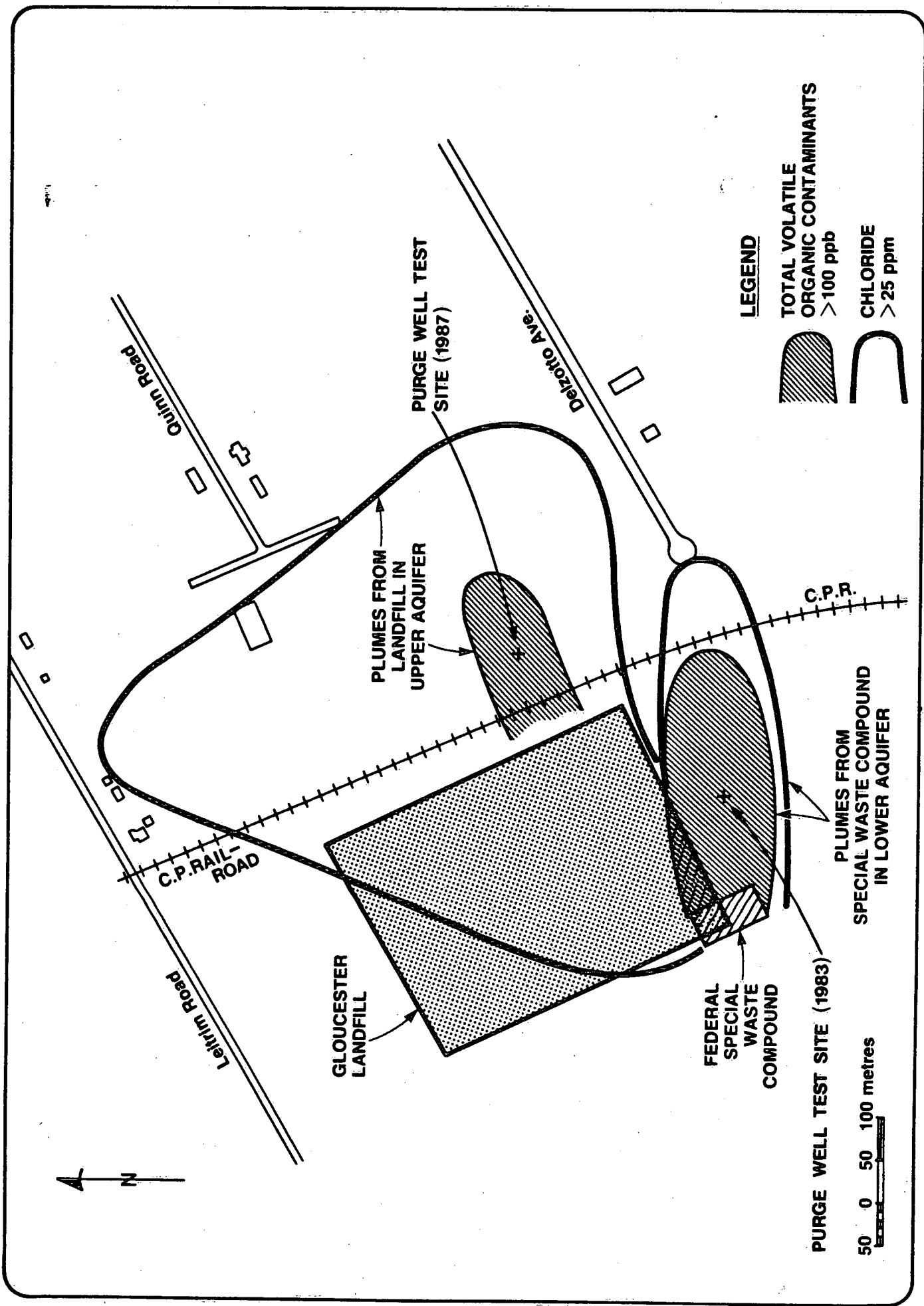
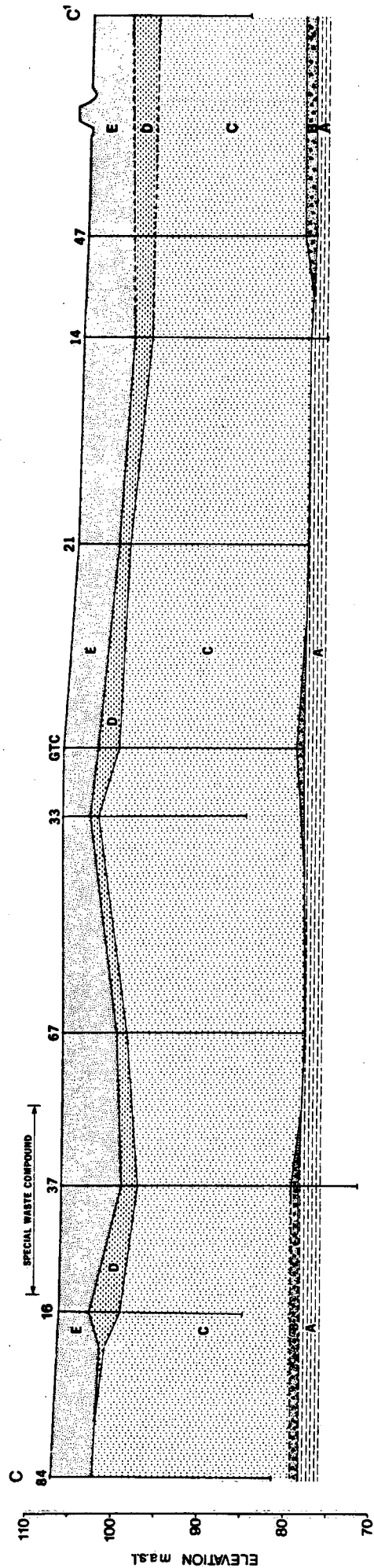


FIGURE 2



0 50 100 metres
Vertical exaggeration 2.4x

- LEGEND**
STRATIGRAPHIC UNIT
- A Limestone; shaley limestone interlayers
 - B Till; coarse angular cobbles and boulders in sand and silt matrix
 - C Sub-squeous outwash poorly sorted gravels, sands and silts
 - D Stratified clayey silt and silt
 - E Regressional sands and gravels

