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ABSTRACT

Due to concern over the potential for widespread groundwater contamination in the sedimentary rock underlying the Niagara Falls area, a study was initiated to investigate the hydrogeology of the Paleozoic stratigraphy underlying the Upper Niagara River and the Eastern Niagara Peninsula. Seven moderately deep boreholes (up to 150 m) have been drilled, instrumented with multiple packer casing, tested for permeability, sampled for inorganic, organic and isotopic geochemistry and monitored for hydraulic head to provide a conceptual model of regional groundwater flow. Preliminary results show that there are at least three distinct groundwater flow regimes in the bedrock stratigraphy. The uppermost regime is comprised of the fracture zones in the Guelph and Lockport Formations. Permeability, hydraulic head measurements and geochemical results indicate active groundwater circulation in this regime, primarily discharging towards the Niagara Gorge and Escarpment. Underlying the Lockport Formation are an overpressured (high hydraulic head) regime in the Clinton-Upper Cataract-Lower Queenston Formation and an underpressured (low hydraulic head) regime in the Lower Cataract-Upper Queenston Formation. Geochemical samples and permeability measurements indicate very old and saline groundwater in both regimes which probably has undergone minimal migration since pre-Pleistocene time. The implication based on the study so far, is that groundwater contamination below the bottom of the Lockport Formation is probably not pervasive in the Niagara Falls area except adjacent to the Niagara Gorge where vertical permeability in the lower flow regimes is enhanced.

RÉSUMÉ

Étant donné les préoccupations au sujet de la possibilité de contamination excessive des eaux souterraines dans la roche sédimentaire sous-jacente de la région de Niagara Falls, une étude a été entreprise pour étudier l'hydrologie de la stratigraphie du Paléozoïque sous-jacente du cours supérieur de la rivière Niagara et de la partie orientale de la péninsule du Niagara. Sept trous de sonde de profondeur moyenne (jusqu'à 150 m) ont été forés, équipés d'un ensemble d'instrumentation multiple, testés pour connaître la perméabilité, échantillonnés pour établir la géochimie inorganique, organique et isotopique, et surveillés pour en connaître la charge statique afin d'obtenir un modèle conceptuel de l'écoulement régional des eaux souterraines. Les résultats préliminaires indiquent qu'il y a au moins trois régimes distincts d'écoulement des eaux souterraines dans la stratigraphie de la roche en place. Le régime supérieur est constitué des zones de fractures dans des formations de Guelph et de Lockport. La perméabilité, les mesures de la charge statique et les résultats géochimiques indiquent une circulation active des eaux souterraines dans ce régime, dont l'évacuation des eaux se fait principalement vers la gorge et l'escarpement du Niagara. Sous la formation de Lockport se trouve un régime à surpression (charge statique élevée) dans la formation de Clinton-Upper Cataract-Lower Queenston et un régime de sous-pression (charge statique faible) dans la formation de Lower Cataract-Upper Queenston. Des échantillons géochimiques et les mesures de la perméabilité indiquent que l'eau souterraine de ces deux régimes est très vieille et saline et qu'elle a probablement connu une migration minime depuis les temps antérieurs au Pléistocène. Jusqu'à présent, les résultats de cette étude indiquent que la contamination des eaux souterraines sous la formation de Lockport ne pénètre probablement pas dans la région de Niagara Falls, sauf dans les zones adjacentes à la gorge du Niagara où la perméabilité verticale dans les régimes d'écoulement inférieur est accrue.

MANAGEMENT PERSPECTIVE

The preliminary results of the study of groundwater flow in the sedimentary rock underlying Niagara Falls have significant importance with regard to Environment Canada's policy on transboundary migration of polluted groundwater. The current position, as stated formally in public documents, is that groundwater pollution is probably occurring below the top of the Rochester Shale Formation in Niagara Falls, N.Y. This is definitely not supported by our field data except near the Niagara Gorge where vertical fractures pervade all formations. Therefore, it is our suggestion that Environment Canada soften its position on deep groundwater pollution, especially with regard to waste sites such as Love Canal and S-Area.

In addition, the results of this study highlight how little we know about the geochemistry and hydrogeology of the Lockport and Guelph Formations. It is these formations that are most contaminated and that discharge into the Niagara River. A shallow drilling program to investigate the hydrogeology of these formations would provide useful data with which to suggest appropriate remedial measures for U.S. waste sites.

PERSPECTIVE-GESTION

Les résultats préliminaires de l'étude de l'écoulement des eaux souterraines dans la roche sédimentaire sous-jacente de Niagara Falls ont une grande importance en ce qui a trait à la politique d'Environnement Canada en matière de migration transfrontalière des eaux souterraines polluées. La position actuelle du Ministère, telle qu'elle est formulée officiellement dans les documents publics, consiste à affirmer que la pollution des eaux souterraines se fait probablement sous le toit de la formation de schiste de Rochester dans la région de Niagara Falls, État de New York. Cette hypothèse n'est pas du tout corroborée par nos données recueillies sur le terrain, à l'exception de la zone qui se trouve près de la gorge du Niagara où des fractures verticales s'infiltrent dans toutes les formations. Nous proposons donc qu'Environnement Canada modère sa position sur la pollution des eaux souterraines profondes, principalement en ce qui a trait aux sites de décharges comme Love Canal et S-Area.

De plus, les résultats de cette étude montrent bien à quel point nous connaissons peu la géochimie et l'hydrogéologie des formations de Lockport et de Guelph. Ce sont ces formations qui sont les plus contaminées et qui déversent leurs eaux dans la rivière Niagara. Un programme de forage peu profond visant à étudier l'hydrogéologie de ces formations fournirait des données utiles qui nous permettront de trouver les mesures correctrices appropriées pour les sites de décharges aux États-Unis.

INTRODUCTION

During the late 1970's and early 1980's, considerable international attention focused on the Niagara Frontier as it became evident that numerous toxic waste disposal sites, particularly on the U.S. side of the Niagara River, were contaminating large volumes of groundwater in the area. In 1982, the U.S. Geological Survey conducted a hydrogeological evaluation of 138 known toxic waste disposal sites in a three mile wide band along the Niagara River in New York State (Koszalka et al., 1985). In the Niagara Falls area alone, one half of the 63 sites investigated showed a major potential for contaminant migration. A few of these sites such as Love Canal, S-area and Hyde Park have garnered considerable media attention as being particularly dangerous with regard to chemical content.

Initially, groundwater studies were conducted on a site-by-site basis to determine the extent of local groundwater contamination in the overburden materials and shallow bedrock. However, additional concerns were raised regarding the potential for more widespread contamination of the deeper, regional groundwater flow system which ultimately discharges into the Niagara River and the Great Lakes Water System. Therefore, as a means of qualifying this potential, a study of the regional groundwater flow in the Silurian and Ordovician sedimentary rock underlying Niagara Falls was initiated.

This study will provide background information for site-specific waste site investigations and will determine the potential of individual sites to contaminate deeper groundwater. The results of this study will help in designing more appropriate remedial actions for many of these sites. Further, the results can be used to obtain estimates of the overall loading to the Upper and Lower Niagara Rivers from non-point sources. The specific objective is to quantify the three-dimensional distribution of hydraulic head, determine hydraulic conductivity in both the horizontal and in particular the vertical direction and estimate deep groundwater flow rates and velocity.

Most of the early work on groundwater in the Niagara River region was conducted as part of much broader water resources surveys (Reck and Simmons, 1953; Lasala, 1967; Haefeli, 1972) or as specific drainage basin and groundwater resource studies (Johnston, 1964; Ostry, 1971). Johnston (1964), in particular, presented a very detailed study of the groundwater in both the overburden and in the Silurian and Ordovician sedimentary rock immediately underlying Niagara Falls, New York. Both Johnston (1964) and Ostry (1971) recognized the importance of the influence of the Niagara Escarpment on regional groundwater flow in the lower stratigraphy. The Niagara Falls themselves were the focus of a detailed international geological study (International Joint Commission, 1974) in which a large component of the work pertained to the flow of groundwater in the fractured caprock and underlying stratigraphy at the Falls.

More recently, most of the study has centered on contaminant migration in the Niagara Frontier, primarily at specific waste disposal sites. Kozalka et al. (1985) provides a review and compilation of the existing hydrogeological information for most of the waste sites identified in the U.S. side of the region. In addition, a number of numerical simulations of the hydrogeological conditions in the overburden and shallow bedrock have been conducted to aid in the interpretation of contaminant migration at several of these sites (Maslia and Johnston, 1984; Mercer et al., 1984; Wong et al., 1985; Osborne and Sykes, 1986). In almost all of these studies, no consideration is given to groundwater flow beneath the shallow bedrock.

In this paper, the approach and preliminary results of a field investigation of regional groundwater flow in the Niagara Falls area will be presented. Most of the results to date have been obtained from a study area loosely bounded by the St. Davids Buried Gorge to the north, the Welland Ship Canal to the east, the Niagara River to the west and the edge of the Silurian gas field to the south (about 12 km south of Niagara Falls). The boreholes utilized for this study lie for the most part in the centre of this area and penetrate to below Lake Ontario water levels. Figure 2 shows the approximate location of the study area with respect to the Great Lakes watershed.

Method

The method selected to conduct this study is based on a systematic approach in which three major sub-models; a geologic model;

a hydrostratigraphic model and a geochemical evolution model together contribute to formulate the conceptual regional groundwater flow model (Fig. 1). The conceptual flow model should be sufficient in meeting the stated objectives of the study, however, it can also be augmented by calibrating a numerical groundwater flow model such as the finite-difference codes USGS-3D or SWIFT II or the finite-element code FE3DGW to existing field data. The conceptual flow model will consist of an interpretation of regional groundwater flow based on a geologic and hydrogeologic data base obtained from direct field investigation. This data base can be used to formulate other interpretations, provide input for numerical modeling, as aforementioned, or be used directly as background for site-specific investigations.

GEOLOGICAL MODEL

The geological model is formulated from hard field data such as stratigraphic and facies maps, joint orientations and surface geophysics and from more interpretive sources such as remote sensing and conceptual structural models. Each of these geological parameters are important to the model only as they influence the movement of groundwater. Most of the information for the geological model was compiled from the published and available literature. Some field mapping was conducted to verify joint orientation patterns.

Regional Geologic Setting and Stratigraphy

The Niagara Falls Region is located on the southeastern flank of the northeast-southwest trending Algonquin-Findlay arch system (Fig. 2) in a thickening sequence of Silurian and Ordovician sediments (Clark and Stern, 1979). The most significant physiographic feature in the Niagara Peninsula is the Niagara Escarpment, which is east-west trending in the Niagara Region. The Niagara Escarpment was formed due to the resistant nature of the middle-Silurian Lockport Dolostone (Liberty, 1981) which acts as caprock for the Escarpment and forms the rim of the Michigan Basin to the north of the Algonquin-Findlay arch system (Telford, 1978). The Escarpment continues into western New York State and becomes discontinuous towards Rochester.

The stratigraphy is generally flat lying between Niagara Falls, Ontario and the Niagara Escarpment and steepens to a southwestward dip of 4 m per km between Niagara Falls and Lake Erie (Liberty, 1981). The City of Niagara Falls is situated in a bedrock depression, lying between the Niagara Escarpment and the Onandaga Cuesta to the south (Flint and Lolcama, 1985). The Onandaga Escarpment forms part of the northern Lake Erie shoreline but only the crest is seen above ground surface (Karrow, 1973).

The bedrock in the Niagara Region is covered in a thin veneer of Quaternary deposits which have a minimum thickness of five m or less near the Niagara Escarpment, thickening to greater than 30 m to the south of Niagara Falls in the centre of the bedrock depression between the two cuestas (Feenstra, 1981). The unconsolidated material is generally comprised of approximately equal thicknesses of flat-lying till sheets and glaciolacustrine deposits, Wisconsinian in age (Calkin and Brett, 1978; Feenstra, 1981). Some sands and gravels were deposited in the Niagara Falls Moraine which trends approximately east-west, just south of the City of Niagara Falls (Calkin and Feenstra, 1985). The basal till immediately overlying the bedrock is coarse textured and the lower part is pervaded by gravel and boulders, possibly ancestral river channel deposits (Calkin and Brett, 1978).

The bedrock surface is generally characterized by the presence of a highly fractured weathered zone (Johnston, 1964). The nature of the weathered zone is largely independent of bedrock lithology and pervasive throughout the study area.

Table 1 shows the Paleozoic stratigraphy as compiled from Bolton (1957), Telford (1975) and Kilgour and Liberty (1981). In general, Canadian nomenclature has been adopted although U.S. and alternate nomenclature is also noted. The following description will briefly introduce the more important stratigraphic groups and formations. The uppermost formation underlying the unconsolidated material in the study area is the Salina Formation, a sequence of Upper-Silurian salts, anhydrite, shales and dolostones at least 90 m thick. The Salina Formation is transitionally underlain by the Guelph Dolostone, a brown, finely crystalline dolomite with interbedded grey shale about 37 m thick. The Guelph Formation conformably overlies the

Lockport Group which consists of three dolostone and limestone members totaling about 30 m in thickness. The Clinton Group underlies the Lockport Formation disconformably, although it is of the same age: the Guelph and Lockport Formations and the Clinton Group are all Middle-Silurian. The Clinton Group is about 32 m thick and is predominated by the Rochester Shale which is under and overlain by thin (2-3 m thick) dolostone and shale units. The contact between the lowermost formation in the Clinton Group and the uppermost formation in the Cataract Group (Lower-Silurian) is transitional and defined by textural change. The Cataract Group is approximately 32 m thick at the Niagara Gorge and consists of three shale and sandstone formations. The lowermost formation which outcrops in the most northerly part of the Niagara Gorge is the Upper Ordovician Queenston Formation which has a thickness of about 520 m at Niagara Falls (well no. 6669 K, Kreidler et al., 1972). The strata underlying the Queenston are Ordovician in age and consist predominantly of shale and shale-limestone formations (Telford, 1978). Pre-Cambrian basement is encountered at 925 m depth (well no. 6669 K, Kreidler et al., 1972).

