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Hydrogeologic implications of a buried linear morphological feature in Essex County, Ontario.

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HYDROGEOLOGIC IMPLICATIONS OF A BURIED LINEAR MORPHOLOGICAL FEATURE IN ESSEX COUNTY, ONTARIO

by

Andrew M. Ainslie

A Thesis
Submitted to the Faculty of Graduate Studies and Research
through the Department of Geology in
Partial Fulfillment of the Requirements for the
Degree of Master of Science at the
University of Windsor

Windsor, Ontario, Canada

1991

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Abstract

The "freshwater aquifer" in Essex County, Ontario, is a thin granular aquifer which lies between the overlying till and underlying bedrock. Morris (1989) has identified a series of linear morphological features, which may be eskers, under the central part of Essex County and above the freshwater aquifer. Crnokrak (1991) and others in unrelated studies have identified an area of anomalously young groundwater in the freshwater aquifer by using the environmental isotopes oxygen-18, deuterium, and tritium. These two areas coincide.

Little is known about the freshwater aquifer, which supplies drinking water to thousands of rural users. The feature investigated in this study is located in Rochester Township east of Woodslee, and trends northwest-southeast. The purpose of this study is to verify the young groundwater noted by Crnokrak(1991), verify the presence of the feature noted by Morris (1989), and determine the hydrogeologic effect of this buried feature on groundwater recharge to the freshwater aquifer. Another objective is to determine if the feature is a recharge area, does water recharge vertically over the feature or does water recharge in the south and travel laterally along the feature. The objectives were addressed by a drilling program, hydrometric monitoring of the installed monitoring wells, and an isotopic and geochemical analysis of groundwater around the feature.

Water samples from nine installed wells and thirteen domestic wells, were analyzed for oxygen-18, tritium, and major ions. Soil samples were analyzed for grain size distribution, lithology, and stratigraphy. Pore water was squeezed from samples and analyzed for oxygen-18. Hydraulic heads, and hydraulic conductivities were determined at the wells to determine groundwater velocities along and perpendicular to the feature.

The young water is confirmed by the isotope study. Stratigraphy supports the theory that the feature is an esker. The tritium data indicates rapid infiltration over the feature. Groundwater flow along the feature from south to north is demonstrated by hydraulic heads, isotopic data, and chemical data. Groundwater flow away from the feature is also indicated by the hydraulic heads.

for Linda

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The author appreciates the assistance and advice of Osman, Jag, and Andy in both the field and labs. Thanks to Ian, Bruce, Mom and Dad for their editorial comments. Thanks also to Linda for her support.

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1.0 INTRODUCTION

The purpose of this study is to analyse the hydrogeologic implications of a linear morphological feature, believed to be buried esker, in Essex County. Crnokrak (1991) has identified an area of young water which coincides with the feature. The purpose of the study is to investigate the feature and its relationship to groundwater recharge.

1.1 Background

The "freshwater aquifer" is the main source of water for many rural residents in Essex County, Ontario. It consists of a layer of coarse sand and gravel plus the underlying fractured bedrock. Overlying the aquifer is a thick confining layer of clay till. This till layer is frequently over 30 m thick. Previous studies in the area have indicated that the clay till has low enough hydraulic conductivity for the material to be capable of safely containing landfills (Desaulniers et al., 1981). Hydraulic conductivity values for the till in this area from laboratory and field analysis are in the range of 10^{-8} to 10^{-7} cm/s (Desaulniers et al., 1981). Average linear porewater velocities in the unfractured till are less than 0.5 cm/yr. (Desaulniers et al., 1981).

Conventional drilling and monitoring methods may yield incorrect and low hydraulic conductivity values. A study by D'Astous et al. (1989) indicates that smearing from augers closes fractures and results in calculated hydraulic conductivities which are lower than actual values by up to 3 orders of magnitude. Fractures in the till may not be intersected by standard drilling methods because the frequency of these fractures decreases with depth. These fractures are difficult to recognize if unweathered. These unseen fractures may allow surface water down to the aquifer below the till sooner than expected (Keller et al., 1986). Therefore the hydraulic conductivity of this till may be higher than indicated by field tests.

Isotopic studies have shown that the water in the freshwater aquifer in central Essex County is much younger than it was expected to be (Crnokrak, 1991). Typically water this young would be found close to a recharge zone. However the area is remote from any obvious recharge zone and the freshwater aquifer is buried beneath a thick layer of relatively impervious clay till.

In an independent study, Morris (1988; 1989) identified linear morphological features buried below the thick clay till. These features were identified by light tones on remote sensing images which indicated areas of better drainage. One large linear morphological feature is coincident with the area of young water.

1.2 Objectives and Scope

The first objective of this study is to verify the anomalously young groundwater that was identified in central Essex County during previous studies by Crnokrak (1991; 1987) and MacGregor (1985). Previous studies used data from domestic wells. The seals of these wells may not be effective and the young water may not be representative of the freshwater aquifer but may represent surface water which has infiltrated along the annulus of the well. This study used drilled wells where the quality of the seal is better known.

The second objective of this study is to confirm the coincidence of young ground water and one of the linear morphological features noted by Morris (1989). This study will determine whether the target in question is an esker, and if it is somehow responsible for the young groundwater.

The third objective of this study is to analyze the hydrogeologic implications of buried eskers by examining the way these features affect groundwater movement both locally and regionally.

This study is limited to only two drill transects that are aligned roughly perpendicular to the linear feature. The feature does not have any surface expression. A deep well was installed approximately at the apex of the feature, based on data from Morris (personal communication), at each transect. Other deep wells were installed away from the feature. A nest of shallower wells was installed at each transect to provide an indication of vertical water movement. Nine wells were installed in the two transects and six of those were deep wells intersecting the freshwater aquifer.

A second part of the study used selected domestic wells, some of which were located in a transect perpendicular to the feature, and some of which lie in an orientation parallel to the feature. These were used to supplement the data from the drilled wells. There were thirteen domestic wells used in this study.

1.3 Structure of the Thesis

There are five chapters in this thesis. Chapter 1 gives a brief description of the background and identifies the objectives and limitations of this report. Chapter 2 describes the study area. This includes background information about the study area such as location, climate, and topography. It also discusses geology of the study area, including bedrock, and Quaternary geology, plus hydrogeology. Chapter 3 discusses methods of the study. This includes information about the drilling, soil sampling, monitoring well installation, grain size analysis, hydraulic head recording, single well tests, isotopic investigations, and major ion analyses. Chapter 4 discusses all the above tests, while highlighting the results of the geological investigations, hydraulic heads, single well tests, isotopic investigations, and major ions. The last part of this chapter contains a summary of findings. Chapter 5 contains conclusions and recommendations of the study.

2.0 THE STUDY AREA

2.1 Introduction

2.1.1 Location

The study area is situated entirely in Essex County, Ontario, Canada. Most of the study area is in Rochester Township, but it does extend into the surrounding townships (Figure 2.1). The entire area of interest lies between the latitudes 42° 09' N and 42° 15' N and longitudes 82° 35' W and 82° 55' W. The study area is covered by 1:50,000 scale National Topographic Series sheet 40 J/2, identified as the Essex Sheet. The hamlet of Woodslee in Rochester Township is close to the primary area under study.