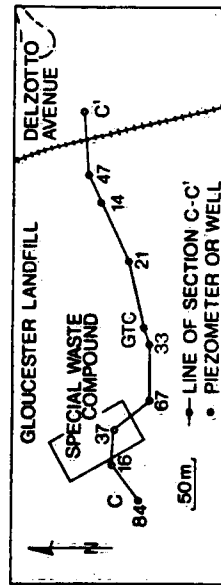
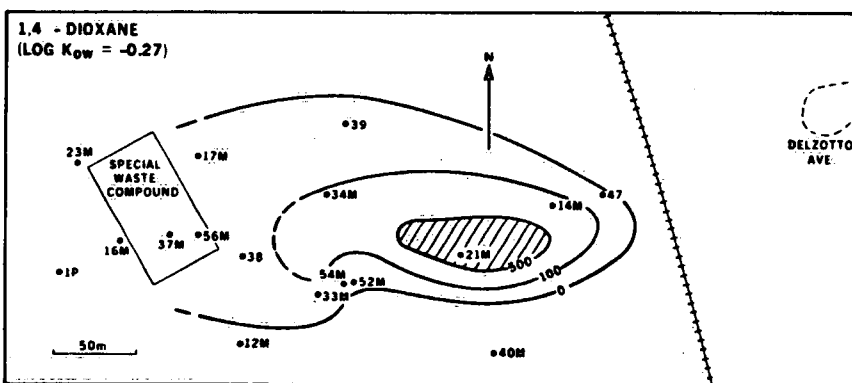
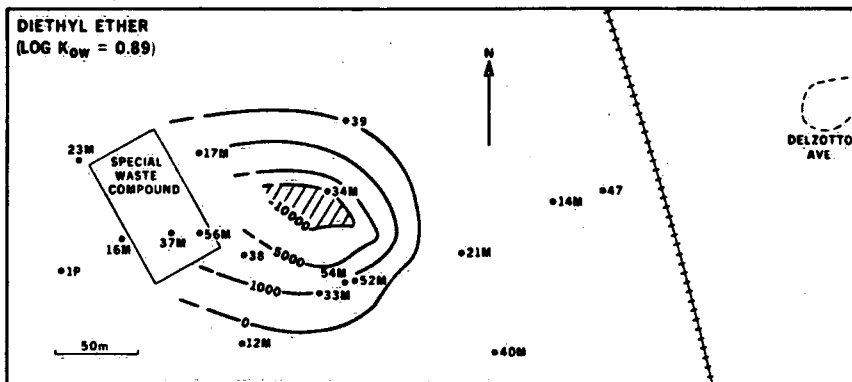
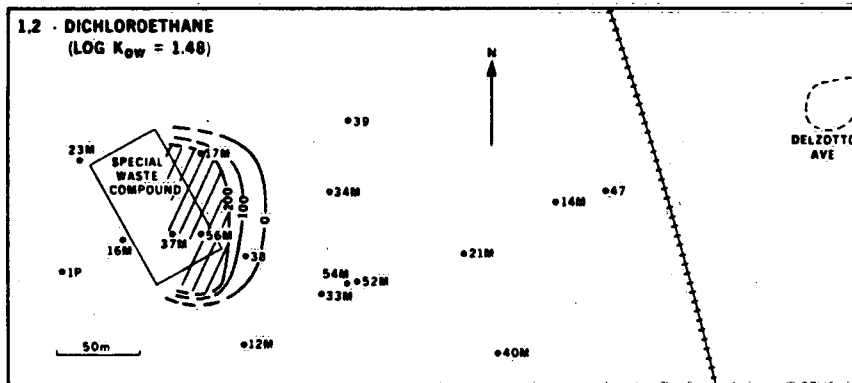


FIGURE 3



LEGEND

- MULTILEVEL SAMPLER OR PIEZOMETER
- CONTOUR OF MAXIMUM CONCENTRATION (PARTS PER BILLION; ENCOUNTERED IN SECTION (1982))
- ▨ AREA OF MAXIMUM CONCENTRATION