Faulting and Structure

The regional stratigraphic structure and facies are controlled by the Basin-Arch complex of the underlying craton in southwestern Ontario. Successive periods of tectonic activity during the Paleozoic, particularly the Taconic and Appalachian Orogens were responsible for changes in compressive stress that generated movement along pre-existing planes of weakness in the basement rocks (Sanford et al., 1985). During periods of fracture rejuvenation, fault bounded blocks were tilted and rotated to form oil and gas traps in the Cambrian, Ordovician and Silurian sediments. Contemporary evidence of these large scale features can be observed by mapping facies changes and the structure of marker beds. A structural map of the base of the Rochester Formation (Koepke and Sanford, 1965) shows evidence of a vertical displacement fault trending in the northeast quadrant and a shorter lineament oriented orthogonally both within the study area on the Canadian side. Recent surface geophysical studies conducted along a line of high-yielding wells in Niagara Falls, N.Y. suggests that the northeast trending fault and associated fractures may be traced on the U.S. side of the River (Yager and Kappel, 1987). The only other major structural features identified in the Niagara Region are a fault with about 30 m throw near Batavia, New York, about 80 km east of Niagara Falls (International Joint Commission, 1974), and a linear recognized on LANDSAT which suggests that a fault or small syncline may provide control for the current position of the Niagara River (Liberty, 1981). Some localized up and downwarping due to the presence of bioherms is evident along the Niagara Gorge (Liberty, 1981).

Regional Stress and Jointing

Contemporary regional stress in the Michigan and Allegheny Basins is compressive near surface and oriented in the northeast quadrant

(Haimson, 1978; Zoback and Zoback, 1980; Plumb and Cox, 1987). In the Niagara Falls locale, maximum principal stress is oriented ranging from 050° to 060° (Lo, 1978; Williams et al., 1985) as determined from direct measurement and pop-ups. As a result of high compressive stress oriented horizontally, joint orientations can be expected to coincide with the general direction of the principal stress (Engelder, 1982). Figure 3 shows the joint orientations obtained from outcrops of the Silurian and Devonian strata exposed in the Niagara Peninsula (Williams et al., 1985). Of the four joint sets evident, the set oriented in the same direction as the contemporary stress is weakest. The other three sets are probably related to paleotectonic events and the influence of local geologic structure. Joint orientations in the Lower Devonian rocks of New York State just southeast of Niagara Falls are predominated by a set trending in the southeast quadrant and show little influence from the contemporary stress field (Engelder and Gieser, 1980).

Geological Model

Figure 4 shows the geological features important in controlling the regional groundwater flows in the Niagara Falls area. Along the Niagara Escarpment to the north and adjacent to the Niagara Gorge a zone of tensile stress generated by these physiographic features has created enhanced vertical and horizontal permeability in the stratigraphy (International Joint Commission, 1974). The St. Davids Buried Gorge is infilled with high permeability glacial outwash material (Hobson and Terasmae, 1968) and will act as a sink for groundwater flowing towards the escarpment to the north. Other bedrock surface features which might influence groundwater flow include the Crystal Beach buried channel system and a buried valley on the U.S. side of the Upper Great Gorge.

The linears identified from the structure of the Rochester Shale are shown, although other more direct evidence of their presence is unavailable. Considerable importance should be placed on confirming the existence of these features because they could provide significantly large conduits for groundwater flow and contaminant migration. This is especially true if these proposed features extend into New York (as suggested) and are currently active under the contemporary stress regime.

Figure 4 also shows the subcrop of the east-west striking and southward dipping Paleozoic strata. Depending on the hydraulic head in the formation, groundwater may prefer to flow along bedding planes toward Lake Erie (Liberty, 1981).

The joint orientations and patterns are considered unimportant in terms of the directional flow properties of the rock. This is because measurements of fracture spacing at undisturbed outcrop of the Lockport Formation, for example, show vertical to sub-vertical fractures to be infrequent with average spacing as high as 20 m. Consequently, the anisotropy of the hydraulic conductivity field will more likely depend on the heterogeneity of individual bedding plane fractures which are far more closely spaced. Because of the infrequency of vertical fractures, vertical hydraulic conductivity between bedding plane fracture zones is expected to be minimal. The southern boundary of the study site is marked as the edge of the Silurian natural gas field in the Clinton-Cataract Groups according to maps compiled by Koepke and Sanford (1965). The presence of natural gas in commercial quantity indicates that most of the strata here has very low vertical permeability. Horizontal and vertical migration of groundwater may be strongly inhibited.

HYDROSTRATIGRAPHIC MODEL

The hydrostratigraphic model is formulated from field based observations of the hydraulic conductivity field and the hydraulic head distribution. These observations are obtained from core-drilled boreholes that have been instrumented with a multiple-packer casing to provide a suitable environment. Figure 5 shows the sequence of steps leading to the hydrostratigraphic model. The required inputs include drilling, borehole geophysics, casing, hydraulic testing, tracer testing and the hydraulic head distribution. In some cases the hydraulic testing was completed before the installation of the multiple-packer casing and sometimes after.

Core Drilling

To date, seven boreholes have been diamond core drilled either in direct support of this study or for alternate purposes and were adopted for this study. Boreholes NF-2 to NF-4 (Fig. 6), for example, were drilled as part of a geotechnical study (Semec and Huang, 1984) and the casing in these holes was subsequently installed as part of this study. The NI series holes and CH-1 were drilled and instrumented specifically for this study. The boreholes are all 76 mm in diameter and drilled using triple-tube techniques (45.0 mm diameter core). Two of the boreholes, NI-1 and NI-3, are inclined at 64° and 65°, respectively; the remainder are drilled in the vertical orientation. Borehole CH-1 and the NI-series boreholes were drilled with an organic dye tracer (Flouroscien LT) in the drill water so that non in-situ water could be detected during subsequent geochemical sampling. The boreholes range in length from 100 to 150 m (Table 2).

Figure 6 shows the location of each of the boreholes used for this study. The precise location of the NF series boreholes was dictated by the objectives of the geotechnical study, however, the spatial distribution of NF-2,3 and 4 proved to be suitable for determining groundwater flow direction beneath the City of Niagara Falls and were selected for instrumentation for this reason. Borehole CH-1 was located to form triangulation with the NF and NI series boreholes and was drilled adjacent to the northeast trending linear identified in the geological model. The NI series boreholes were drilled to provide a geochemical monitor for the down-dip seepage of contaminants from the New York side and to provide an environment for vertical and horizontal cross-hole hydraulic tests.

The core collected from the boreholes was systematically logged for lithology and structure. Particular attention was paid to identification of vertical fractures in the core from the two inclined boreholes. Although numerous short (a few cm in length) and healed vertical and subvertical fractures were identified in both boreholes no through-going open vertical fractures were observed. These small fractures show no evidence of displacement and are oriented randomly.

Borehole Geophysics

Each borehole was logged with a standard suite of downhole geophysical sondes including at least the basic electric (40 cm, 160 cm resistivity and single point resistance) and nuclear (natural gamma, density and porosity) logs. In addition, caliper, fluid temperature and resistivity and sonic (for fracture identification) logs were conducted in the NF and NI series boreholes. The borehole geophysics were used in conjunction with the core logs to identify lithologic boundaries and locate structural features (bioherms, cross-bedding, fractures and vugs).

The electric logs and the natural gamma log were found to be most useful in terms of lithologic identification. The caliper log was most useful in identifying larger fractures and fracture zones which appeared as wash-outs. The sonic logs proved to be unsatisfactory in identifying smaller fractures, the bulk of which provide the permeability in each formation. The porosity and neutron logs were also valuable tools for lithologic identification and were helpful in identifying larger fracture zones. Fluid resistivity logs show water of very high conductivity in the boreholes, in the order of 6000 to 10,000 μ $S.cm^{-1}$, but significant anomolies with depth that might indicate flux of water in or out of the borehole are not apparent. Fluid temperature and especially differential temperature show some influence of groundwater flow through fracture zones near the bedrock surface.

Multiple-Packer Casing Strings

After completion of the borehole logging and develoment of the boreholes by pumping (and after the hydraulic testing in the case of the NF series boreholes) each borehole was completed with a commercially available multiple-packer casing string. The casing strings prevent vertical groundwater flow between fracture zones intersecting the boreholes and provide access through valved ports for sampling and monitoring the isolated intervals. Black et al. (1986) present a more complete description of the casing string and associated equipment. The casing strings were installed usually within two weeks to a month after the borehole was drilled so that the hydraulic head and groundwater geochemistry in individual hydraulic regimes were not significantly perturbed.

Table 2 shows a summary of the isolated intervals for each borehole. There are a total of 94 intervals distributed amongst the seven boreholes with average interval lengths ranging from 5.0 m to 12.3 m. Table 2 also shows the percentage of the borehole length sealed by packer inflation. The greater the percent seal, the greater the confidence in the measured hydraulic head in each borehole.

The location of each packer in an individual borehole was determined based on the core logs, geophysical logs and hydraulic conductivity (where available). Figure 7 shows the location of three packers in borehole NI-2 between the depths 100-130 m. The packer locations are shown against the corresponding core log (fracture log), lithology, 40 cm electric log and the nuclear logs. The packer locations here were determined irrespective of stratigraphic boundaries and were placed primarily to isolate suspected open fractures and lithologic changes. For example, the packers at 110 and 120 m isolate four suspected open fractures as well as an increased volume of sand in the Cabot Head Shale (electric log and natural gamma logs), decreased porosity (neutron log) and decreased density signatures. Particular geophysical signatures such as these were also isolated in other boreholes to facilitate correlation.

Hydraulic Testing

Hydraulic testing to measure hydraulic conductivity in single boreholes was conducted using constant head injection and slug testing techniques. The constant head tests were generally conducted in all accessable intervals, except for those in which natural gas exsolution prevented stable shut-in pressure (about 25-30% of all intervals). Slug tests were conducted only in the medium to higher permeability (10^{-8} m/s to 10^{-5} m/s) intervals except for a few shut-in slug tests conducted in lower permeability intervals in borehole NI-2.

Constant head injection tests are conducted by pumping or injecting water at a constant injection pressure until a steady flowrate of water is achieved. This method can be used either within the multiple-packer casing string or using a double-packer arrangement with a spacing or interval length of 1 to 5 m which can be moved incrementally up or down the borehole. The flowrate, Q, and the injection head, ΔH, is related to the transmissivity, T, of the test interval by the expression (Hvorslev, 1951):

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

where r_e is the radius of influence of the test, which according to Bliss and Rushton (1984) can usually be approximated at 10 m, and r_w is the radius of the borehole. With equipment available for this study, the range of testing capability using the constant head injection method was between 10^{-6} m/s and 10^{-11} m/s for horizontal hydraulic conductivity, K_h($T = Kb$, where b is the test interval length). Doe and Remer (1980) provide a more complete discussion on conducting constant head tests in fractured rock.

Slug tests are commonly employed in overburden materials where hydraulic conductivity is high and less frequently in fractured rock. These tests, however, can be a valuable check on the results from constant head tests and can also provide information on borehole skin effects (Hawkins, 1956; Sageev, 1986). Slug tests are conducted (open-wellbore format) by adding or removing a known volume of water and recording the rise or fall in hydraulic head in the borehole with time. Alternatively, for measuring lower permeabilities, slug tests can be conducted in a shut-in format where the water column in the isolated interval is in turn isolated from the free surface and a small slug of water is added by means of injection to generate a pressure rise. The subsequent response to the change in pressure is then dependent on the compressibility of the water, test equipment and formation as well as the permeability. Slug tests completed following the open-wellbore format are also dependent on the volume of water in the open standpipe. The overall range of detection for horizontal hydraulic conductivity is from 10^{-4} m/s to less than 10^{-13} m/s with the appropriate equipment. Open-wellbore tests have a practical range of about 10^{-4} m/s to 10^{-8} m/s for 76 mm boreholes in fractured rock. Slug test results were analysed using both steady state (Hvorslev, 1951) and transient (Cooper et al., 1967; Sageev, 1986) solutions.

Table 3 shows the results of the hydraulic testing expressed as a range of hydraulic conductivities for each major lithologic unit and for each borehole. The negative log of the geometric mean of each range is also given. The overall range of hydraulic conductivity is between 10^{-4} m/s to $<10^{-11}$ m/s. The values expressed here are reliably representative of the formation properties in the higher hydraulic conductivity range but less so for reported K_h of 10^{-10} to 10^{-11} m/s. The lower K values were determined largely from constant head tests of relatively short duration (200 min or less). Preliminary longer term slug tests show K_h of the formation is much lower in the order of 10^{-12} to 10^{-14} m/s. Further long-term tests will be carried out to validate these numbers.

As the above suggests, there are significant skin effects, in the form of permeability enhancement generated during drilling. This is true for these holes, however, only for K_h of less than 10^{-9} m/s: for K_h greater than 10^{-9} the permeability near the borehole is reduced by up to several orders of magnitude. The reason for this is not immediately evident but may be the result of reduced rock flour penetration at lower permeabilities. The high permeability intervals near the bedrock surface show no skin effects whatsoever.

The general range of hydraulic conductivity shows decline in permeability with depth with the shale formations having the lowest permeability. The boreholes nearest to the Niagara Gorge (the NF series boreholes) show greater permeability in the Lockport and Clinton Groups probably as a result of increased vertical and horizontal fracturing here. The presence of natural gas in many of the intervals impeded the hydraulic testing procedures. This was especially true for the CH-1 and the NI series of holes.

Cross hole and vertical interference tests are currently being conducted to determine the nature of the vertical hydraulic conductivity, K_v. It is expected that K_v will be several orders of magnitude lower than corresponding K_h as a result of the minimal number of vertical fractures.

Hydraulic Head Distribution

Hydraulic head measurements were initiated soon after the multiple-packer casing was installed in each borehole. Because the boreholes were drilled over a period of several years, there are varying lengths of record for each hole. The measurements were obtained mostly on a quarterly basis using a monitoring device equipped with a pressure transducer. The observed pressures were converted to hydraulic head, h, using (Freeze and Cherry, 1979):

$$h = z + \frac{p}{\rho g} \qquad (2)$$

where z is the elevation above datum (sea level - IGLD), p is the gage pressure as measured by the pressure transducer, ρ is the density of the water and g is gravitational acceleration. The density of the water was found to be variable with depth during geochemical sampling and observed densities (estimated where no data was available) were used to calculate hydraulic head. The hydraulic head measurements will be discussed in the following section on the hydrostratigraphic model.