2.1.2 Climate

The climate of Essex County is temperate. Warm humid air from the south covers the region in the summer, and cold dry air from the Arctic dominates the region in the winter. The climate is slightly modified by the surrounding Great Lakes and the proximity to the urban heat island generated by Detroit and Windsor (Sanderson, 1980). Temperatures at Woodslee indicate that the high monthly mean temperature is 21.7° C (July), the low monthly mean temperature is -4.4° C (January), and the annual mean temperature is 8.9° C. The Woodslee station receives a mean of 812 mm of precipitation annually (Sanderson, 1980).

2.1.3 Topography

The area is covered by the Essex Clay Plain, which is a subdivision of the St. Clair Clay

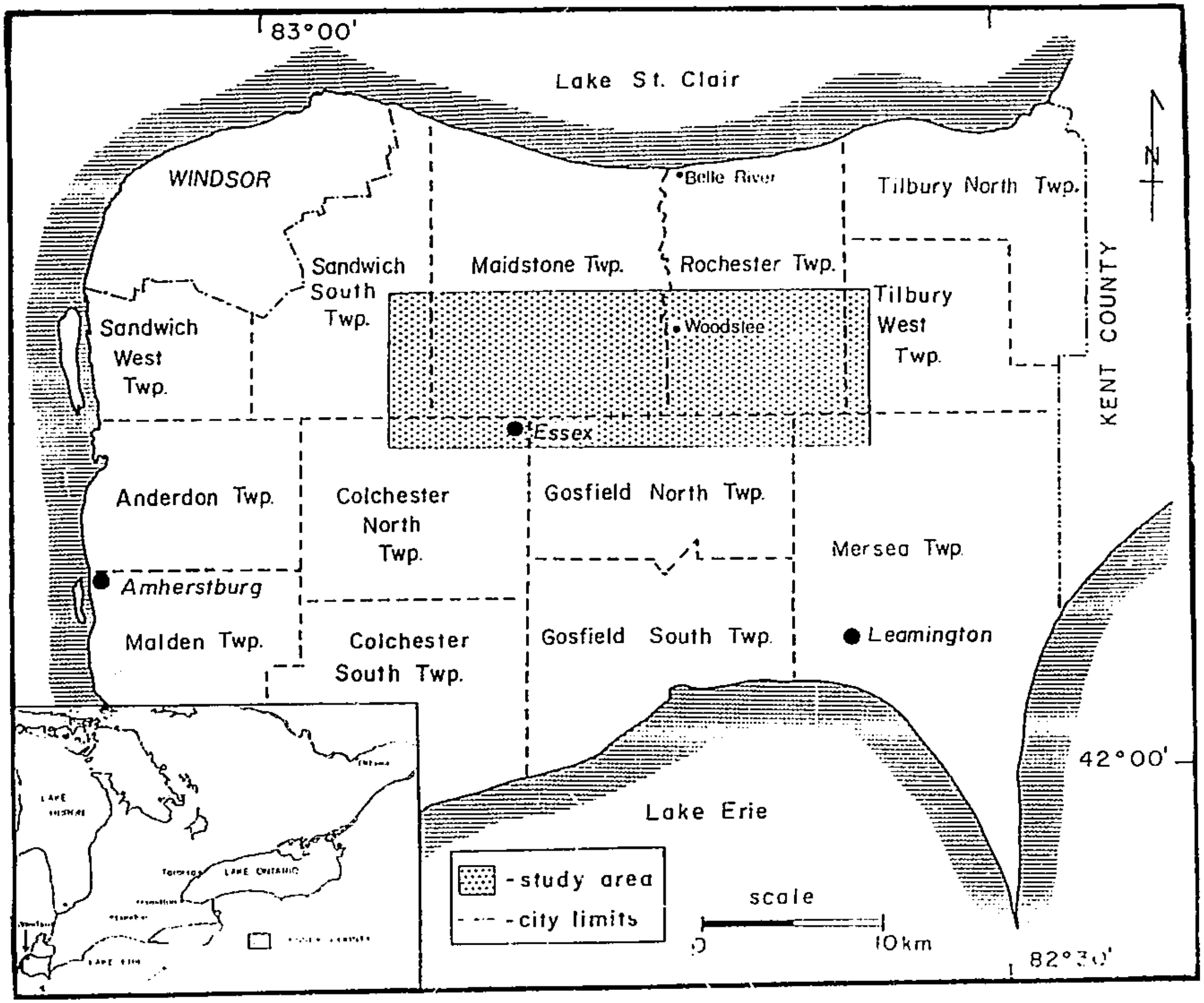

Figure 2.1 - Map of study area in Essex County.

Plain (Chapman and Putnam, 1984). This plain has very little topographic relief. The surface drainage generally flows to the north towards Lake St. Clair. The gradient is so small that some locations require ditches or drainage tiles to make the land useful for agriculture (Chapman and Putnam, 1984). There are, however, some very minor surface features in the study area.

Just east of Rochester Concession Road #2 and located to the north of the study area, is a north-south trending linear ridge. The relief of this ridge is 2-3 m above the clay plain. There are also many isolated knolls that are mainly composed of sand. These have very little relief with a maximum height of approximately 0.5 - 1.0 m above the clay plain. To the south in the Leamington area, a sandy moraine hill rises approximately 30 m above the surrounding clay plain. This feature, although deposited by glaciers, has been smoothed and reworked by wave action from post-glacial lakes (Chapman and Putnam, 1984). There is a group of sandy hills in the Harrow area that are considered to have been formed as sand bars in the post glacial lakes. The only other break in the flat topography of the clay plain is a low gravelly ridge running through Maidstone, Essex, and Cottam, on which Highway #3 is built (Chapman and Putnam, 1984).

2.2 Geology

2.2.1 Bedrock Geology

The bedrock of the area is listed in stratigraphic order in Appendix I. On the mainland of Essex County, there are no outcrops of bedrock. All the information is assembled from drill logs and quarries. Since the bedrock type is of interest to oil and gas companies, there has been extensive drilling in the area. A complete description of the stratigraphic assemblage is found in Sanford and Brady (1955).

Figure 2.2, from Sanford (1969), is a map of Devonian rocks that subcrop in the study area. The bedrock under the study area is primarily of the Dundee Formation. This formation consists mostly of fine grained limestone. The most northerly section of the study area may overlie some of the Hamilton Formation. This formation consists of members alternating between black shale and limestone. The southwest section of the study area may intersect part of the Detroit River Formation.

Figure 2.3 is a contour map of the bedrock surface (from Crnokrak, 1987). The highest bedrock elevations occur in the Leamington and Amherstburg areas. There is a bedrock valley underlying the eastern part of the study area.