FIGURE 4

MULTILEVEL SAMPLER

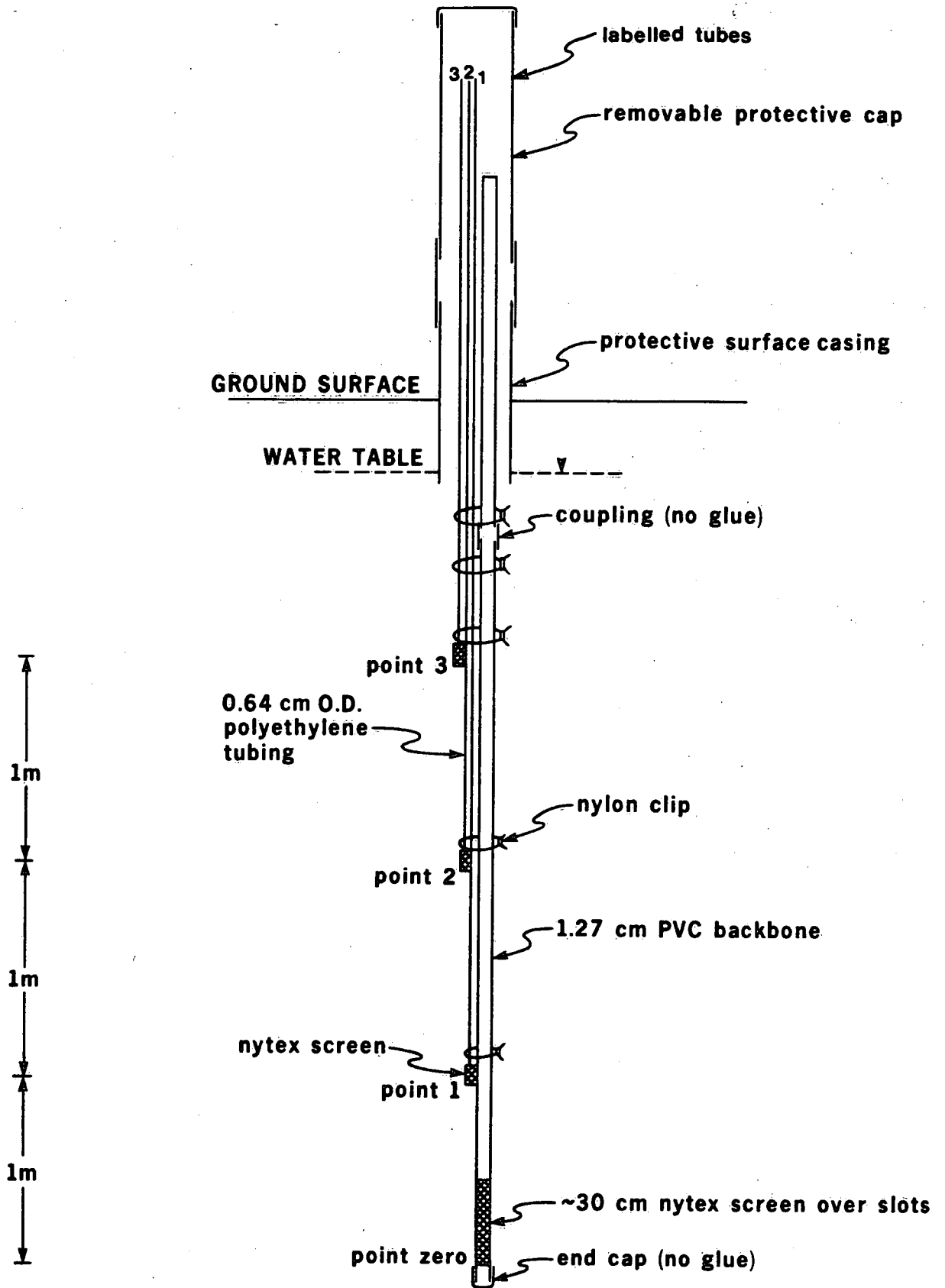


FIGURE 5

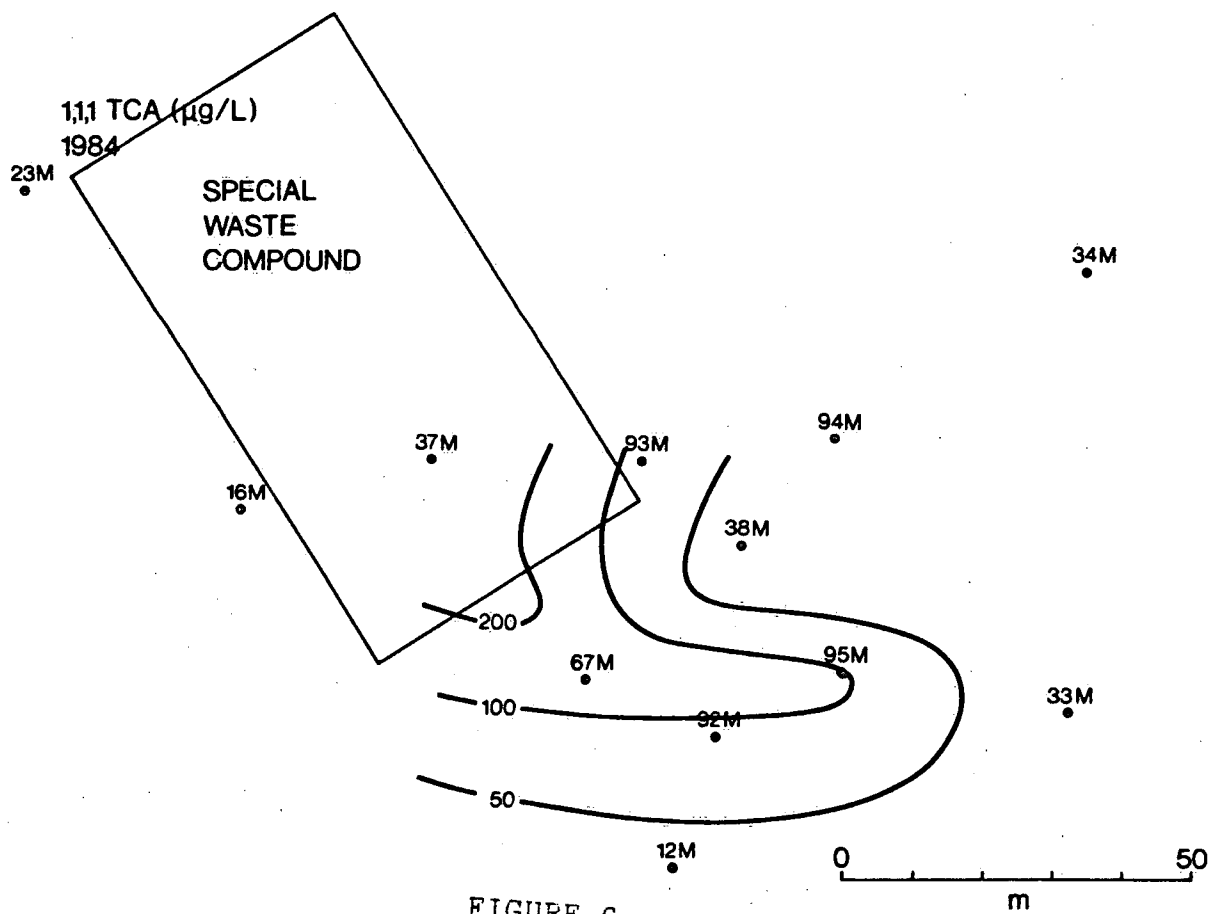