Hydrostratigraphic Model

Figures 8 and 9 show the stratigraphy, hydraulic conductivity and hydraulic head distribution for boreholes NI-2 and NF-2 respectively. Diagrams such as these can be assembled for each of the seven boreholes to provide a complete picture of the hydrostratigraphy. The results for NF-2 and NI-2 are used here to illustrate the difference between boreholes close to the Niagara Gorge (i.e. NF-2) and those away from the Gorge (i.e. NI-2).

The hydraulic conductivity near the top of borehole NI-2 (Fig. 8) is highest in the Guelph Formation and decreases uniformly to 10^{-11} m/s and lower in the Clinton and Cataract Groups (long-term analysis of the gas zone permeability is currently underway). Some permeability is evident at the top of the Queenston Formation perhaps at the Queenston-Whirlpool contact.

Hydraulic head (density corrected) in the Guelph Formation and top of the Lockport Dolostone is fairly uniform and well connected to the water level in the Upper Niagara River. The uniformity of the hydraulic head suggests some vertical connection here. In the middle of the Lockport where the permeability begins to decline, the hydraulic head increases dramatically to almost 70 m above ground surface in the Rochester Shale. Except for the extremely high heads in the Rochester Formation the bulk of the measurements in the Clinton and Cataract Groups are distributed fairly uniformly about 35 m above ground level. The lower Cataract Group shows a significant decline in hydraulic head towards a low between 125 and 130 m at the top of the Queenston Formation. This low-head feature is probably associated with the higher permeability zone here and suggests strong hydraulic connection to the Niagara Gorge. In fact, the elevation of the water level in the plunge pool below the Horseshoe Falls is about 125 m on average.

The permeability in borehole NF-2 is generally somewhat higher than in borehole NI-2, likely as a result of the increased fracturing, both vertical and horizontal, near to the Gorge. Other measurements of permeability in the Lockport Formation and upper Rochester

Formation (Maslia and Johnston, 1984) near to the Gorge are in agreement if not somewhat higher than at borehole NF-2. Several distinct high permeability zones, some in the Lockport Formation, are evident in this borehole. However, below the Upper Clinton Group, the permeability declines to about 10^{-11} m/s or perhaps less, again except for a slightly higher permeability zone at the top of the Queenston Formation.

The hydraulic head measurements in the Guelph, like in borehole NI-2, are uniform and close to the elevation of the Niagara River. Here, however, the top of the Lockport (high permeability zone) shows hydraulic heads about 10 to 15 m below river level suggesting good connection to the Niagara Gorge. High hydraulic head is evident in the Clinton Group, at about 10 m above river level but not at nearly the magnitudes observed in borehole NI-2. The Cataract Group shows declining heads toward the low-head feature at the top of the Queenston Formation, as seen in NI-2. Here also, the level is at about 125 to 130 m. Borehole NF-2 penetrates the Queenston Formation more than any other of the study boreholes. The hydraulic head in the Queenston Formation in borehole NF-2 is the highest in the hole at about 20 m above river level. High hydraulic heads here are also observed in borehole NI-1 which also deeply penetrates the Queenston Formation.

Based on existing information, the Paleozoic strata underlying Niagara Falls can be divided into at least four separate hydrostratigraphic units. The uppermost high permeability weathered zone, which in some areas will extend through the Guelph Formation into the Lockport, forms the top unit. This unit will be of most interest to those concerned with groundwater pollution in the area, and can in turn be subdivided on the basis of individual fracture zones. For example, based on the existing data, at least two high K zones are evident, one in the upper weathered zone and another at the contact between the Eramosa and Goat Island members of the Lockport Formation in boreholes NI-2 and NF-2. Other boreholes also show at least two or more often three high K fracture zones. The Clinton and Upper Cataract Groups make up the second hydrostratigraphic unit. This unit is predominated by very low permeability and high hydraulic head suggesting stagnant groundwater flow. The Lower Cataract and Upper Queenston Formation (or the disconformity marking the contact) comprise the third unit. The lowermost unit is defined by the thick Queenston Formation. Each of the last three hydrostratigraphic units could be subdivided for numerical modeling purposes. The four units as described, however, will probably suffice for the conceptual groundwater flow model.

GEOCHEMICAL EVOLUTION MODEL

Geochemical samples of both the groundwater and natural gas were obtained from the study boreholes and analysed to form the basis of the geochemical evolution model. The groundwater samples were analysed for inorganic and organic chemistry and $\delta^{18}O$, $\delta^{2}H$ and Tritium contents. The organic composition of the natural gas was determined and $\delta^{13}C$ and $\delta^{2}H$ values are being obtained. The geochemical evolution model is formulated in order to help determine the rate of movement and provenance of the groundwater in the various units.

Groundwater Chemistry

The groundwater samples were obtained through the multiple-packer casing strings using standard procedures and protocols (Barcelona et al., 1985). Where permeability was greater than 10^{-7} m/s and hydraulic head elevations near ground surface, water was purged from the interval by continual pumping and the sample was taken when Eh and pH measurements showed that stable conditions were achieved. For lower permeabilities and in low-hydraulic-head features, groundwater was purged from the intervals using very large hydraulic gradients over long periods of time (up to a month). Samples were obtained using a bailer when at least two interval volumes had been purged. In most cases the samples were fluoresced to determine if any non-indigenous water was present. No trace of the drill water was found in any sample. Groundwater sampling was not undertaken until at least one year after the installation of the multiple-packer casing. Samples for inorganic, organic and isotopic analysis were collected at the same time for each sampling period.

Figure 10 shows the results of the inorganic chemical analysis for samples obtained from the Guelph and Lockport Formations, the Clinton and Upper Cataract Group and the Lower Cataract Group (or the

Upper Queenston Formation). These samples were mostly obtained from borehole NF-2, NI-1 and NI-2. Guelph and Lockport Formation samples show an evolutionary trend from fresh bi-carbonate type water (Niagara River water composition) towards seawater composition with increasing depth. However, because the hydraulic gradients are predominantly vertically upwards and because the number of samples are few, it is also possible to suggest that the evolutionary trend is simply a mixing line between fresh and salt water. The total dissolved solids (TDS) of the Clinton and Cataract samples are in the order of 35 to 38 g/L which is about the same salinity as modern seawater. The composition is principally NaCl and is similar to other highly saline connate water found in sedimentary basins in Europe (Andrews et al., 1987). The pH generally ranges from values of 7.0 to 8.0 where the higher values were obtained from the shallower intervals. Eh measurements indicate a pervasively reducing environment.

The seawater composition and high TDS in the low permeability rock suggests that the groundwater is very slow moving. In fact, because of the large sampling intervals (10 m or greater) in the Clinton and Cataract Groups, most of the sampled water was probably obtained from the higher permeability zones within these intervals. Therefore, water with much larger TDS contents as seen elsewhere in the Niagara Peninsula (Barker et al., 1987) may be found in adjacent lower permeability rock. The generation of brines in such environments is usually attributed to osmotic filtration across the shale units (Graf, 1982). The shorter intervals in borehole NI-1 can be used for determining this in future borehole sampling. Because of the significant hydraulic gradient toward the low-hydraulic head feature at the Lower Cataract-Upper Queenston Formation, the groundwater obtained from the intervals straddling this feature is very similar to that obtained from the rest of the Clinton and Cataract Groups. Good quality sample from deeper in the Queenston Formation has yet to be obtained.

The $\delta^{18}O$ and $\delta^{2}H$ of the groundwater samples is shown on Fig. 11. Although there are few samples, a faint trend towards ^{18}O enrichment is evident in the Clinton Group samples in particular. Unfortunately, as the Niagara River water sample shows, some of the these samples may be contaminated by drill water (river water was used during drilling and shows ^{18}O enrichment due to evaporation) though no drill water was detected using the drill water tracer. Therefore, further sampling is required before it is concluded that the ^{18}O enrichment is due to anything other than mixing with drill water.

Analysis for bomb Tritium also suggests that Clinton and Cataract samples are slightly contaminated as some ^{3}H is evident (at levels less than present-day precipitation). In consideration of the very low permeability in these rocks, the source of the Tritium is unlikely to be modern groundwater migrating through fractures connected to ground surface.

The organic chemistry of the groundwater was scanned for volatile content using a gas chromatograph. Preliminary results from samples of the Guelph and Lockport Formations show low organic chemical content (on the order of <2 ppb) near the top of the bedrock increasing to benzene concentrations of 20 ppb near the contact with the Rochester Shale of the Clinton Group. Some near surface samples also show high benzene concentrations locally. Samples from the Rochester Shale show the highest benzene concentrations at slightly greater than 20 ppb. Benzene concentrations decline somewhat but remain relatively high in the groundwater in the lower Clinton and Cataract Groups. Related hydrocarbons such as toluene and xylenes are also identified at much lower concentrations in all samples containing benzene. The Rochester Formation and Clinton Group is well known as one of the principal source beds for hydrocarbons in southwestern Ontario (Sanford et al., 1983). Therefore the high benzene concentrations in the black shale Rochester Formation are very probably natural constituents evolved from the sedimentary matter. The concentration of hydrocarbons in saline water or brines can vary widely and benzene concentrations as high as 10 mg/L have been observed in source rocks (McAuliffe, 1969). Further confirmation of the organic composition using a GC-MS is required to provide a more comprehensive zonation of the formation waters.

Natural Gas Chemistry

Natural gas was found during drilling in every borehole at a wide variety of depths. In borehole NI-1 gas is found as shallow as 25 m in one of the high permeability zones in the Guelph Formation. The presence of gas is most prevalent in the Clinton Group, particularly the Rochester Formation and is ubiquitous through the rest of the borehole below the Clinton Group irrespective of hydraulic head. Samples of the gas were obtained by collecting headspace samples of exsolving gas where gas volumes were large enough and by collecting water and dissolved gas samples downhole in crimped copper tubing where volumes were lower (samples taken using the latter technique were obtained by the University of Waterloo). Samples were obtained from the Lockport Formation, Clinton Groups and Queenston Formation in borehole NI-1 and from the Clinton and Cataract Groups and the Queenston Formation in borehole CH-1. All gas sample analyses were provided by the University of Waterloo (Sherwood, 1987).

The composition of the gas is predominantly methane, CH_4, ranging in % volume from about 75% to 80%. The composition is generally similar to gas compositions from samples taken elsewhere in southwestern Ontario (Barker and Pollock, 1984). No trend in composition with depth or between boreholes was evident.

Of the stable isotope analyses conducted only the $\delta^{13}C$ results were available at the time of writing. The $\delta^{13}C$ of the methane can be used as an indicator of the source of the gas. Values of $\delta^{13}C$ of less than $-50^{\circ}/_{\circ\circ}$ suggest biogenic (shallow burial-low temperature) production (Whiticar et al., 1986). Values between $-50^{\circ}/_{\circ\circ}$ and $-20^{\circ}/_{\circ\circ}$ indicate increasing maturity of the source (Schoell, 1984) and values greater than $-20^{\circ}/_{\circ\circ}$ suggest an abiotic source such as mantle gas (Welhan, 1987).

Table 4 shows the $\delta^{13}C$ of the methane samples obtained from NI-1 and CH-1. The results from CH-1 show fairly uniform isotopic content at about $-40°/_{oo}$ $\delta^{13}C$ which can be classified as mature to overmature gas (Stahl, 1974). Values of $-40°/_{oo}$ $\delta^{13}C$ are quite common for Lower Silurian gases in southern Ontario (Barker and Pollock, 1984). Values for borehole NI-1 are quite different showing an enrichment in ^{13}C with depth, ranging from $-40°/_{oo}$ in the Lockport Formation to $-30°/_{oo}$ in the Clinton Group and Queenston Formation. Values in the order of $-30°/_{oo}$ are lower than any other measured in southern Ontario and suggest a thermally overmature gas. This means that the gas has either migrated from depth (Schoell, 1984) or erosion during the Phanerozoic has removed kms of overlying rock. Alternatively, a secondary fractionation process such as diffusion which leaves the heavier isotope behind preferentially (Fritz et al., 1987) may be responsible for the ^{13}C enrichment. Further gas sampling is needed to validate the initial findings.

Geochemical Evolution Model

The results of the geochemical analyses generally support the hydrostatigraphic model. That is, there are distinct hydrogeochemical zones characterized by the inorganic and isotopic chemistry of the water and gas found in them.

The groundwater in the Guelph-Lockport Formations largely reflects modern day precipitation in isotopic content and reflects typical surface water in inorganic composition. This is not the case farther inland on the Niagara Peninsula where the glacial deposits thicken and direct groundwater recharge is very slow (Desaulniers et al., 1981). Therefore, in the Niagara Falls region, groundwater recharge in the Guelph-Lockport is probably localized along the Niagara River, Welland River, Niagara Falls Moraine and possibly through man-made water diversions and sewers. Local gas pockets observed throughout the Guelph and Lockport Formations suggest that these are zones of very reduced vertical permeability. These zones are probably discontinuous as evidenced by the upward mixing and diffusion of groundwater from the very-low-permeability Clinton Group. This process has inundated the high yield weathered zone with very-poor-quality highly-saline water and renders most of the groundwater in the Niagara Falls area unsuitable for human consumption or agricultural use.

The groundwater and gas samples obtained from below the Guelph and Lockport Formations indicate generally old perhaps connate water with uniformly high hydrocarbon content. Based on the results obtained thus far, there are virtually indistinguishable differences in chemical character in the hydrostatigraphic layers below the bottom of the Lockport Formation. More detailed water and gas samples, particularly from the Queenston Formation and Cataract Group, are required to completely characterize the geochemistry of the groundwater.

Current results also indicate very little distinction between borehole CH-1 and other boreholes in the network with regard to chemical character. This suggests that the supposed fault identified by structural mapping is either nonexistent or has not been active since the Paleozoic and has no influence on groundwater flow.