2.2.1.1 Devonian Bedrock Geology

The following description of the Devonian geology subcropping Essex County is from Sanford and Brady (1955). The Bois Blanc Formation is the oldest formation of the Devonian. This formation and the Detroit River Formation can only be distinguished from one another if the Sylvania Sandstone, which would lie between the two formations, is present. The Sylvania Sandstone consists of loosely cemented large frosted quartz grains. The Bois Blanc Formation and the Detroit River Formation consist of buff to brown finely crystalline dolomite and grey dolomitic limestone. These formations may have a total thickness of 65 - 171 m. The Detroit River Formation is present throughout the area but is covered by the Dundee Formation, except in the southwestern part of Essex County where the Detroit River Formation subcrops the Quaternary deposits. The Dundee Formation contains fine grained clastic limestone. It ranges in

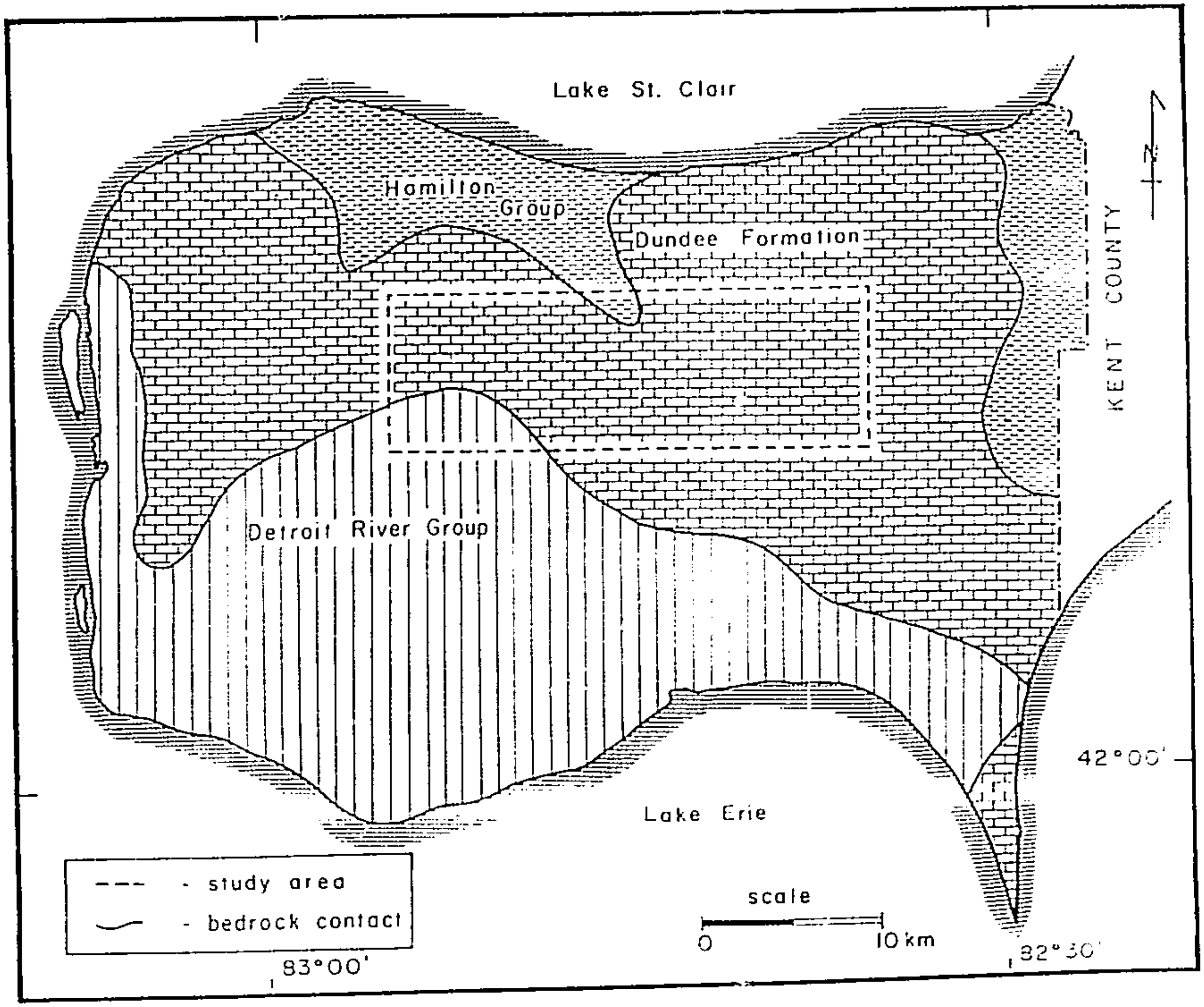

Figure 2.2 - Map of subcropping bedrock in Essex County

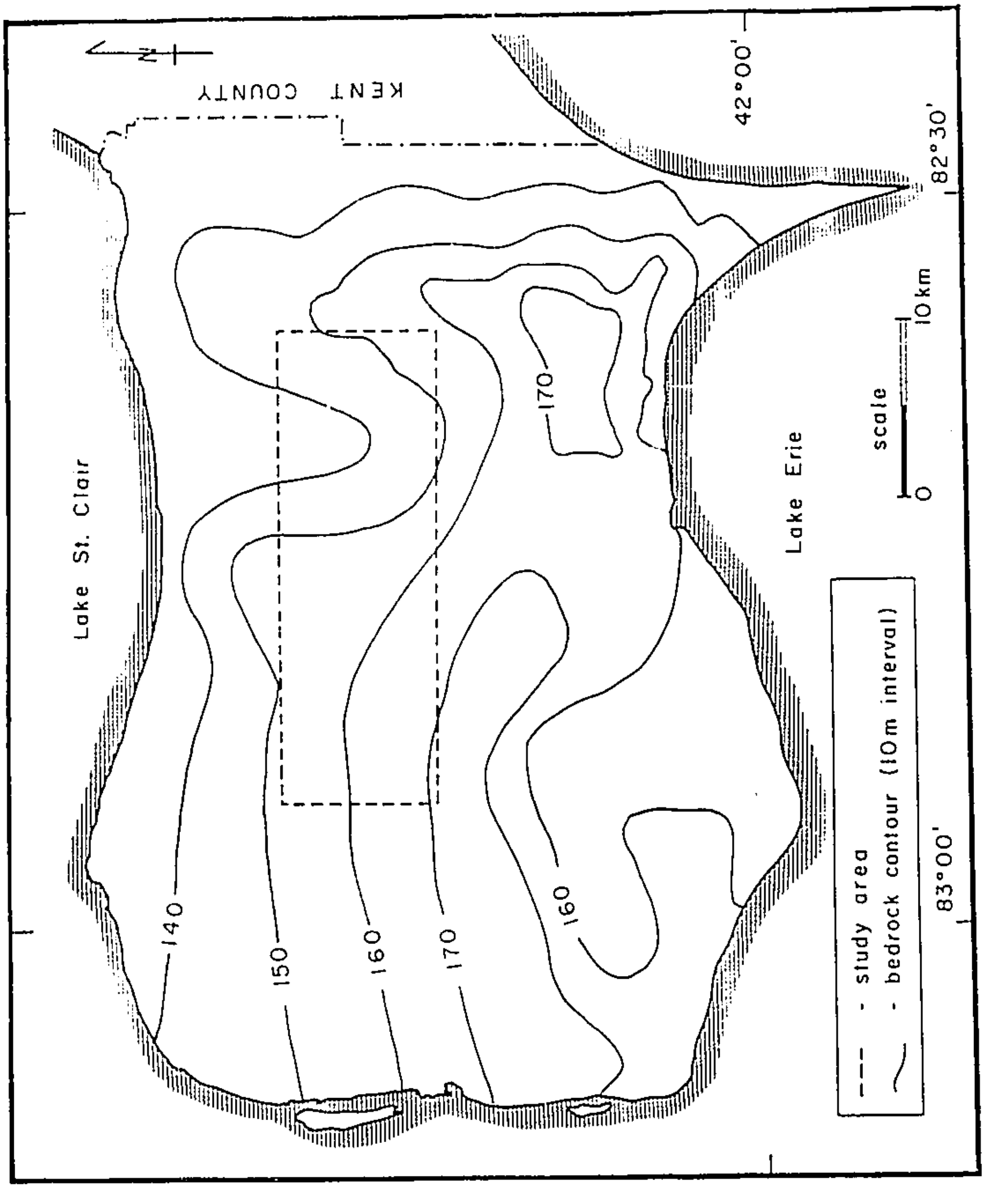

Figure 2.3 - Contour map of the bedrock surface in Essex County (contours in metres, from Crnokrak,1991)