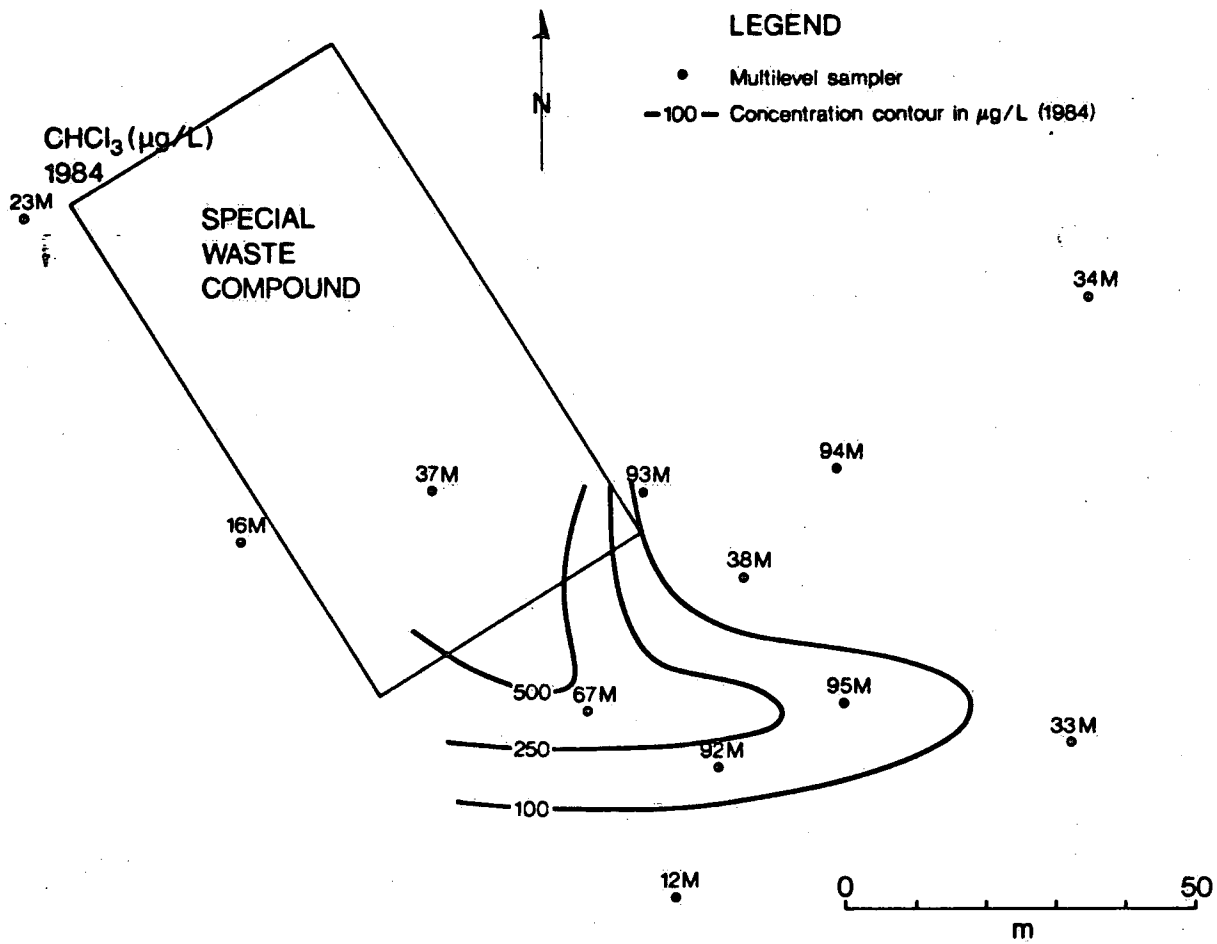
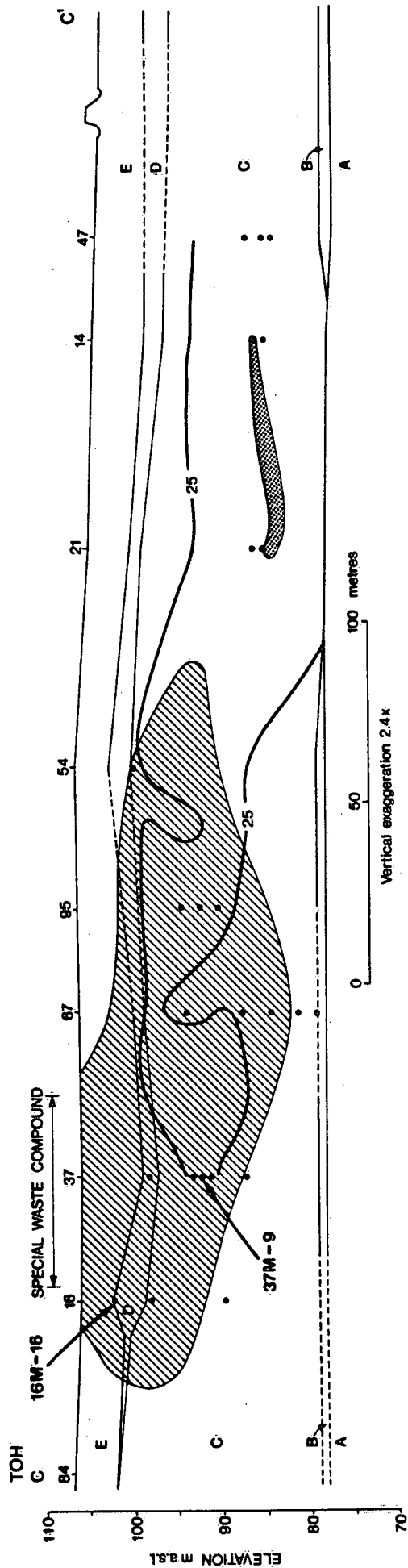