CONCEPTUAL GROUNDWATER FLOW MODEL

Based on the hydrostratigraphic, geological and geochemical evolution models, groundwater flow in the stratigraphy underlying Niagara Falls can be divided into three flow regimes: the upper weathered zone and fracture zone in the Guelph and Lockport Formations; the low permeability-high hydraulic head Clinton-Upper Cataract Group and Lower Queenston Formation and the moderate permeability-low hydraulic head feature in the Lower Cataract Group - Upper Queenston Formation. Figure 12 depicts, in an simplistic way, an example of the conceptual groundwater flow regime beneath the Upper Niagara River between Navy Island and the Horseshoe Falls. The more traditional cross-sectional diagram showing lines of equipotential is not appropriate here due to the substantial differences in hydraulic head between the flow regimes. Figure 12 will be used as an aid to discuss each individual flow regime.

Guelph-Lockport Flow Regime

Generally the groundwater flow in the Guelph and Lockport Formations is strongly influenced by the Niagara Gorge (Fig. 12). Hydraulic gradients toward the Gorge between NI-2 and NF-2 in the weathered zone are consistently about $4x10^{-4}$ and much higher at about

$3x10^{-3}$ in the fracture zone at the Eramosa and Goat Island contacts (see Fig. 8). The continuity of the weathered zone is pervasive while the continuity of the lower high K zone in the Lockport is unknown. It is probably safe to assume that groundwater is flowing along the high K zone toward the Gorge gathering water from the underlying Lockport Formation away from the Gorge and from both the underlying Lockport and the overlying Guelph Formations closer to the Gorge. The upward mixing of Clinton Group water is less pronounced nearer to the Gorge as a result of more strongly vertical downward gradients. Directly adjacent to the Gorge where vertical fracturing is enhanced (see Fig. 4), groundwater from the Guelph-Lockport Formations mix with Clinton and Cataract Group discharge (although the volumetric flux of Clinton/Cataract Group water is probably very small). Borehole NF-2 is almost one km from the Gorge yet an increase in downward flow is evident even here relative to borehole NI-1.

Figure 13 shows the approximate directions of groundwater flow in the weathered zone for both the Canadian (based on data from this study) and U.S. sides (adapted from Johnston, 1964 and Miller and Kappel, 1986). Additional information from water well records, Ontario Hydro and observations wells drilled by groundwater consultants (Gartner Lee, 1987) support this interpretation although the data to the west and south are particularly weak. The groundwater in the weathered zone is flowing predominantly northward towards the Niagara Gorge and Escarpment on the Canadian side with a small southward component in the western part of the area and predominantly southward and towards the Gorge on the U.S. side. Man-made water diversions on both sides of the river act as drains for groundwater from the weathered zone as do the St. Davids Buried Gorge and another small buried valley oriented northeast adjacent to the Niagara Gorge. Local discharge and recharge into and from buried ancestral river channels (Fig. 4) probably have little influence on the regional flow. Regional flow in the balance of the Guelph-Lockport Formations is likely very slow with the exception of the high K zone at the Eramasa-Goat Island contact which probably mimics the flow in the weathered zone to a large degree.

The groundwater flow regimes in this hydrostratigraphic unit likely formed as erosional features through geologic time (the weathered zone) and through stress release due to isostatic rebound and erosional unloading during the Cenozoic (both the weathered zone and the Eramosa-Goat Island contact).

Clinton-Upper Cataract and Lower Queenston Formation Flow Regime

Groundwater flow in the Clinton-Upper Cataract Groups and the Lower Queenston Formation is virtually non-existent. Flow direction is primarily vertical except near the Niagara Gorge (Fig. 12) where some horizontal discharge may occur. The vertical flow likely takes place only near the upper part of the Rochester Formation and lower towards the base of the Cataract Group. This flow is solely a result of the very large vertical gradients here and occurs as a means of readjusting the hydraulic head at these boundaries. The influence of vertical faults through these strata would be substantial in consideration of the vertical gradients although the exact direction groundwater flow might take (i.e. upwards or downwards) is unclear. In fact, the presence of a vertical fault would probably act to dissipate the high heads near to the feature. Observations in borehole CH-1 (near to a suspected vertical fault) show hydraulic head measurements equally as high as observed in other boreholes.

The very high hydraulic head observed in the Clinton Group and Queenston Formation likely reflect a pre-Pleistocene perhaps Paleozoic groundwater pressure. Anomolously high pressures in sedimentary and hydrocarbon bearing rock have been observed by others (Hanshaw and Hill, 1969; Toth and Corbet, 1986). There are several potentially viable explanations for these pressures including osmotic filtration (Graf, 1982; Back, 1985) lateral tectonic compression (Graf, 1982) and erosional unloading (Toth and Millar, 1983). Determination of the geopressuring process will require further field investigation and is beyond the scope of this paper.

Lower Cataract-Upper Queenston Flow Regime

The Lower Cataract Group-Upper Queenston Formation exhibits a moderately low permeability of about 10^{-8} to 10^{-9} m/s and a pervasively low hydraulic head. Groundwater flows in this regime are slow and in a lateral direction. Hydraulic gradients between boreholes NI-2 and NF-2 are in the order of $1x10^{-4}$ (Fig. 12). In general, the lateral flow direction is likely northward and towards the Niagara Gorge, although due to the minor fluctuations in hydraulic head at this depth as a result of small changes in the borehole chemistry during measurement, actual directions are difficult to define. The groundwater in this feature is derived from both the overlying and the underlying formations at all study boreholes and therefore reflects the chemical character of the water in these units. There is probably no influence on the magnitude and direction of groundwater flow here by man-made surface drainage or the Upper Niagara River. Again, evidence of the influence of a large scale fault is not observed either in the chemical character of the water or in the measured hydraulic heads.

The anomolously low hydraulic heads in the Lower Cataract-Upper Queenston flow regime are observed in all the study boreholes and have been observed elsewhere along the Niagara Escarpment (Nadon, 1981). Two explanations can be offered as to the source of the underpressured zone. First and most obvious is that the presence of the Gorge and Escarpment have provided a source for low hydraulic heads which are accessed along the moderate permeability feature. This means that the low heads observed in the Niagara Falls area and immediately south are likely Holocene aged phenomenon generated by the advance of the Niagara Gorge since the last glaciation. Alternatively, erosional unloading may have enlarged the pore structure and enhanced the permeability (Neuzil and Pollock, 1983) in the Whirlpool sandstone. Surrounded by very low permeability material, the decline in pore pressure has yet to readjust through the influx of water. This would probably be a longer term geologic process directly related to the periods of erosional unloading. An additional borehole, well south of the influence of the Niagara Escarpment would provide information as to the correct underpressuring mechanism.

CONCLUSIONS

Based on the data and observations collected so far, the following preliminary conclusions can be drawn:

1) There are at least three major and distinct groundwater flow regimes in the stratigraphy underlying Niagara Falls.
2) The uppermost flow regime in the Guelph and Lockport Formation is characterized by high permeability zones with some potential vertical interconnectivity.
3) Groundwater flux in the high K zones is not large except near the Niagara Gorge and Escarpment.
4) Groundwater from the upper flow regime is of very poor quality and has high background concentrations of hydrocarbons. The hydrocarbon concentrations will interfere in identifying other organic contaminants.
5) The Clinton Group exhibits pervasively high hydraulic heads which act as a barrier to any vertically downward groundwater migration.

6) Vertical and horizontal permeability increases in proximity to the Niagara Gorge in all stratigraphic units.

7) Groundwater movement in the Clinton and Cataract Groups and the Queenston Formation is extremely slow to non-existent within the study area.

It is evident that pollution of the lower part of the Lockport Formation and in particular the Clinton-Cataract Groups by groundwater migrating from landfills which are well away from the Lower Niagara River is very unlikely even in consideration of the propensity for downward migration of dense non-aqueous phase liquids. However, in proximity to the Niagara Gorge and to the Niagara Escarpment (within for example the zone of stress relief fracturing as drawn in Fig. 4), there is a substantial potential for vertical migration of contaminants and contaminated groundwater. Furthermore, although apparent hydraulic gradients in the Guelph and Lockport Formations are not large, contaminant migration along individual fractures can be very swift indeed. For example, using a gradient of $3x10^{-3}$ as observed in the Eramosa-Goat Island contact between NI-2 and NF-2 and ignoring matrix diffusion effects, the velocity of groundwater migrating in a single 500 μ wide fracture (equal to a hydraulic conductivity of about 10^{-6} m/s) is about 40 m per day. Over just a few years and in consideration of hydrodynamic dispersion in single fractures (Novakowski et al., 1985) contamination may travel several kms and pollute large volumes of water at low concentration. However, discontinuity within individual bedding plane fractures due to the heterogeneity of stress release and the presence of fracture zones developed en echelon will mitigate against such widespread contamination. Of course, nearer to the Niagara Gorge where gradients are higher these problems are exacerbated.

FUTURE WORK

The following are a list of influences and processes for which a better understanding is required to aid in the overall interpretation of the regional groundwater flow in the bedrock beneath Niagara Falls.

1) More investigation of the contaminant transport properties of the Guelph and Lockport Formations is required before reliable prediction of contaminant migration to the Niagara River can be made. To carry out this study two to three shallow borehole arrays (three holes each array) should be drilled to the top of the Clinton Group. Hydraulic tests to determine the vertical distribution of fracture zones and interconvectivity should be conducted. In addition these boreholes can be drilled and oriented in such a way as to provide a suitable environment for conducting tracer experiments. Tracer tests will provide estimates of porous-media-equivalent porosity and hydrodynamic dispersion, two parameters of which there no values available for the Niagara Area. A detailed joint study of the Lockport Formation can also be conducted to determine the frequency and orientation of vertical fractures that might hydraulically connect the individual high K zones.

2) More detailed geochemical samples, long-term monitoring of hydraulic head and long-term slug tests are required to assess the influence of potential faults in the Niagara area. Detailed review of gas well logs and geophysical and remote sensing information may reveal new targets that could be drilled as part of item (1) or investigated with one or two deep boreholes.

3) The influence of the Niagara Gorge with regard to enhanced horizontal and vertical permeability should be more thoroughly investigated. This also could be achieved as part of item (1) by drilling one array of boreholes well into or through the Rochester Formation adjacent to the Gorge.

4) The origin and areal extent of both the overpressured and the underpressured zones is still unclear. A detailed review of drill stem test shut-in pressures from gas wells completed in the Clinton and Cataract Groups within the region in conjunction with more long-term monitoring of the hydraulic head in the study holes and some analytical modeling, may help elucidate the matter. Drilling and instrumentation of a very deep borehole would provide very substantial information on this matter as well as providing a link for more basin/trough wide study.