thickness from 26 - 49 m and subcrops most of Essex County. The Dundee Formation is overlain by the Hamilton Formation, which is divided into four members. These members alternate shale with limestone. The combined thickness of these members may be over 91 m. The Hamilton Formation subcrops in most of Lambton and Kent Counties and has a small outlier in Maidstone Township in Essex County. This outlier subcrops the study area and contains the Olentangy Member. The Olentangy Member consists of soft, light grey, calcareous shale.

2.2.2 Quaternary Geology

The surface geology is shown in Figure 2.4 (Vagners,1972). The study area is covered by predominately clayey silt tills, however, there are a few scattered areas where the till is covered by a thin layer of medium grained sand. The southern parts of the county are covered by various sands (Vagners, 1972). The till unit consists of two textural units, a clayey silt till and a sandy silt till (Vagners,1972). Morris (1989) identifies two tills describing the lower one as a grey, clast poor, massive silty clay diamicton. The lower till may correlate to the Catfish Creek Till (Dreimanis 1961). These till units are fairly extensive throughout southern Ontario but are difficult to correlate because they can vary from site to site (Dreimanis, 1961).

The differences in the tills suggest that each unit was laid down during two different advances of the glaciers (Dreimanis and Reavely, 1953). Both Morris (1989) and Dreimanis (1961) suggest that the tills were probably deposited from an ice lobe extending out of the Lake Huron basin.

In a recent study, Morris (1989) identified several proglacial features, buried beneath

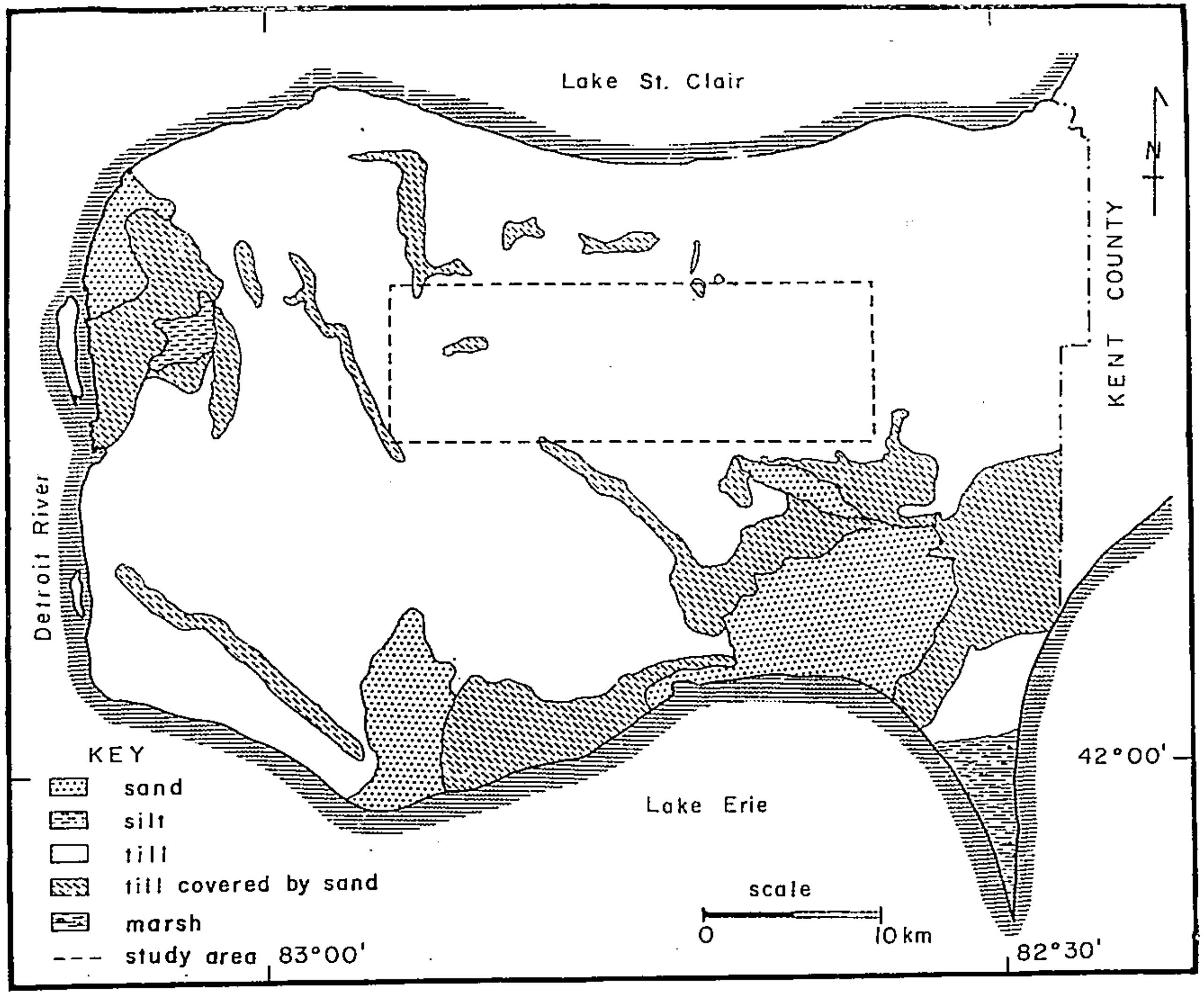

Figure 2.4 - Map of surficial geology in Essex County, (after Vagners, 1972).

the till. A proglacial delta was identified in an aggregate quarry to the south of the study area. Morris (1989) also identified several subaquatic proglacial fans, in the southern third of Essex County. In addition, he identified seven belts of recessional moraines, in the Amherstburg and Leamington areas, and five linear morphological features which may be eskers. Three of the linear morphological features are buried beneath the till. One of these buried linear morphological features, trending north-south, is the target of this study. Figure 2.5 shows the drift thickness for all of Essex County. The entire study area lies between the 30- 38 m (100 - 125') drift thickness contours (Vagners et. al, 1973).