FIGURE 6



LEGEND

- STRATIGRAPHIC UNIT**
- A Limestone; shaly limestone interlayers
 - B Till; coarse angular cobbles and boulders in sand and silt matrix
 - C Sub-aqueous outwash poorly sorted gravels, sands and silts
 - D Stratified clayey silt and silt
 - E Regressional sands and gravels

- Sample location for organic analyses
- 25- Concentration contour in mg Cl/L (1988)
- [Hatched Box] > 250 mg Cl/L (1988)
- [Diagonal Lines Box] > 100 µg TOH/L (1987)

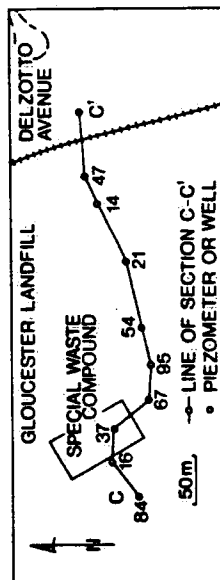
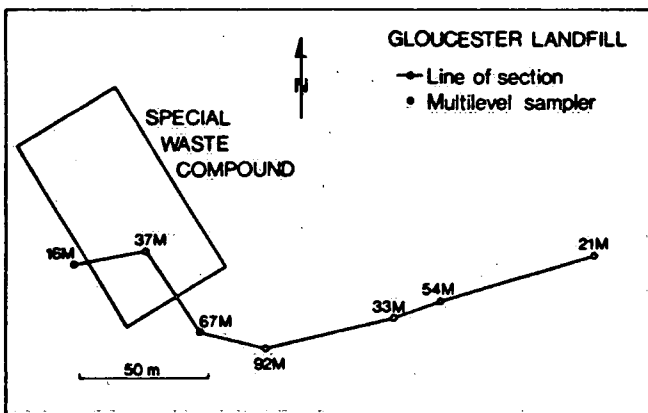
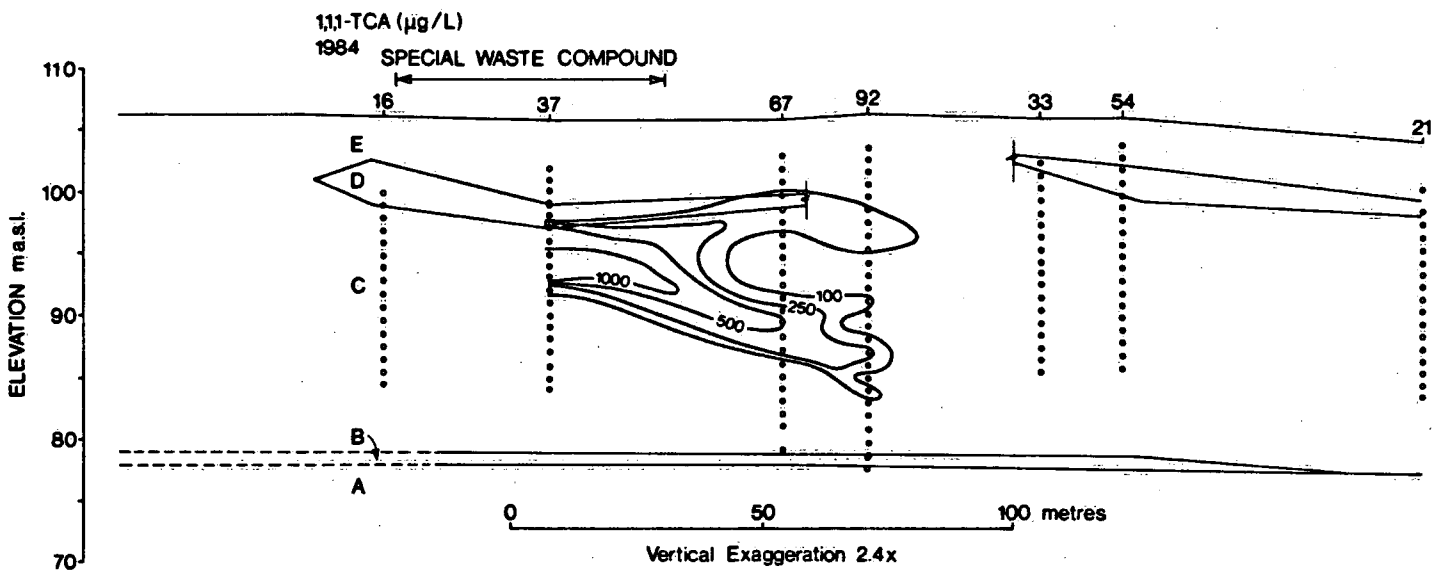
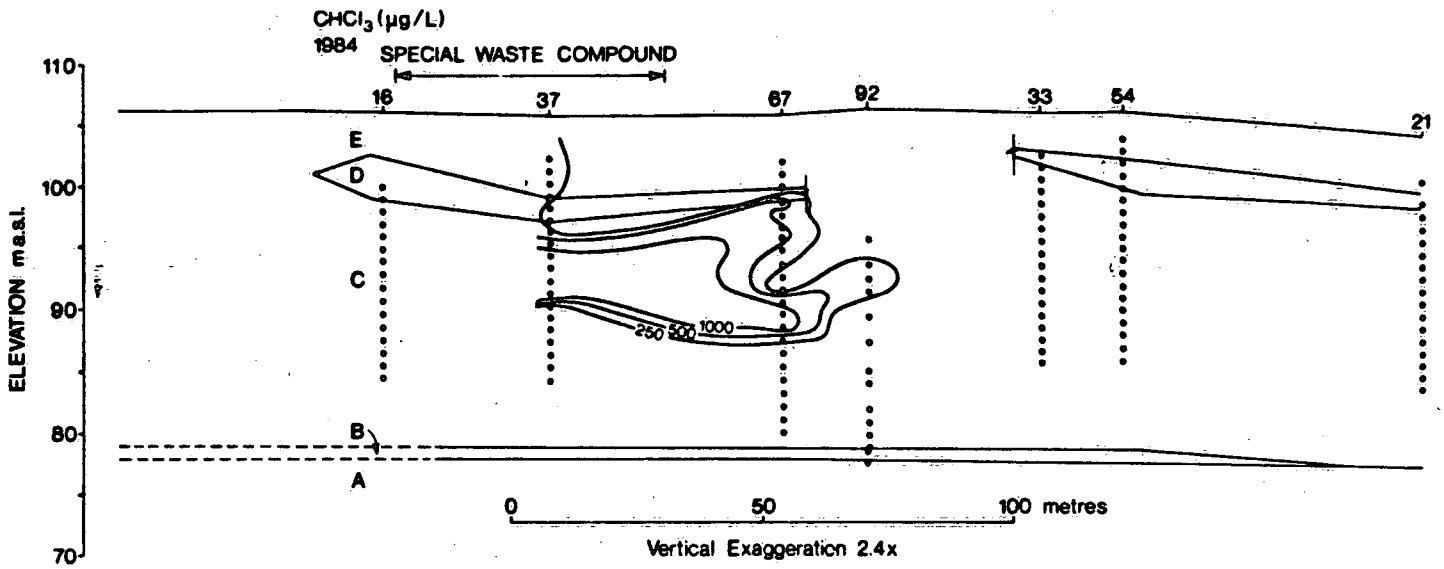


FIGURE 7



LEGEND

STRATIGRAPHIC UNIT

- A Limestone; shaley limestone interlayers
- B Till; coarse angular cobbles and boulders in sand and silt matrix
- C Sub-aqueous outwash poorly sorted gravels, sands and silts
- D Stratified clayey silt and silt
- E Regressional sands and gravels

- Sample location
- 100- Concentration contour in µg/L (1984)