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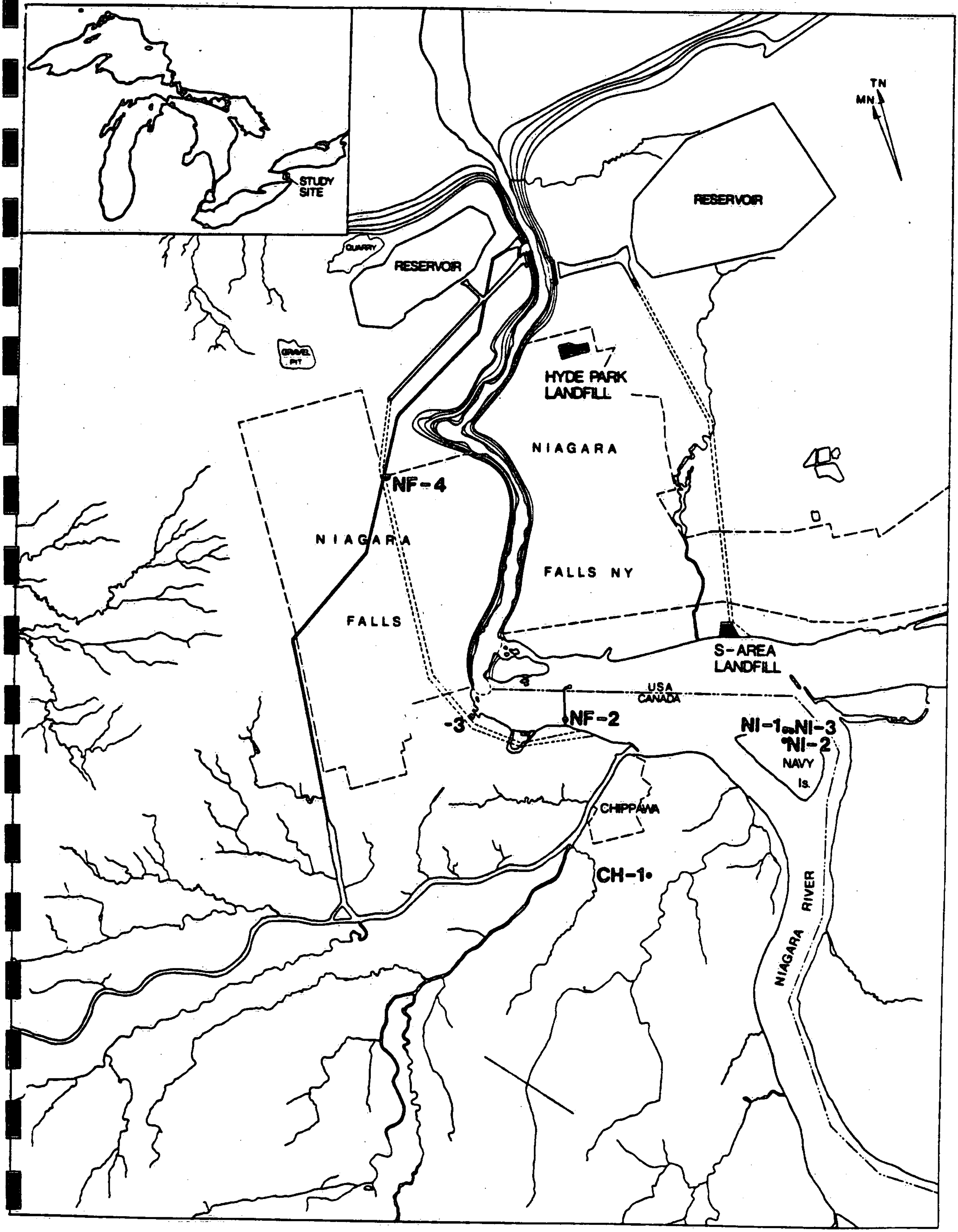
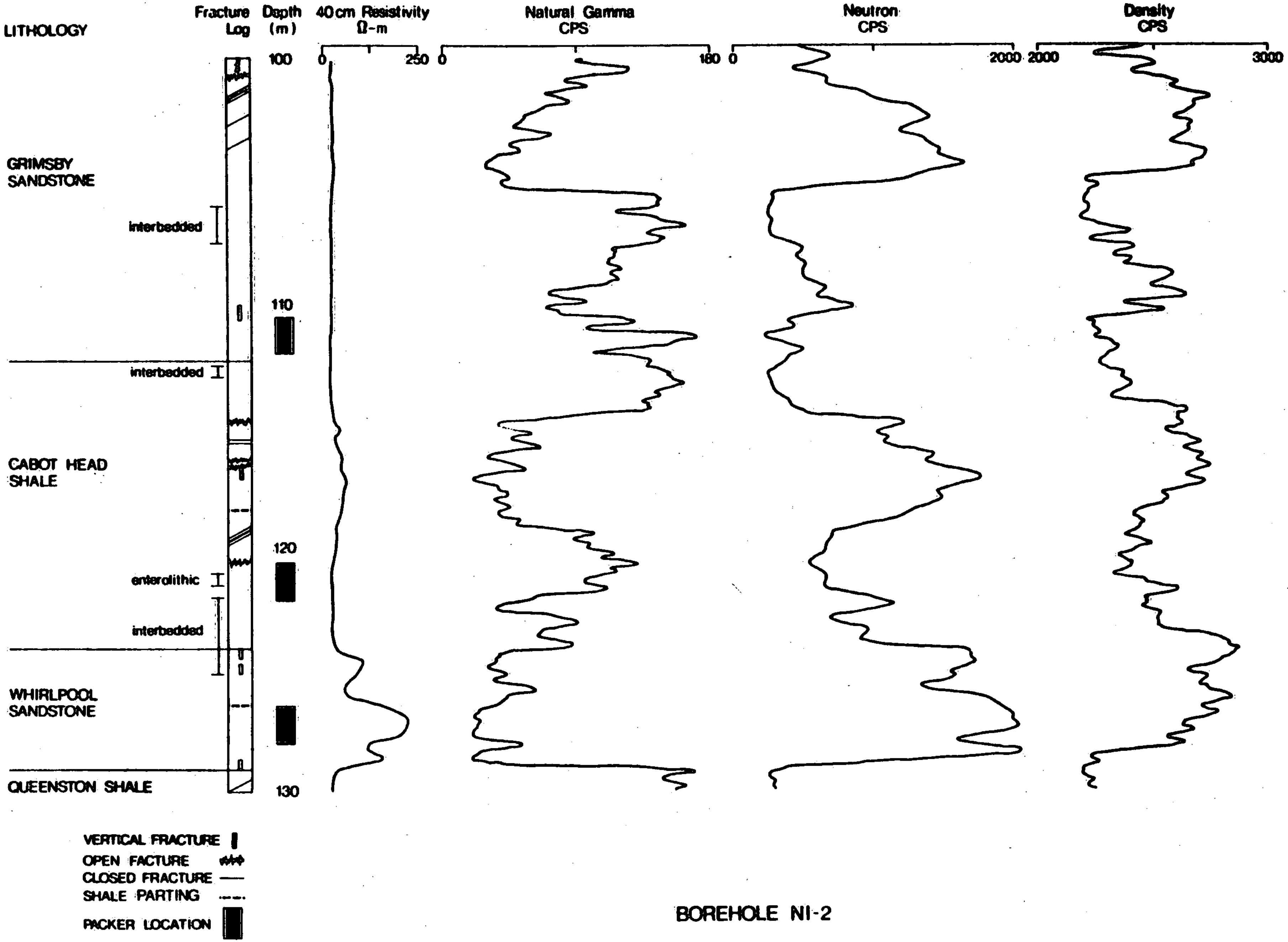
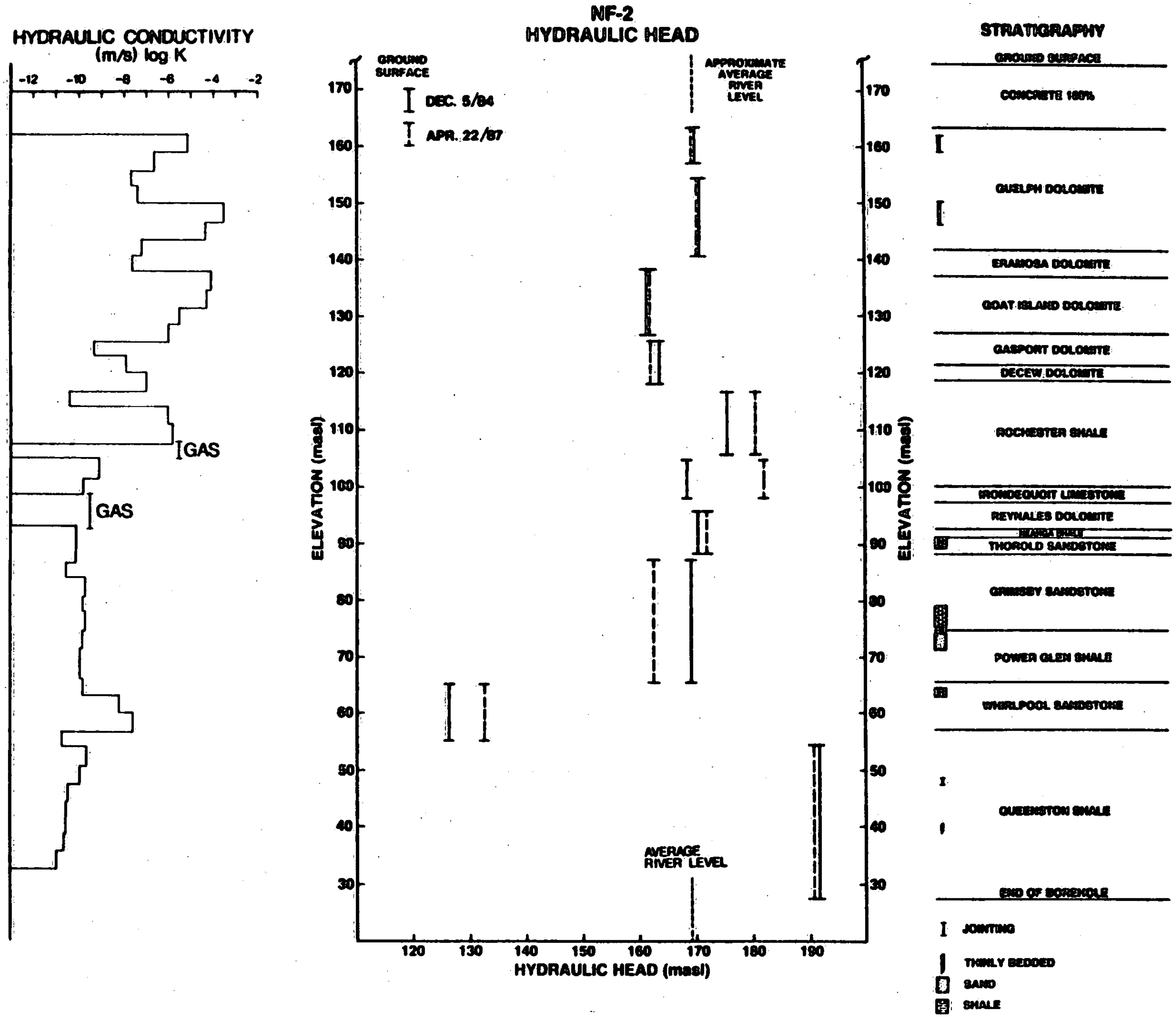
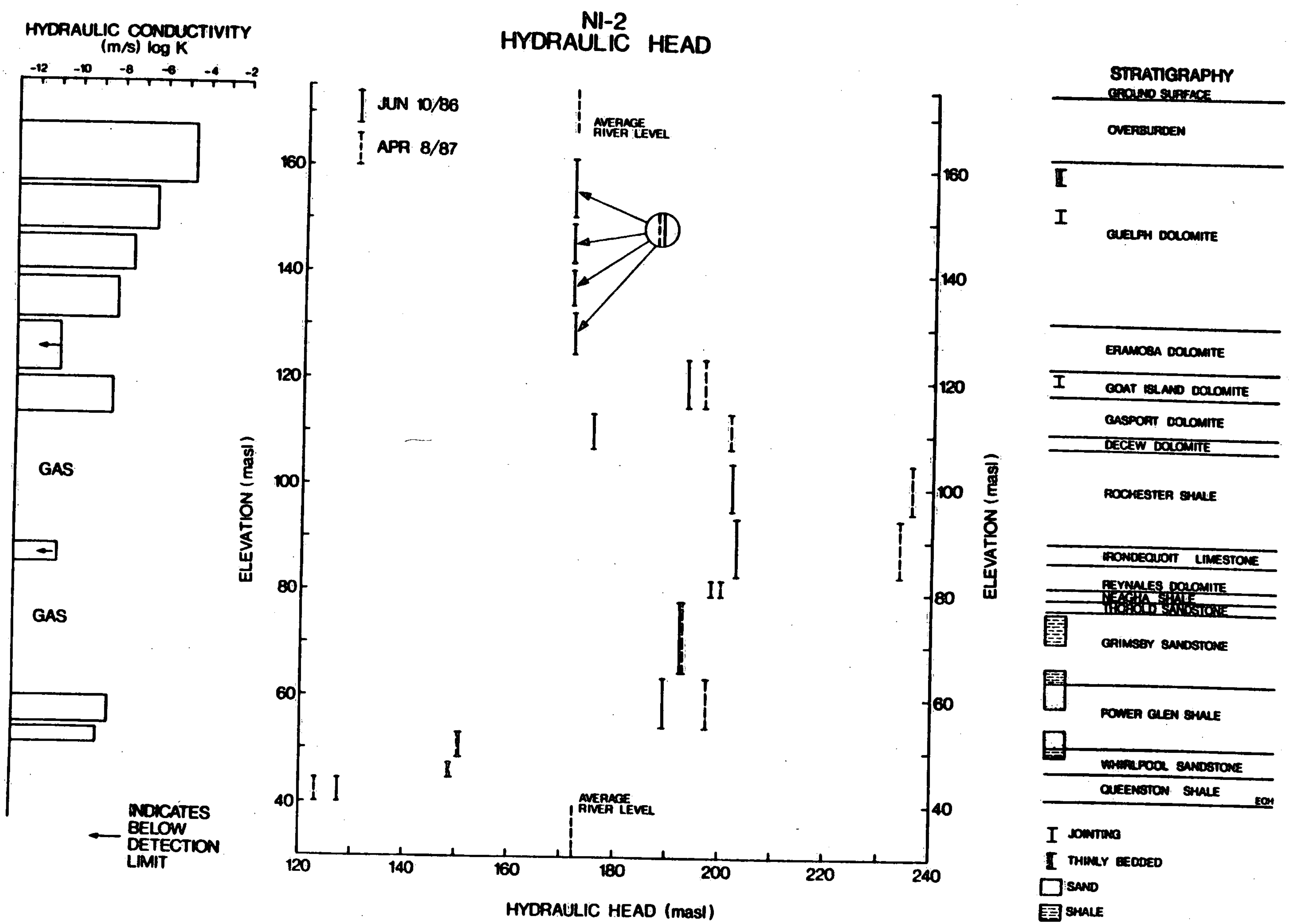

STUDY SITE
TN
MN
RESERVOIR
QUARRY
RESERVOIR
GRAVEL PIT
HYDE PARK LANDFILL
NIAGARA
NF-4
NIAGARA
FALLS NY
FALLS
S-AREA LANDFILL
USA
CANADA
NF-2
-3
NI-1
NI-3
NI-2
NAVY Is.
CHIPPAWA
CH-1
NIAGARA RIVER