2.3 Hydrogeology

2.3.1 Aquifers and Aquitards

The main water supply aquifer in the study area, known as the freshwater aquifer, is located at the bedrock-till interface. The clayey silt till that overlies the aquifer confines the freshwater aquifer throughout most of Essex County. The hydraulic conductivity of this till is reported to have values between 1.2×10^{-8} and 9.3×10^{-8} cm/s on the basis of lab tests and between 2.4×10^{-7} and 6.0×10^{-7} cm/s on the basis of field tests (Desaulniers et al., 1981). The porosity of the till varies between 0.31 - 0.37 (Desaulniers et al., 1981). The difference in the two hydraulic conductivity values was attributed by D'Astous et al. (1989) and Keller et al. (1986) to unseen fractures in the till.

Fracturing in the till may be a concern since this till was identified as being good for waste disposal (Desaulniers et al., 1981, Allendorf, 1981). If fracturing is extensive

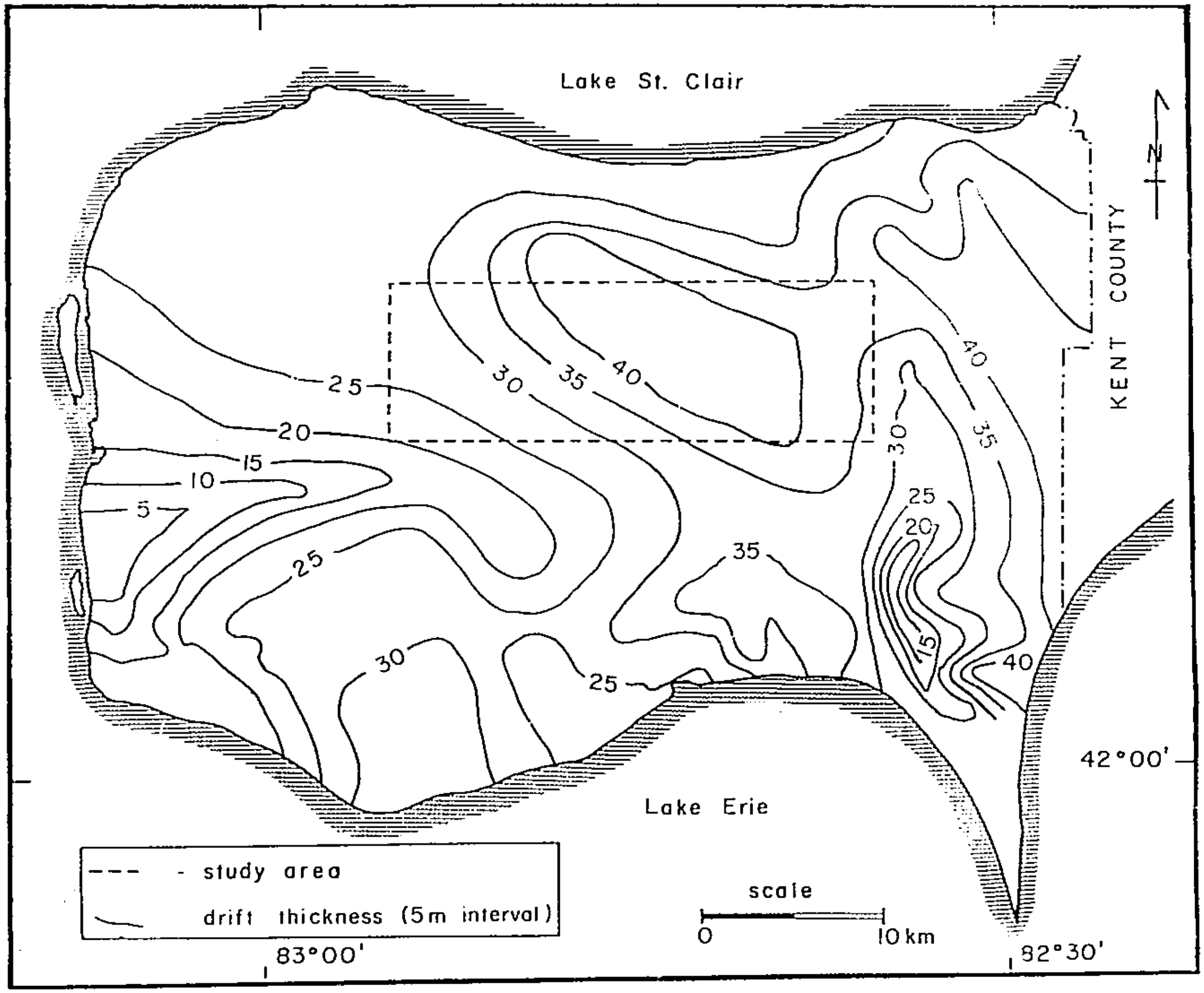

Figure 2.5 - Map of drift thickness in Essex County (contours are in metres, from Crnokrak, 1991).

and deep, surface water may be able to infiltrate and move through this till faster than otherwise expected. Also, throughout the till lie scattered discontinuous lenses of medium to coarse grained sand and gravel (Desaulniers et al., 1981). If these are mutually connected and connected to the surface, then surface water may have access to the aquifer by travelling through these lenses.

At the base of the clayey silt till is a mostly continuous layer of coarse sand and gravel (Intera, 1989). This is the freshwater aquifer for the region and it directly overlies the bedrock. In the Sarnia area, the freshwater aquifer is similar to the one f ound in Essex County. The average hydraulic conductivity for the granular aquifer is 5×10^{-6} m/s (Intera, 1989). The hydraulic conductivities of the freshwater aquifer, as reported by Intera (1989), lie between the range of 4×10^{-11} m/s to 2×10^{-3} m/s. The aquifer thickness ranges between 1 and 6 m and is thickest where it overlies valleys in the surface of the bedrock (Intera, 1989). The mean hydraulic conductivty for the freshwater aquifer in Essex County is 1×10^{-5} cm / s.

The bedrock under most of the study area is fractured limestone and dolomite. The fractured rock is also considered to be part of the freshwater aquifer (Intera, 1989). In the few areas where the underlying bedrock is shale, the aquifer is confined to the granular layer above the bedrock, unless the clay is fractured. The fractured limestones and dolomites yield substantial volumes of water. Wells in Wayne County, Michigan that penetrate too deeply may intersect brackish water (Mozola, 1969). The same principle is true for wells located in the northern part of Essex County.

2.3.2 Groundwater Flow Directions

The bedrock surface dips to the north as indicated on Figure 2.3 (from Crnokrak,1991). The hydraulic head distribution in the freshwater aquifer was plotted by Crnokrak (1991) and the resulting potentiometric surface is shown in Figure 2.6 (from Crnokrak, 1991). The hydraulic heads were determined from the static water levels from well logs (Ministry of the Environment, 1984). The potentiometric surface indicates that the groundwater radiates outward from a high in the Leamington area. Crnokrak (1991) determined the hydraulic gradient from the potentiometric surface map. The gradient is steeper to the south of this potentiometric high ($i=0.0043$) and less steep to the north of this feature ($i_{avg}=0.0011$). A combination of the bedrock topography, the surface topography, and the potentiometric surface of the freshwater aquifer suggest that the groundwater generally flows from the southern part of the county to the north through the study area. There are however, minor deviations from this general flow direction in the area. From the potentiometric map it is clear that the main recharge area for the freshwater aquifer in Essex County is the potentiometric and topographic high near Leamington. This corresponds to the Leamington Moraine as identified by Morris (1989) and Chapman and Putnam (1984). This feature is composed of sand and gravel, which allows the water to infiltrate the system and enter the aquifer. Crnokrak (1991) indicates that the groundwater flow radiates from the area of this sandy feature towards the discharge areas of Lake St. Clair, the Detroit River, and Lake Erie.