FIGURE 8

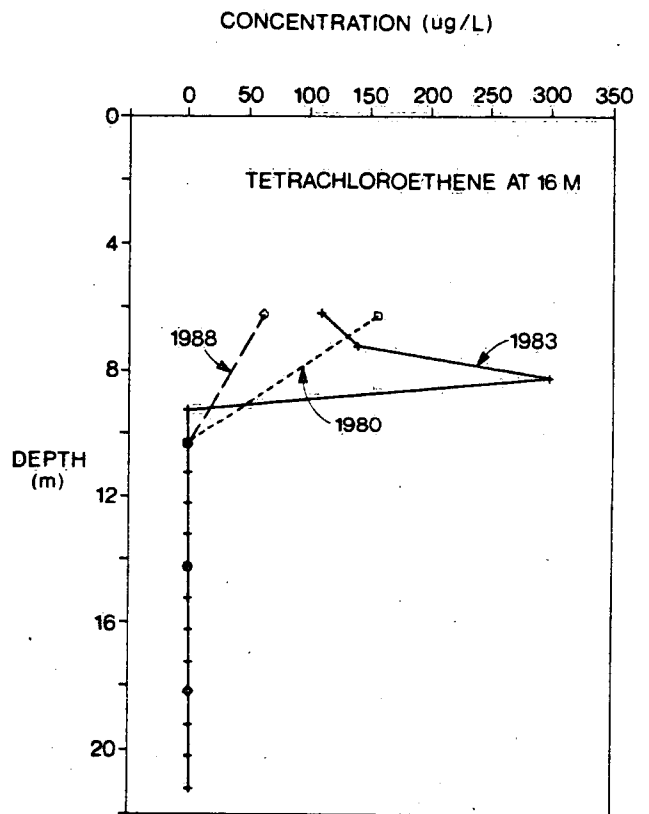
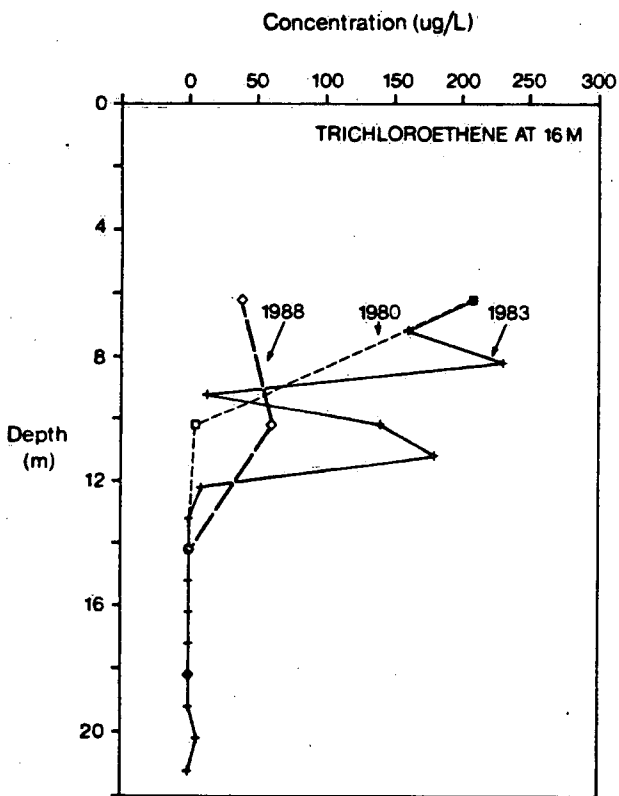
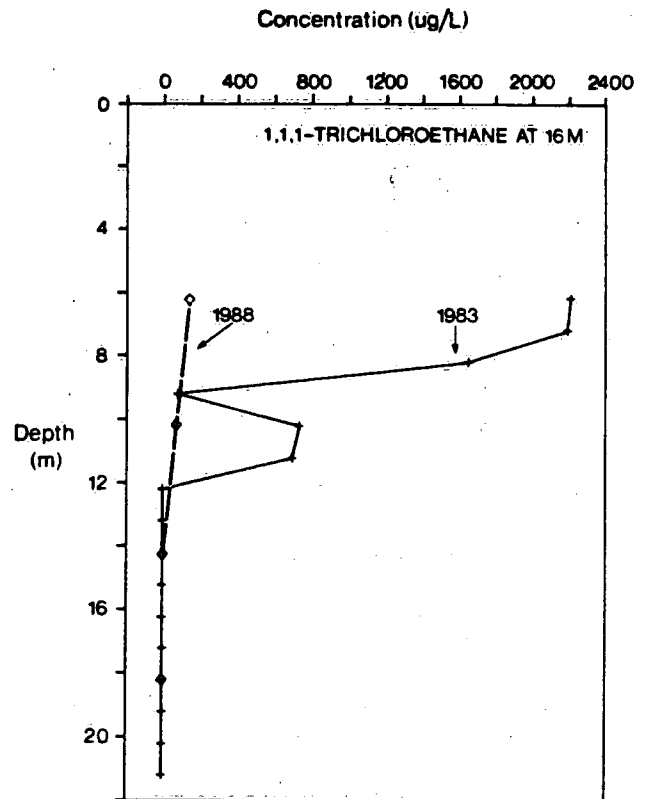
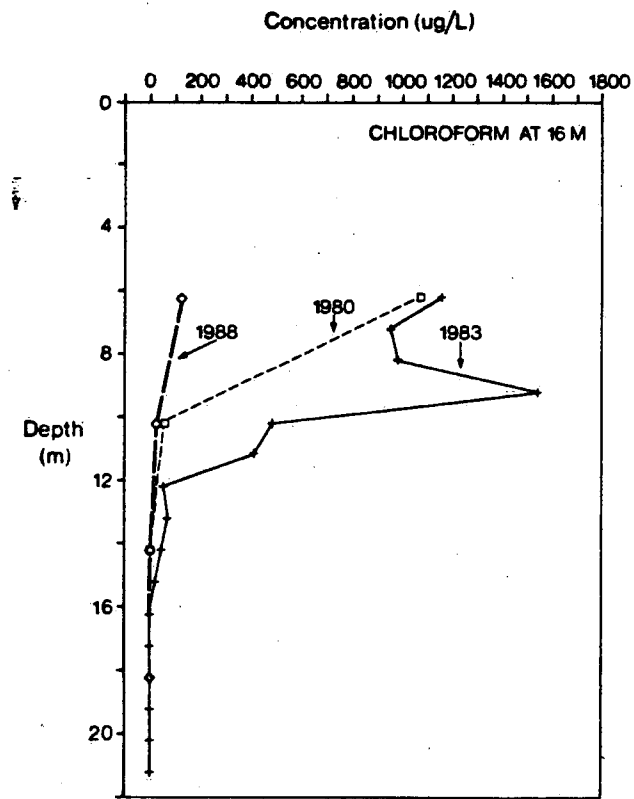