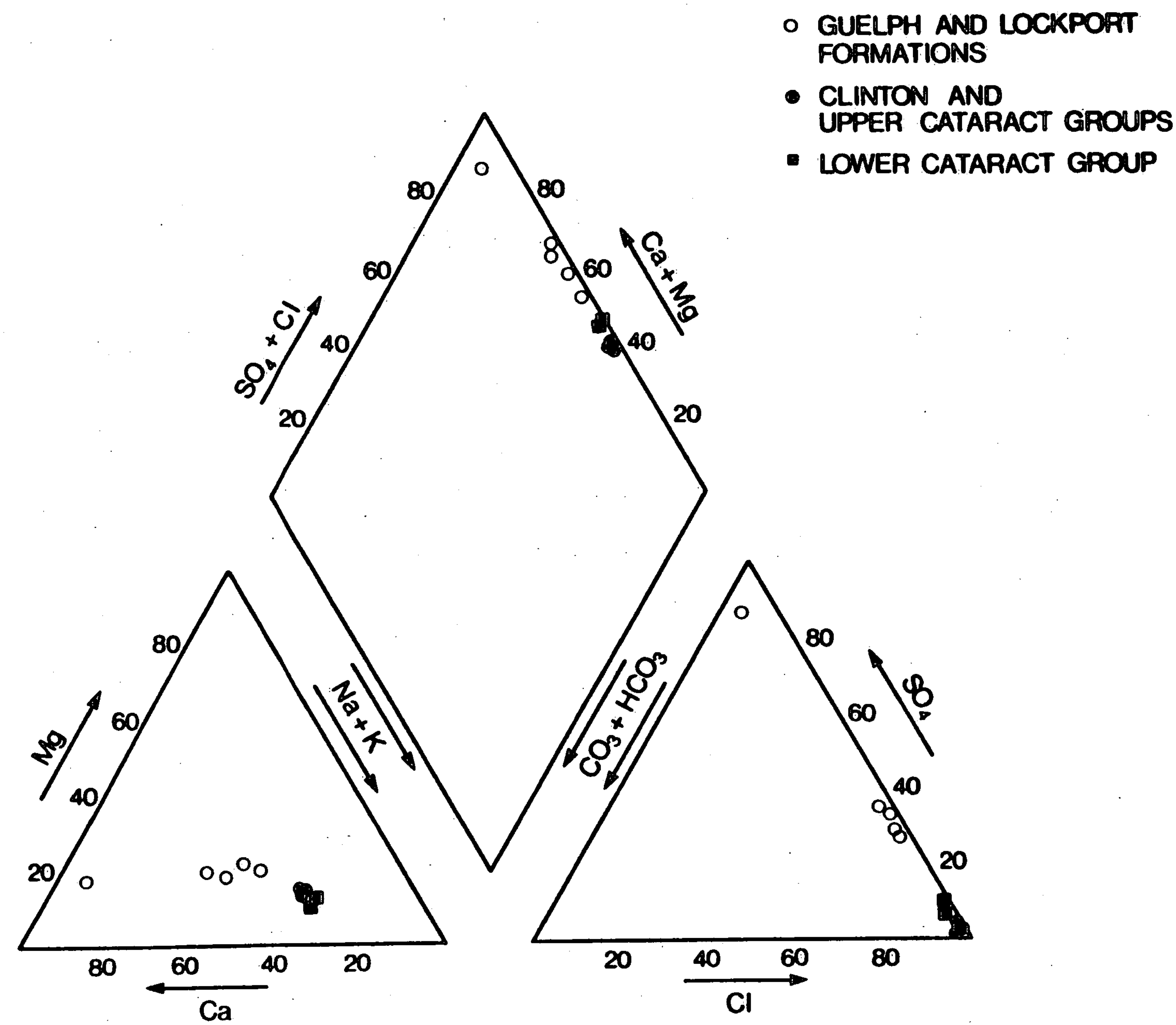


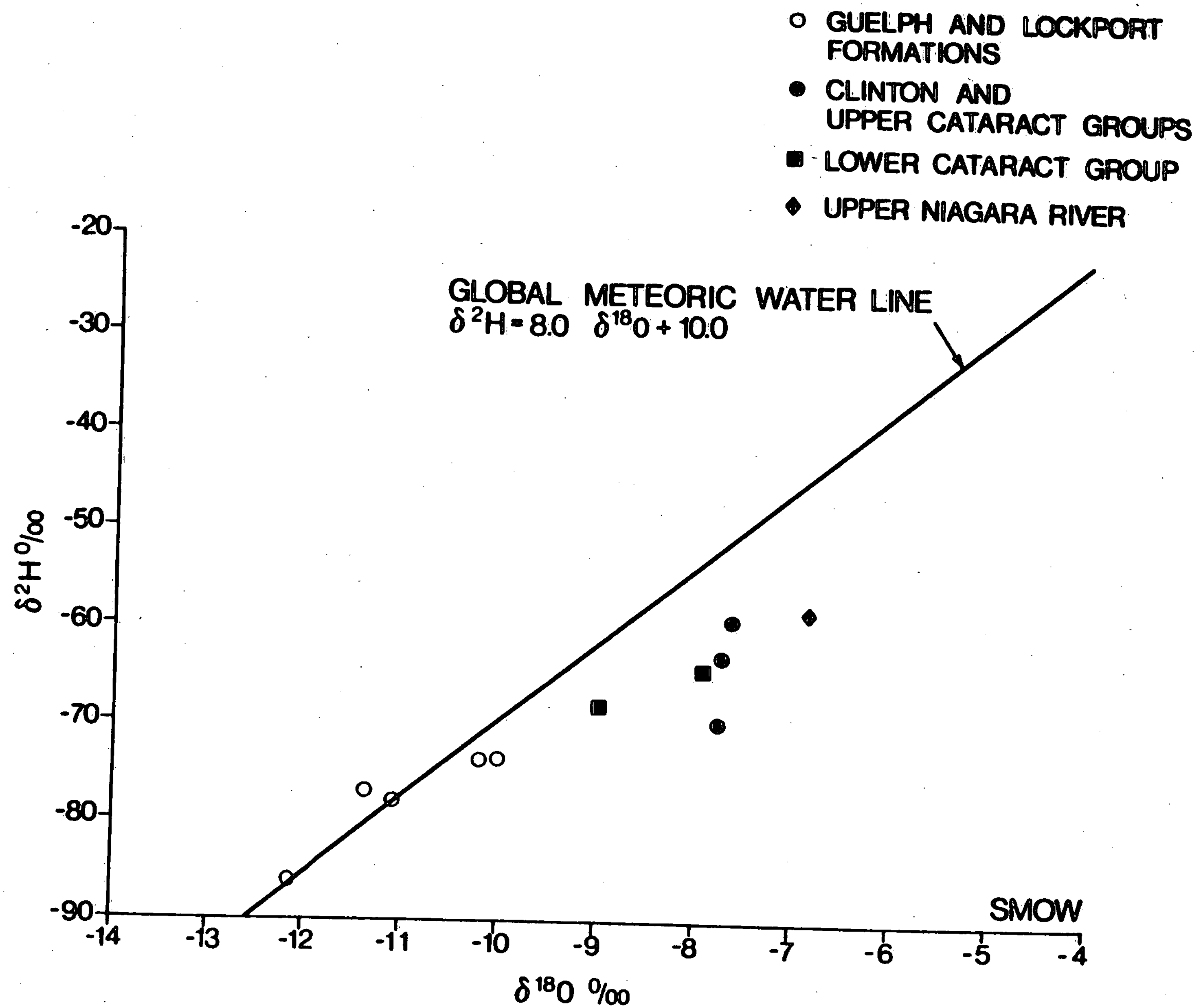
BOREHOLE NI-2

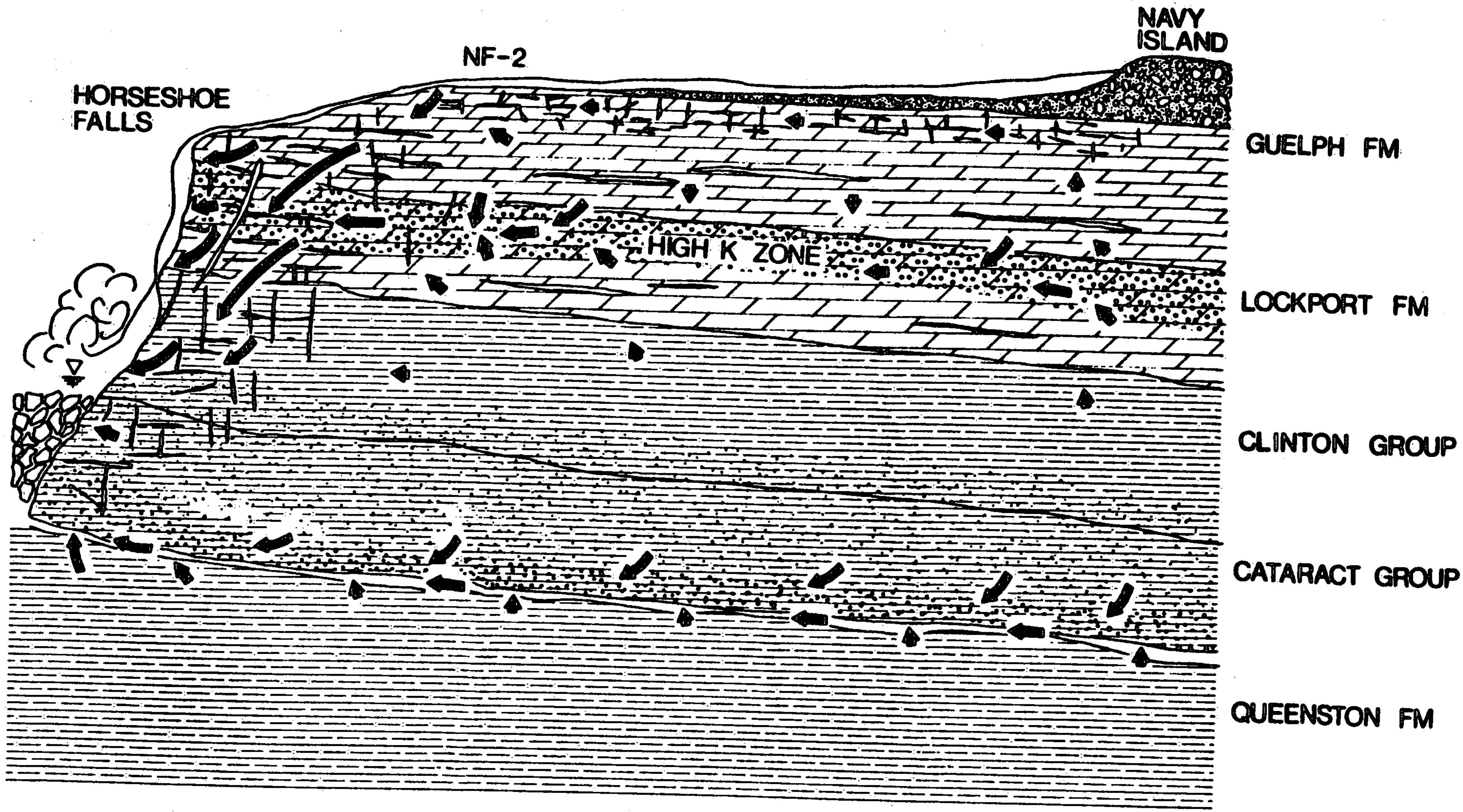

NF-2
HYDRAULIC CONDUCTIVITY
(m/s) log K
-12 -10 -8 -6 -4 -2
GAS
GAS
HYDRAULIC HEAD
GROUND SURFACE
DEC. 5/84
APR. 22/87
APPROXIMATE AVERAGE RIVER LEVEL
AVERAGE RIVER LEVEL
ELEVATION (masl)
170 160 150 140 130 120 110 100 90 80 70 60 50 40 30
120 130 140 150 160 170 180 190
HYDRAULIC HEAD (masl)
STRATIGRAPHY
GROUND SURFACE
CONCRETE
GUELPH DOLOMITE
ERAMOSA DOLOMITE
GOAT ISLAND DOLOMITE
GASPORT DOLOMITE
DECEW DOLOMITE
ROCHESTER SHALE
IRONDEQUOIT LIMESTONE
REYNALES DOLOMITE
THOROLD SANDSTONE
GRIMSBY SANDSTONE
POWER GLEN SHALE
WHIRLPOOL SANDSTONE
QUEENSTON SHALE
END OF BOREHOLE
JOINTING
THINLY BEDDED
SAND
SHALE

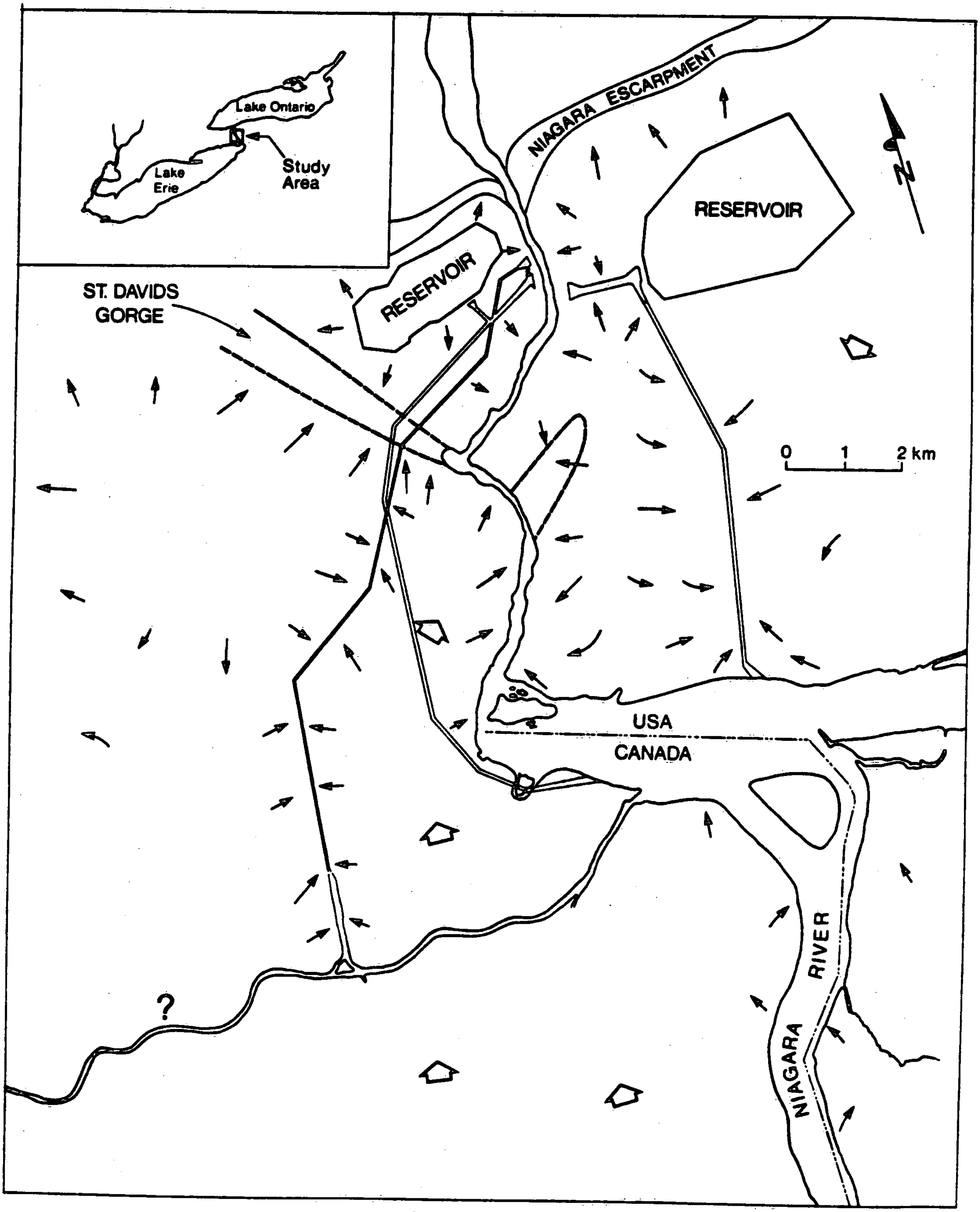


NI-2
HYDRAULIC HEAD
HYDRAULIC CONDUCTIVITY
(m/s) log K
-12
-10
-8
-6
-4
-2
GAS
GAS
INDICATES BELOW DETECTION LIMIT
JUN 10/86
APR 8/87
AVERAGE RIVER LEVEL
AVERAGE RIVER LEVEL
160
140
120
100
80
60
40
ELEVATION (masl)
120
140
160
180
200
220
240
HYDRAULIC HEAD (masl)
ELEVATION (masl)
STRATIGRAPHY
GROUND SURFACE
OVERBURDEN
GUELPH DOLOMITE
ERAMOSA DOLOMITE
GOAT ISLAND DOLOMITE
GASPORT DOLOMITE
DECEW DOLOMITE
ROCHESTER SHALE
IRONDEQUOIT LIMESTONE
REYNALES DOLOMITE
NEAGHA SHALE
THOROLD SANDSTONE
GRIMSBY SANDSTONE
POWER GLEN SHALE
WHIRLPOOL SANDSTONE
QUEENSTON SHALE
EOH
JOINTING
THINLY BEDDED
SAND
SHALE