2.3.3 Groundwater Flow Rates

The horizontal flow rate in the freshwater aquifer in Essex County, just west of the study area, was determined by Dillon (1987) to be 2.5 m per year. This corresponds to

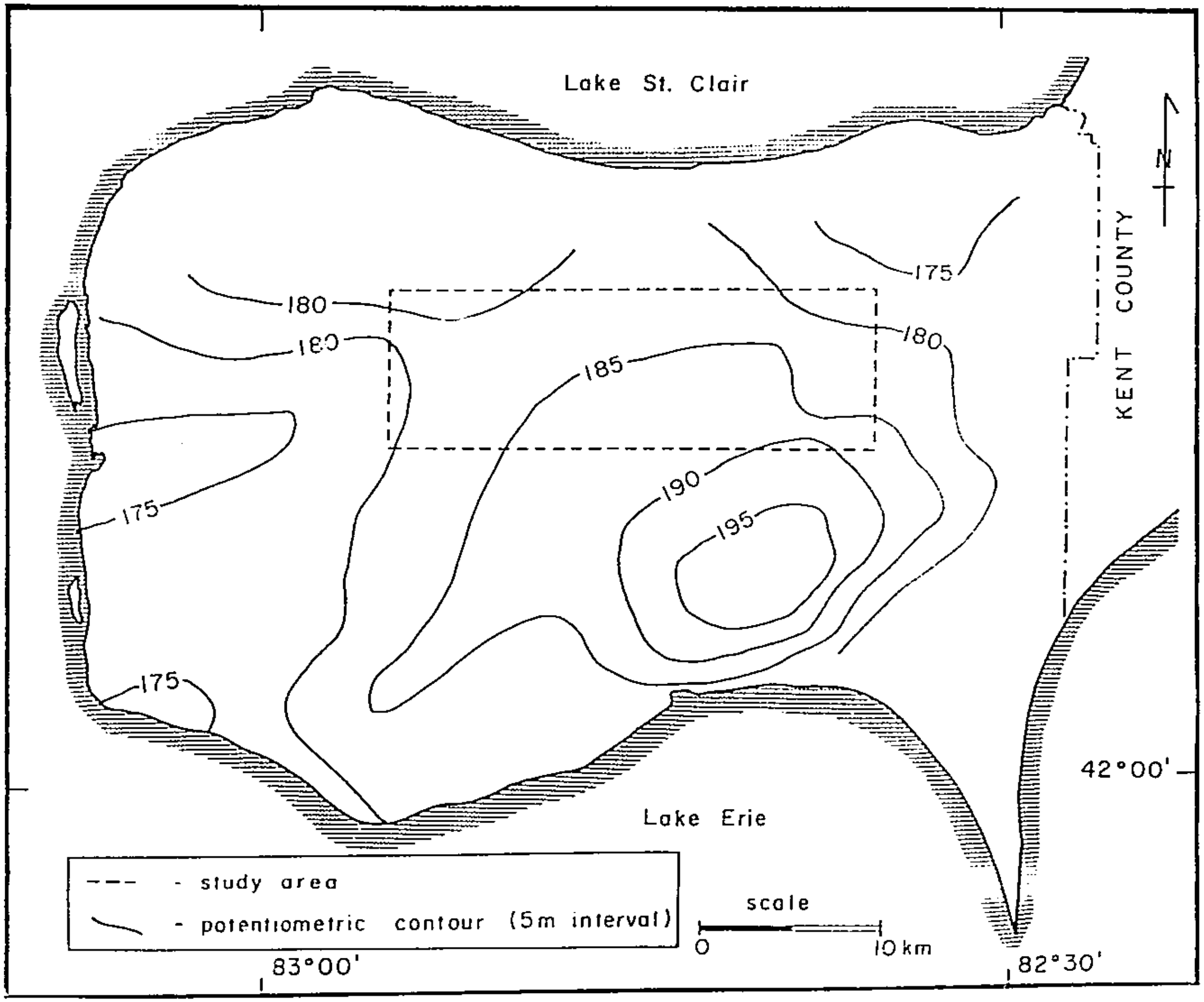

Figure 2.6 - Potentiometric surface of the freshwater aquifer (from Crnokrak, 1991).

the 3 m per year flow rate in the bedrock aquifer from eastern Michigan, as determined by Long et al. (1988).

The southern border of the study area is approximately 12 km from the recharge zone near Leamington. The northern border of the study area is approximately 21 km from the recharge zone. This was determined from the recharge area indicated by area within the highest potentiometric contour on Figure 2.6. Using Darcy's Law the groundwater in the aquifer at the southern border of the study area should have been recharged approximately 4,800 years ago, while groundwater from the aquifer at the northern border of the study area should have been recharged 8,400 years ago. These numbers are valid only if the recharge originated in the main recharge zone. The actual hydraulic conductivity and porosity values vary throughout the freshwater aquifer, and these variations will obviously affect the estimated values.

Oxygen-18 values from Crnokrak (1991) indicate that water in the freshwater aquifer in the northwest part of Essex County, which represents the oldest water in the county, was recharged at least 10,000 years before present. This area is approximately 45 km from the main recharge zone near Leamington. Velocity values indicate that this water should have been recharged approximately 18,000 years ago, if the recharge originated in the main recharge zone.

The vertical groundwater flow in the clayey aquitard was determined by Desaulniers et al. (1981) to be between 0.04 and 0.16 cm/yr. Carbon-14 analysis determined that the groundwater at the 20 m depth of the clayey aquitard in the study area, is between 8,770 and 9,870 years before present (Desaulniers et al., 1981).

2.3.4 Groundwater Chemistry

The chloride content from the freshwater aquifer is variable and ranges between 6 - 2, 600 ppm. The alkalinity ranges from 103 to 377 ppm as calcium carbonate. This water also contains between 0.1 - 1.8 ppm of iron (Dillon, 1987). In the study area the chloride content ranges between 9 - 515 ppm, and the alkalinity as bicarbonate ranges between 80 -493 ppm. The water often contains very noticeable amounts of hydrogen sulfide. Where the ground water comes up from deep formational bedrock it may be brackish. Some wells installed just to the south of Lake St. Clair are very salty and have a high chloride, sodium and even potassium content (Ibrahim, personal communication). For the most part the water from the freshwater aquifer is potable. Some locations have very minimal problems where there is not a high mineral content. Other places in the county, however, cannot use the water from the so called freshwater aquifer and have their water brought in from different sources.

3.0 METHODS OF STUDY

3.1 General Strategy

Drilled wells were installed to determine the stratigraphy over the feature. There is not any surface expression of the feature, therefore the drill sites were selected based on data from Morris (personal communication) and by access.