FIGURE 10

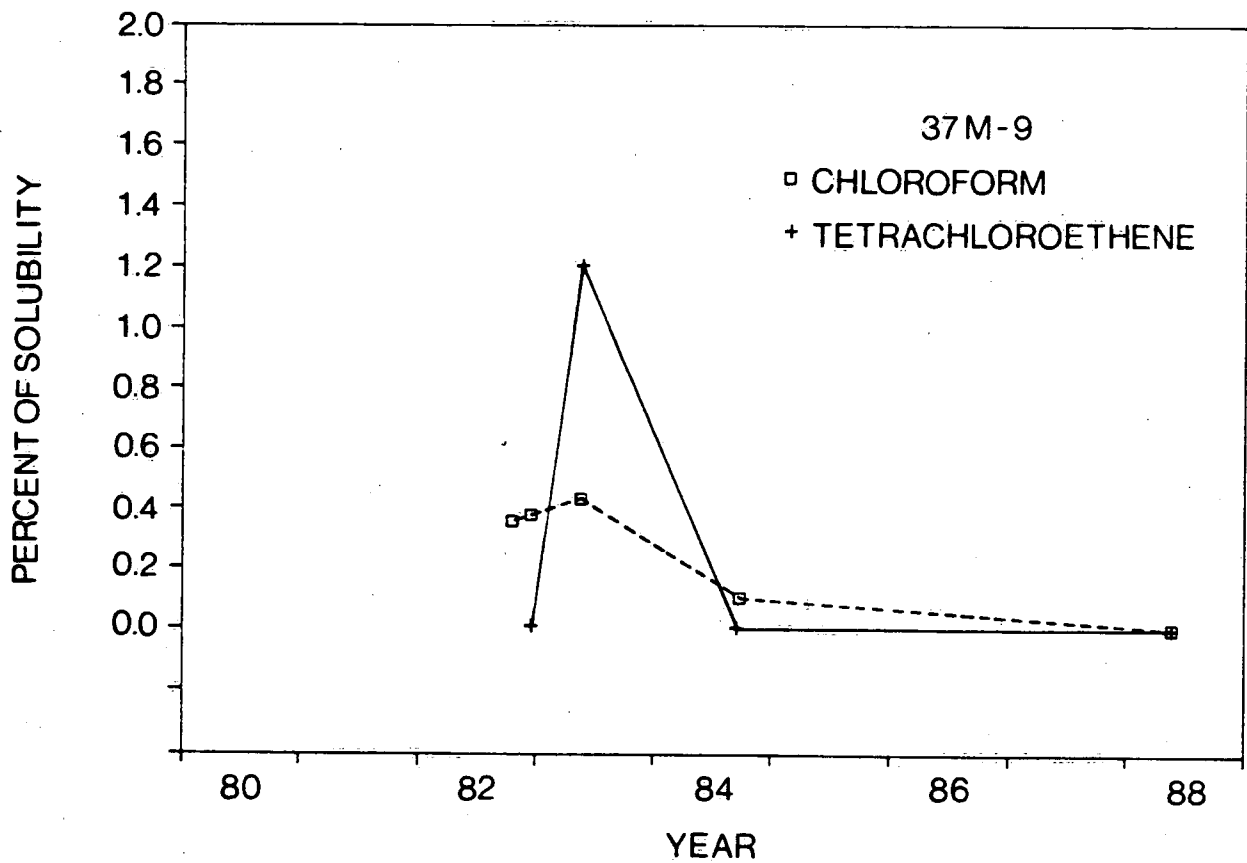
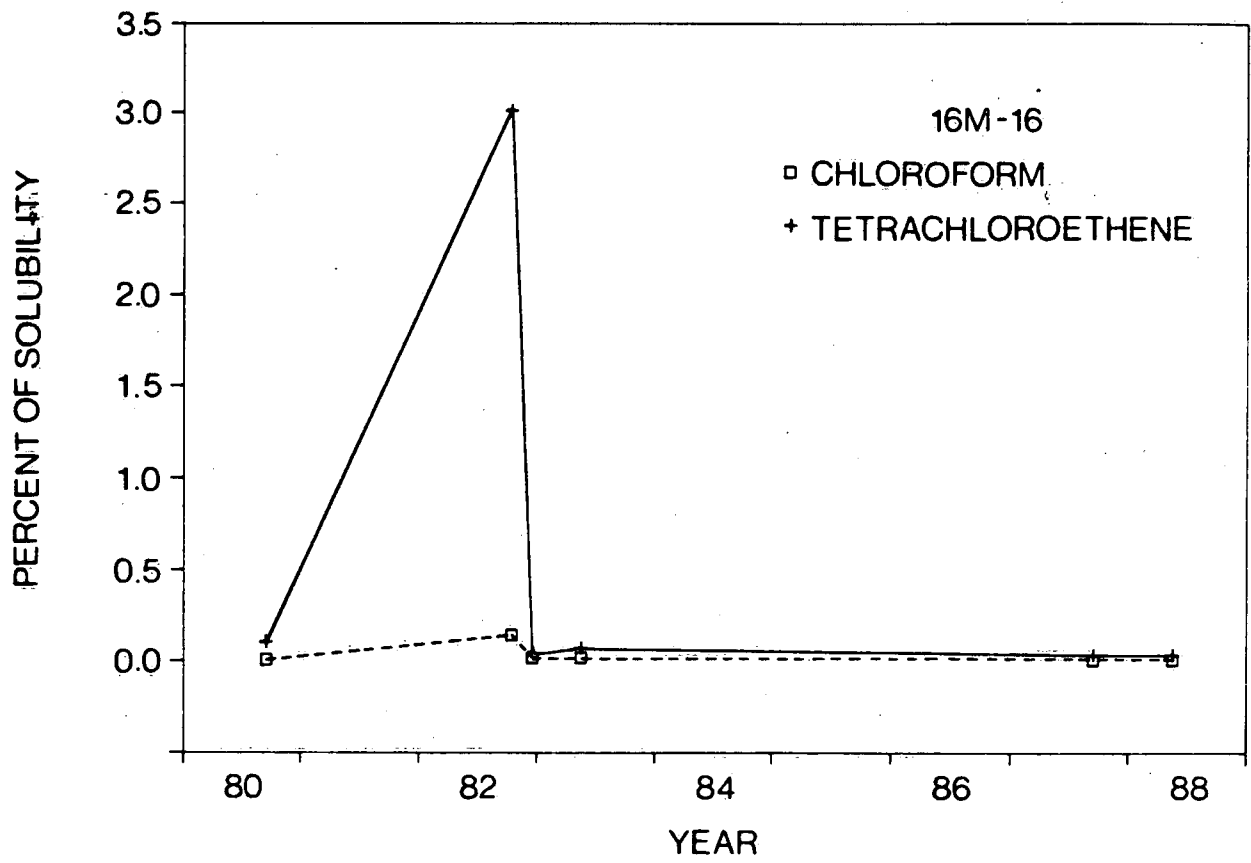
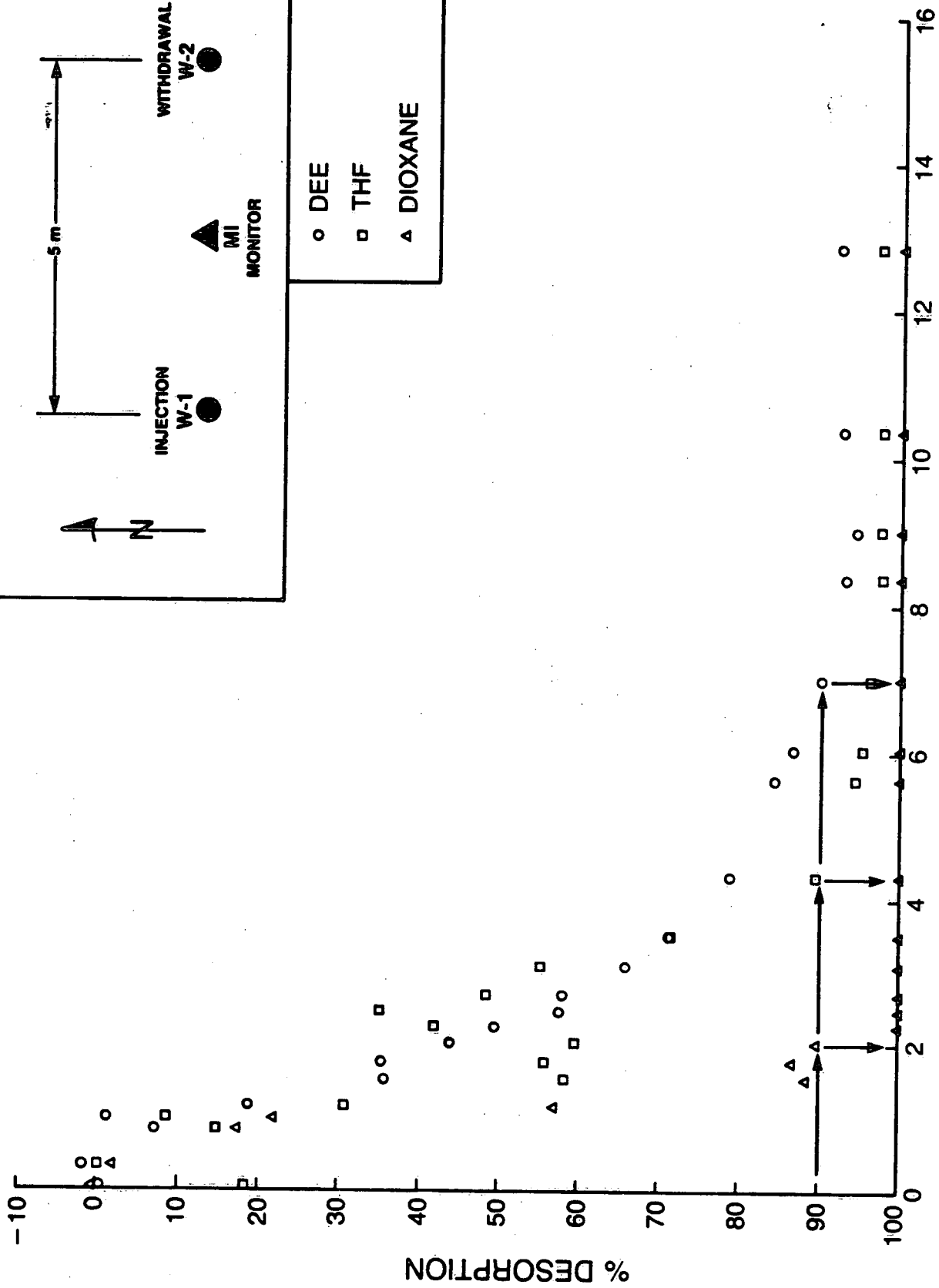