GUELPH AND LOCKPORT FORMATIONS
CLINTON AND UPPER CATARACT GROUPS
LOWER CATARACT GROUP
SO4 + Cl
Ca + Mg
Mg
Na + K
CO3 + HCO3
SO4
Ca
Cl
20
40
60
80


GUELPH AND LOCKPORT FORMATIONS
CLINTON AND UPPER CATARACT GROUPS
LOWER CATARACT GROUP
UPPER NIAGARA RIVER
GLOBAL METEORIC WATER LINE
δ²H = 8.0 δ¹⁸O + 10.0
SMOW
δ²H ‰
δ¹⁸O ‰
-20
-30
-40
-50
-60
-70
-80
-90
-14
-13
-12
-11
-10
-9
-8
-7
-6
-5
-4


NAVY ISLAND
NF-2
HORSESHOE FALLS
HIGH K ZONE
GUELPH FM
LOCKPORT FM
CLINTON GROUP
CATARACT GROUP
QUEENSTON FM



Lake Ontario
Lake Erie
Study Area
NIAGARA ESCARPMENT
RESERVOIR
RESERVOIR
N
ST. DAVIDS GORGE
0 1 2 km
USA
CANADA
?
NIAGARA RIVER

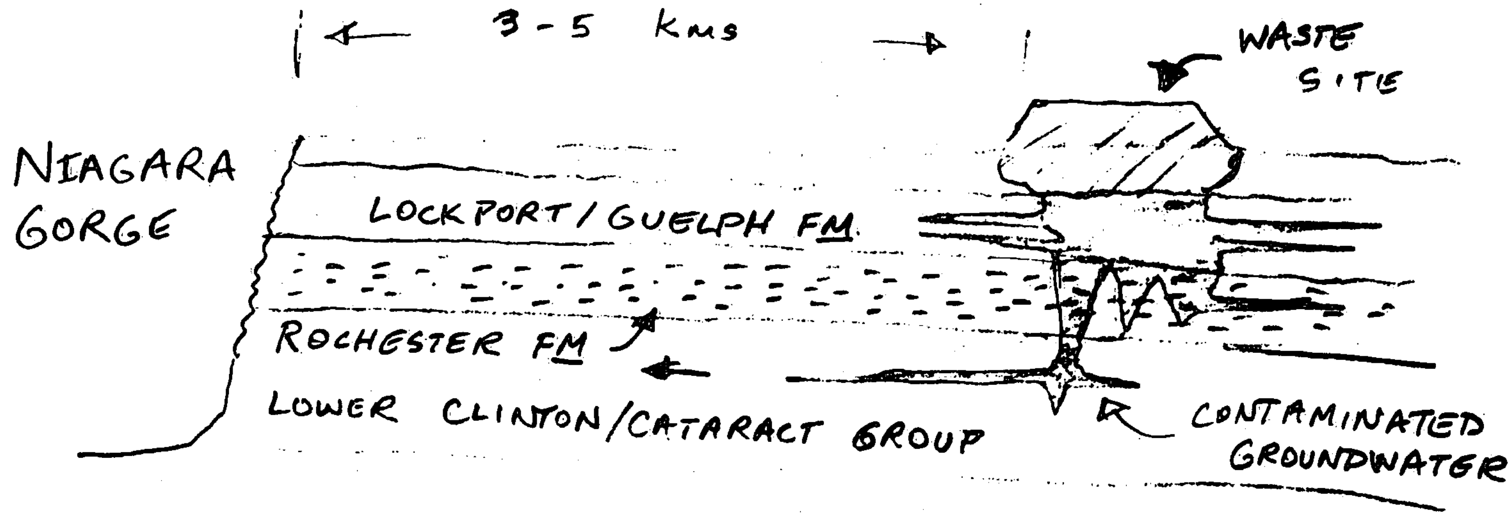

3 - 5 KMS
WASTE SITE
NIAGARA GORGE
LOCKPORT / GUELPH FM
ROCHESTER FM
LOWER CLINTON/CATARACT GROUP
CONTAMINATED GROUNDWATER

Fig. A

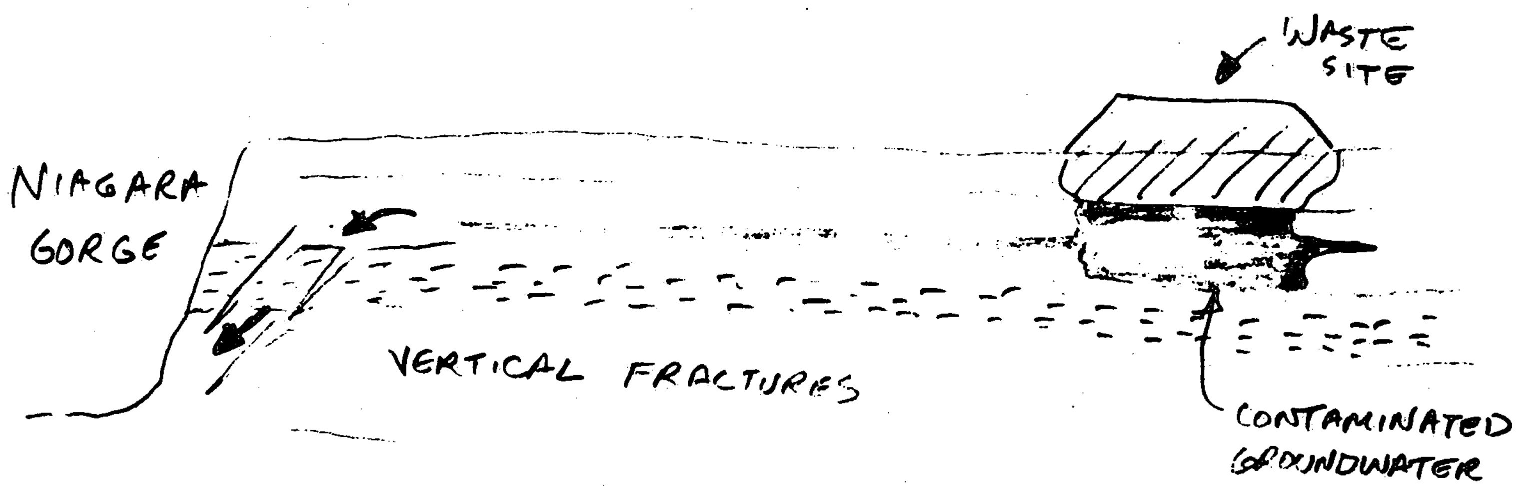

WASTE SITE
NIAGARA GORGE
VERTICAL FRACTURES
CONTAMINATED GROUNDWATER

Fig. B

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LIST OF FIGURES

Table 1. The Silurian and Ordovician stratigraphy underlying Niagara Falls, Ontario.

Age	Group	Formation	Description	Lower Contact	Thickness
Upper Silurian — Cayugan		Salina	brown dolomite and grey calcareous shale, abundant gypsum, anhydrite sparse fossils.	transitional	up to 60 m
Middle Silurian — Niagaran	Lockport Group*	Guelph Oak Orchard*	tan or brown, uniformly textured, sugary, finely crystalline dolostone. Thick bedded, sparse fossils, stylolites, carbonaceous partings and vugs common.	sharp, conformable	37 m
		Eramosa Member — Lockport Formation	dark grey to brown or black, very finely crystalline, dense and laminated dolostone, gypsum filled vugs, carbonaceous partings, black chert throughout.	arbitrary at lowest occurrence of very finely crystalline dolostone	range from 3 m to 10 m
		Goat Island Member — Lockport Formation	brownish-grey, locally grey, medium to fine grained, sugary dolostone. medium to thick bedded, white chert with stylolites and carbonaceous partings.	sharp conformable; determined by change in crystallinity	range from 5 m to 8 m
		Gasport Member — Lockport Formation	grey or blue grey, locally pink, fine to locally coarse grained limestone and dolostone. medium to massive bedded, fossiliferous, shale partings, stylolites common, vuggy.	sharp, disconformable	13.5 m at Niagara Gorge
	Clinton	Decew	medium to dark grey, very finely crystalline, thin to medium bedded dolostone. conchoidal fracture in upper part, cross-bedded in lower part, some solution cavities.	transitional	3.5 m at Niagara Gorge
		Rochester	dark bluish to brownish grey, calcareous fossilferous, some argillaceous limestone layers. upper half grey shale, lower half brownish grey.	sharp, conformable	16.75 m
		Irondequoit	white to tan weathered, light to dark grey fresh, fine to medium crystalline limestone. massive to thin bedded, porous, fossiliferous locally, basal conglomerate.	sharp, possible disconformity	3 m
		Rockway Member* Reynales Merritton Member*	upper member-grey blue lithographic to sublithographic, thin to massive bedded, dolostone. lower member-blue, thin bedded, fine grained, dolostone.	sharp, conformable	4.2 m at Niagara Gorge
		Neagha	green to olive green shale. minor very finely crystalline limestone. shale weathers to a light grey colour.	sharp, conformable	2.1 m at Niagara Gorge
		Thorold	greenish, thinly bedded, very fine grained sandstone. thin, green shale partings.	transitional defined by textural change	range from 2.0 to 3.0 m
Lower Silurian — Alexandrian	Cataract Medina*	Grimsby	red with pale green and yellow mottling, massive, fine grained, red sandstone. red shale interbedded in lower part; some red shale in upper part.	transitional	12.8 m to 15.8 m
		Cabot Head Power Glen*	grey and greenish-grey, finely laminated shales with sandstone interbeds. fine grained with occasional limestone interbeds.	transitional	11 m at Niagara Gorge
		Whirlpool	light grey to white-brown, weathered sandstone. medium to thick bedded with fine to very fine grained sub-rounded, sub-sorted grains. shale partings.	sharp, disconformity	up to 7.6 m
Upper Ordovician — Cincinnatian		Queenston	purplish-red, with thin greenish beds and streaks, hematitic calcareous shale. fissile and micaceous.	unknown	> 250 m Niagara Gorge

* denotes alternate nomenclature.

Table 2. **Summary of intervals isolated using the multiple-packer casing string in each borehole.**

	NF-2	NF-3	NF-4	NI-1	NI-2	NI-3	CH-1
Total Length of Borehole (m)	147.4	130.2	117.4	152.9	135.4	101.2	154.0
Average Number of Intervals	10	9	8	23	14	15	15
Average Length of Intervals (m)	12.3	12.2	11.9	5.3	7.9	5.0	8.4
Percent Seal (%)	6.1	6.2	6.1	13.5	9.3	13.3	8.8

Table 3. Range of hydraulic conductivities, K (m/s), for each major lithologic unit in each borehole. Also shown is the negative log of the geometric mean for each range. Some intervals were indeterminant as a result of high gas exsolution.