The installed wells would also provide water samples which would verify the young groundwater. The static water levels from these wells would determine the hydraulic gradients and groundwater flow directions. The installed wells would determine how the groundwater in the freshwater aquifer is laterally affected by the feature. Piezometric nests were installed to give an indication of the vertical groundwater flow.

Two transects of drilled wells, called the Series A wells, were used to locate the feature. One deep well at each site was drilled through the approximate apex of the feature. Additional wells were installed in a transect aligned perpendicular to the feature. A piezometric nest was installed along with the deep well installed in the feature at each site.

At the northern site, Site #1, well AMA-90-01 was targeted for the feature. AMA-90-02a was located approximately 25 m from AMA-90-01. AMA-90-02b is a shallow well designed to be part of a piezometric nest. AMA-90-03 was located approximately 200 m from AMA-90-01.

At the southern site, Site #2, well AMA-90-04a was located on top of the feature, while AMA-90-04b, and AMA-90-04c were part of a piezometric nest. AMA-90-05 and AMA-90-06 were located approximately 30 m and 80 m respectively from AMA-90-04a. This group of wells was placed parallel to the road, which was only roughly perpendicular to the feature.

A group of domestic wells, termed the Series B wells, was also sampled to assess flow patterns and provide additional information on a larger scale than could be provided by the relatively closely spaced drilled transects. Two transects of domestic wells were sampled. One transect ran parallel to the feature, which would indicate whether the ground water flows along it. The other transect was perpendicular to the feature, which would indicate the lateral effect of the feature. These domestic wells were selected so that the resulting data could be used.

3.2 Drilling, Soil Sampling and Monitoring Well Installation

3.2.1 Drilling and Soil Sampling

Most of the bore holes were drilled using a truck mounted CME Model 750 drilling rig equipped with hollow stem augers from Dominion Soil Investigations Inc (Windsor). The augers have a 159 mm outer diameter and a 75 mm inside diameter. Three holes at Site #2 were completed using a track mounted BOA-3M drill rig and solid stem augers. The sampling procedure was similar except that the solid stem augers had to be pulled out before sampling could take place.

In one hole, AMA-90-04a, the sampling devices could not retrieve a sample because the material was too coarse. The drilling progressed in a continuous flight without any sampling through the coarse material. The stratigraphy and geology was determined using the response of the drill and noting the material adhering to the augers at various levels.

In one other hole, AMA-90-06, the material was very wet, and collapsed when the solid stem augers were pulled out. When this occurred, rotary drilling was used. Lengths of 75 mm inside diameter steel casing were fed down the hole. The bottom section had a casing shoe attached, which was used as the bit. The casing was turned and then flushed with pressurized water. The cuttings would then be flushed out of the casing. The geology of the hole was assessed by examining the cuttings as they came to the top of the casing.

Sampling was generally done by split spoon, however, sampling of the till was done using Shelby tubes in holes AMA-90-01 and AMA-90-04a. Typically the sampling interval was 3.0 m, unless the geology required a more detailed sampling. After retrieval, the samples were examined, classified, and recorded. Split spoon samples were then put in heavy duty resealable clear plastic bags and labelled for subsequent grain size and hydrometric analysis. The material visible at the ends of the Shelby tubes was examined and classified. The Shelby tubes were immediately sealed with paraffin wax. After the wax solidified, the ends of the tubes were wrapped with clear "heavy duty" plastic and electrical tape. The plastic was then labelled and the tubes set aside for later sample extraction.

3.2.2 Sample Extraction

The material in the Shelby tubes was extracted using a Shelby tube extractor (Figure 3.1). The tube was locked into a vise and the material was extruded into a long plastic bag by turning a large screw. Most samples required two bags taped together with electrical tape. The stratigraphy and geology of the material were recorded. Aluminum foil was then wrapped around the sample with its shiny side towards the sample, to reduce the effects of heat and to minimize evaporation. The samples were sealed with more electrical tape. The sealed samples were stored in a cool (15° C) dark room for not more than a week before the pore water extraction was undertaken.

3.2.3 Monitoring Wells

Monitoring wells were installed in the drill holes to measure piezometric heads and obtain water samples. The wells consist of flush threaded schedule 40 PVC pipe, with "O" rings at the joints. There were two different diameters used for the wells, 50 mm (2 inch) inside diameter and 32 mm (1.25 inch) inside diameter. The well screens are a slotted PVC #10 screen size with a slot width of 0.025 mm (0.01 inches). Each well was installed with an appropriate length of screen, a lower bentonite seal and an upper bentonite seal. The length of screen was determined by the nature of the aquifer, but typically was 1.5 m.

A sand pack of industrial coarse grained quartz sand was installed if it was deemed necessary. The bentonite seals were made of 9.5 mm (3/8 inch) Bentonite tablets under the brand name Volclay ®. These pellets were poured down the annulus after the sand was added or the natural sand pack was given time to collapse around the well screen. The hole was then infilled with the drill cuttings. Care was taken so that the cuttings

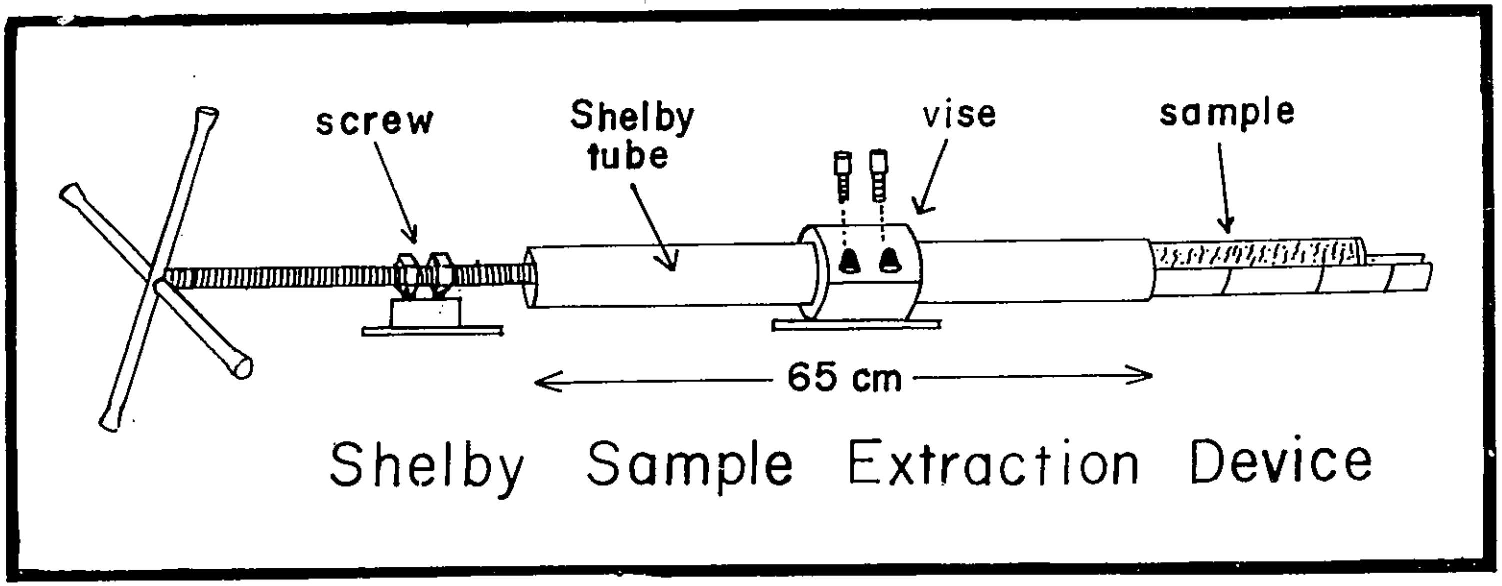

Figure 3.1 - Shelby tube sample extraction apparatus

would not get stuck part of the way down and thus not entirely fill the hole. When the cuttings reached 1.5 m below the surface another bentonite seal was installed. The remaining part of the hole was back filled.