FIGURE 9



NUMBER OF PORE VOLUMES AT MULTILEVEL MI-12

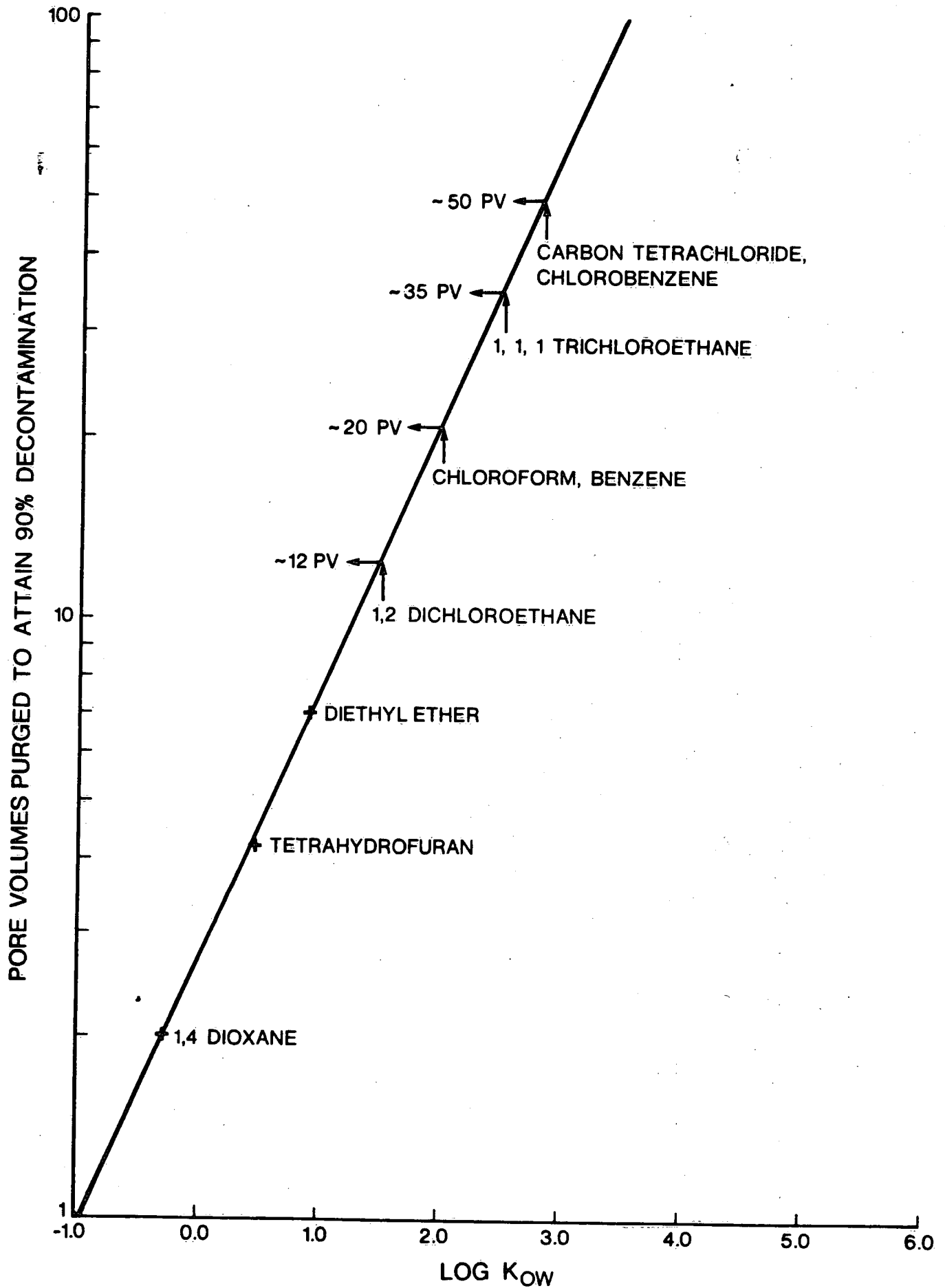


FIGURE 12