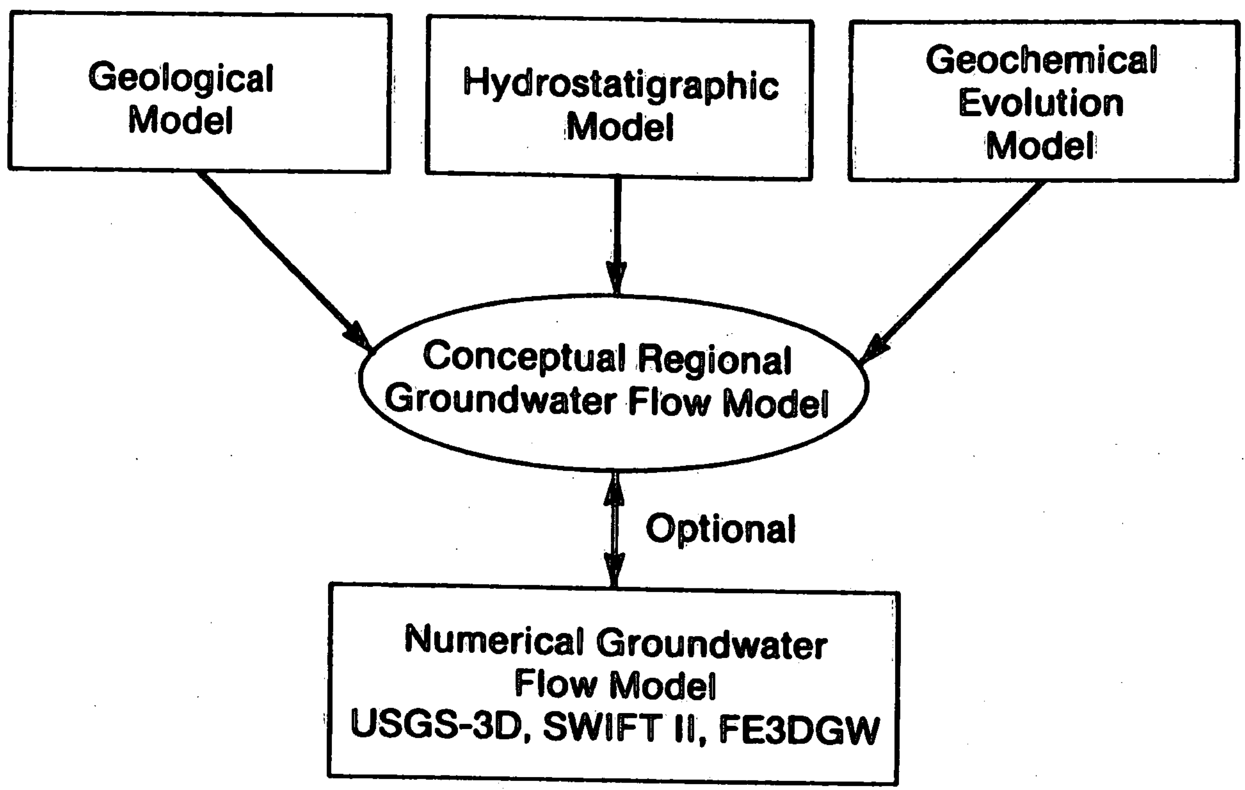
	NF-2≠	NF-3*≠	NF-4≠	NI-1	NI-2	NI-3	CH-1
Guelph Formation	$2.8x10^{-4}$ $-2.2x10^{-8}$ 6.0	$1.0x10^{-6}$ 6.0	-	$9.2x10^{-5}$ $-2.7x10^{-8}$ 6.0	$2.4x10^{-5}$ $-1.4x10^{-8}$ 6.6	$4.0x10^{-5}$ $-2.0x10^{-8}$ 6.2	$4.5x10^{-5}$ $2.0x10^{-5}$ 4.5
Lockport Group	$5.5x10^{-4}$ $-4.5x10^{-10}$ 6.1	$1.0x10^{-5}$ $-7.0x10^{-7}$ 5.6	$2.3x10^{-5}$ $-3.7x10^{-9}$ 6.6	$4.9x10^{-5}$ $-4.1x10^{-9}$ 6.8	$1.4x10^{-8}$ $-7.8x10^{-11}$ 8.8	$2.7x10^{-8}$ $-1.7x10^{-9}$ 8.2	$3.5x10^{-6}$ $-6.1x10^{-8}$ 6.6
Clinton Group	$1.7x10^{-6}$ $-3.6x10^{-11}$ 8.3	$2.0x10^{-6}$ $-2.0x10^{-8}$ 6.9	$1.4x10^{-7}$ $-1.1x10^{-11}$ 8.6	$3.1x10^{-8}$ $-1.2x10^{-9}$ 8.1	$3.2x10^{-9}$ $-7.8x10^{-11}$ 9.3	$5.4x10^{-11}$ $-3.5x10^{-11}$ 10.4	$2.3x10^{-9}$ gas 8.6
Cataract Group	$2.7x10^{-8}$ $-3.0x10^{-11}$ 9.5	$2.0x10^{-8}$ $-2.0x10^{-9}$ 8.2	$2.0x10^{-7}$ $-<1.0x10^{-11}$ 9.6	$5.7x10^{-10}$ $-4.8x10^{-11}$ 9.9	$2.2x10^{-8}$ $-7.7x10^{-9}$ 7.9	-	$3.5x10^{-9}$ $-5.8x10^{-10}$ 8.8
Queenston Formation	$2.7x10^{-10}$ $-1.2x10^{-11}$ 10.4	$1.0x10^{-8}$ $-8.0x10^{-9}$ 8.0	$5.6x10^{-10}$ $-<1.0x10^{-11}$ 10.4	$1.1x10^{-9}$ $-5.3x10^{-11}$ 9.6	gas	-	$1.8x10^{-10}$ 9.7

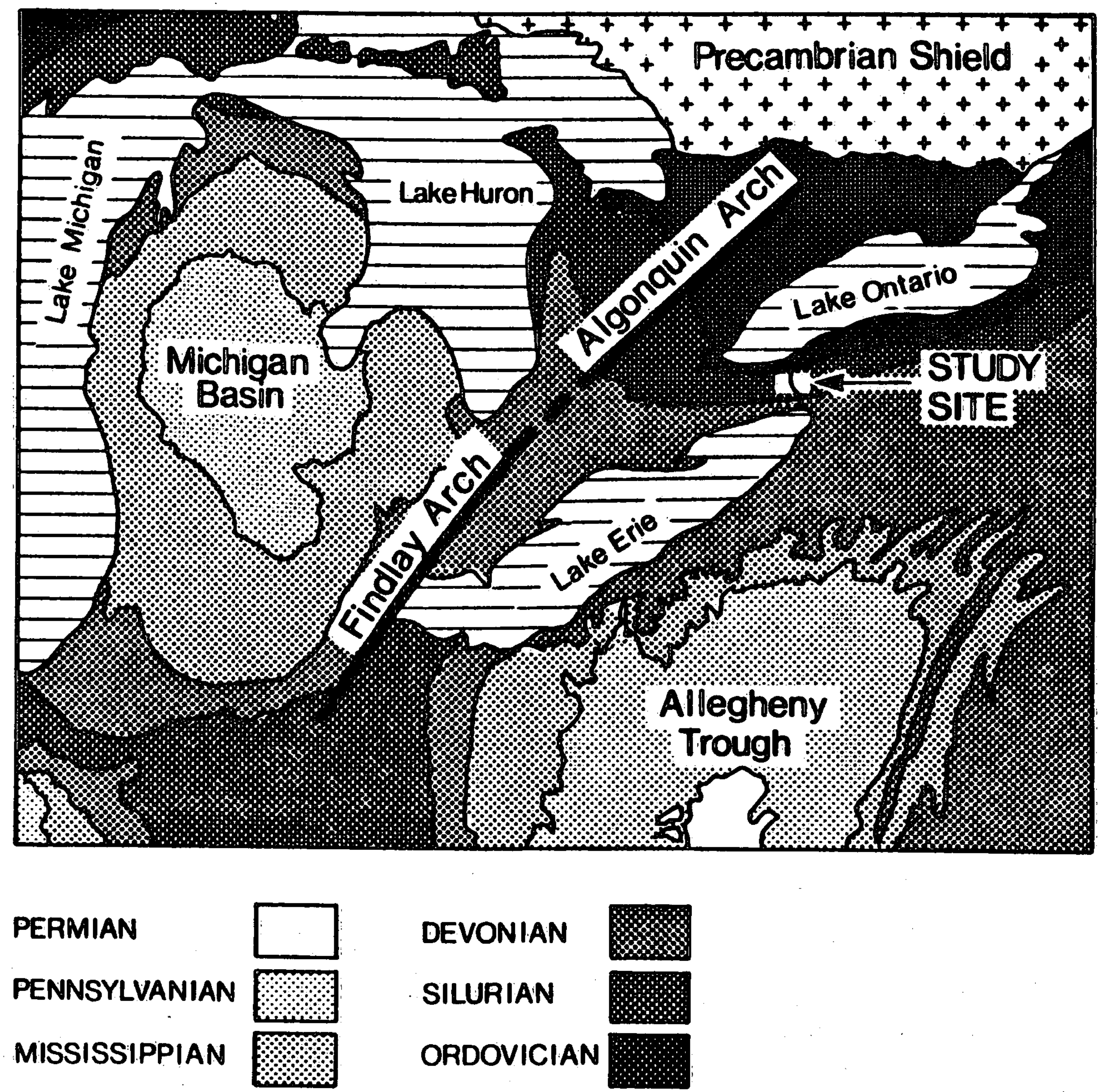
* Drill stem tests: poor reliability
≠ From Semec and Huang (1984)

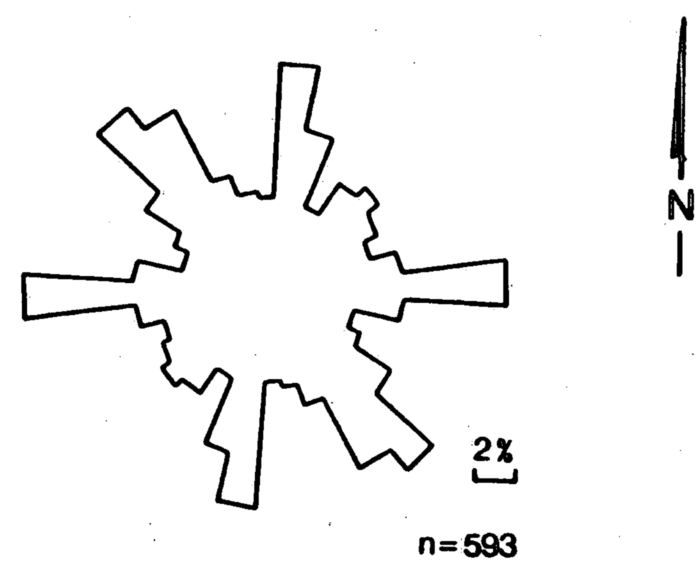
Table 4. The $\delta^{13}C$ content of methane gas samples collected from boreholes NI-1 and CH-1. Values in per millage.

	CH-1	NI-1
Guelph-Lockport Formations	-	-40
Clinton Group	-37	-29
Cataract Group	-41	-
Queenston Formation	-42	-34

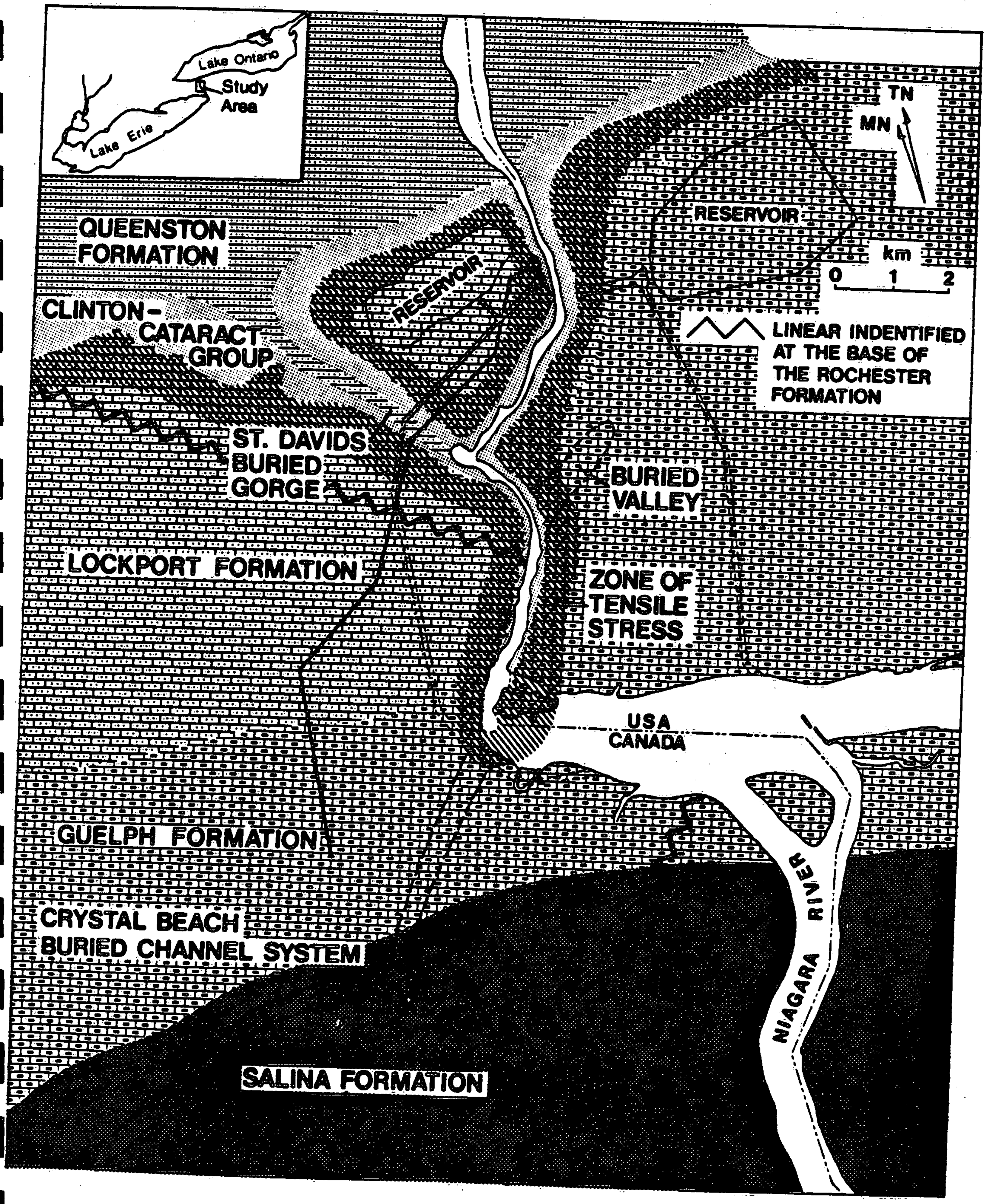
LIST OF FIGURES


Geological Model
Hydrostatigraphic Model
Geochemical Evolution Model
Conceptual Regional Groundwater Flow Model
Optional
Numerical Groundwater Flow Model
USGS-3D, SWIFT II, FE3DGW


Precambrian Shield
Lake Michigan
Lake Huron
Algonquin Arch
Lake Ontario
STUDY SITE
Michigan Basin
Findlay Arch
Lake Erie
Allegheny Trough
PERMIAN
PENNSYLVANIAN
MISSISSIPPIAN
DEVONIAN
SILURIAN
ORDOVICIAN



N
2%
n=593


Lake Ontario
Study Area
Lake Erie
TN
MN
QUEENSTON FORMATION
RESERVOIR
RESERVOIR
km
0 1 2
CLINTON - CATARACT GROUP
LINEAR INDENTIFIED AT THE BASE OF THE ROCHESTER FORMATION
ST. DAVIDS BURIED GORGE
BURIED VALLEY
LOCKPORT FORMATION
ZONE OF TENSILE STRESS
USA
CANADA
GUELPH FORMATION
CRYSTAL BEACH BURIED CHANNEL SYSTEM
NIAGARA RIVER
SALINA FORMATION