The first four wells, at Site #1, were installed with approximately 0.3 to 0.5 m of pipe extending from the ground. With these wells the cuttings were mounded up against the well pipe. This apron was installed to prevent surface water from flowing down the annulus. The remaining five wells, at Site #2, were cut off at ground level. Local drainage was modified to keep surface water away from the mouths of the wells. Extension pipes were added to the wells so that the tops of the wells would not be submerged in times of high water. These extensions were fastened to the wells by PVC pipe connectors. After all the tests had been completed and all samples retrieved, wells at the first site were cut off to ground level. Then all wells were covered with steel well covers set in a bentonite seal. Table 3.1 gives the depth of completion, the diameter of the pipe, the length of screen, length of pipe, the thickness of the sand pack, the thickness of the bottom bentonite seal, and the thickness of the top bentonite seal for each well.

At Site #1 all three of the boreholes (AMA-90-01, AMA-90-02a, and AMA-90-03) filled with water before the bentonite was added. This may have affected the quality of the seal since the pellets might have started to expand as they sank through the column of water. The seal, therefore, may not have been as tightly compressed as was required. The isotopic data from the water samples indicate that the seals were sufficient. Wells AMA-90-01 and AMA-90-03 are both artesian. Well AMA-90-04a did not have an artificial sand pack installed, however, the sand may not have caved in and the bentonite

Table 3.1 : Monitoring well characteristics.

Well #	Depth (m)	Pipe Diameter (mm)	Screen Length (m)	Pipe Length (m)	Height of Sand Pack (m)	Height of Bottom Seal (m)	Height of Top Seal (m)
AMA-90-01	31.70	50	3.0	28.7	n.c.i.*	1.5	0.61
AMA-90-02a	27.80	50	1.5	26.3	n.c.i.	0.61	0.61
AMA-90-02b	7.62	50	1.5	6.12	1.83	0.3	0.46
AMA-90-03	31.09	32	1.5	29.59	n.c.i.	0.61	0.61
AMA-90-04a	30.48	50	1.5	28.98	1.83	0.46	0.46
AMA-90-04b	23.16	32	1.5	21.66	n.c.i.	0.3	0.46
AMA-90-04c	7.62	32	1.5	6.12	1.83	0.3	0.46
AMA-90-05	33.68	50	1.5	31.85	n.c.i.	0.61	0.61
AMA-90-06	34.14	32	1.5	32.64	n.c.i.	0.46	0.3

* natural cave in

could have plugged the screen. The hydraulic response from these wells is slow.

3.3 Grain Size Distributions

Methods used for the grain size and hydrometric analysis are found in Lambe (1951). All of the samples were analyzed using a combination of the sieve analysis and hydrometric analysis.

3.4 Hydraulic Heads

The hydraulic heads of the installed wells were measured using a Solinst Model #101 flat tape electric contact gauge and a Solinst P2 probe. The various wells at each Series A site were tied into each other by a differential levelling survey to establish the relative elevation of each well. The relative elevation and the water levels are used together to calculate the relative hydraulic heads.

At Site #1, all three deep wells (AMA-90-01, AMA-90-02a, and AMA-90-03) are flowing. To determine the height of the static water level, extension pipes were added to the top of the casing until the water no longer flowed. The water level was then measured from the top of the pipe once the water reached static level. The height of the additional pipe was measured and the elevation of the water level above ground was determined.

Hydraulic heads from the domestic wells were calculated from the static water levels and elevations recorded in the published well records (Ministry of the Environment Well Records, 1984). The depth to static water level was subtracted from the elevation of the site to obtain the hydraulic heads. If the records for a particular well were not available, the information was estimated from a nearby well.

3.5 Single Well Tests

Single well tests to determine hydraulic conductivity were performed on the Series A wells. The method described by Hvorslev (1951) was used to directly determine the hydraulic conductivity of the immediate area surrounding the wells. Most of the analysis was done by bail tests although some wells were analyzed using both the slug and bail tests.

The Hvorslev method is used for short screened piezometers and assumes that the piezometer screen is installed in a homogeneous, isotropic, infinite medium. This method also assumes that the formational material and the water are both incompressible.

Hydraulic conductivity (K) can be determined using the following equation:

$$K = (r^2 \ln (L/R))/(2 L T_0)$$

where:

$L =$ length of the screen.

$R =$ radius of the screen

$r =$ radius of the casing.

$T_0 =$ basic time lag. This value is read from a graph.

Unless the screen was installed in coarse sand and gravel, the radius of the screen was the radius of the borehole. The single well tests may be affected by the completion of the well. These tests may provide unreliable hydraulic conductivity values if the wells were surged. The hydraulic conductivity value in this case represents the artificial sand pack as the fines have been washed away. In the case of some of the drilled wells for this project, some of the natural sand packs may not have been developed well enough. This would provide an artificially low hydraulic conductivity.

3.6 Isotopic Investigations

3.6.1 Theoretical Considerations

Naturally occurring isotopes can be used to determine the history of the groundwater or they can be used to determine the origin of the groundwater (Fontes, 1980). If the water does not mix with any other water, the isotopic content will remain the same as the time when it was recharged. The isotopes can be used to determine the atmospheric conditions at the time of recharge, and this will give an indication when recharge occurred. If the water does mix with isotopically different water, the history of mixing can be determined using the isotopic content. Radioactive isotopes decay at a known constant rate. The age of the water can be determined by the amount of decay that has taken place, if the initial concentration of the isotope is known.

The isotopes used most often by hydrogeologists, oxygen -18 (^{18}O), deuterium (^{2}H), and tritium (^{3}H), are constituents of the water molecule. The ^{18}O atom makes up 0.1995 % of all oxygen atoms. The ^{2}H (D) atom makes up 0.0156% of all the hydrogen atoms (Hoefs, 1973). The concentration of the ^{3}H (T) atom is measured in tritium units (TU), where one tritium unit represents one ^{3}H atom in 10^{18} hydrogen atoms.

The absolute quantity of ^{18}O and ^{2}H in water samples is very difficult to determine, so for most purposes, a ratio of the heavy isotope to light isotope is adequate. When this ratio is compared to a standard value, the relative difference is an indication of the isotopic content. R is the ratio of the heavy isotope divided by light isotope. The relative difference is called delta or del value (∂) and is measured in parts per mille ($^{o}/_{oo}$). The ratio is represented by (Craig, 1961):

$$\partial_x \, ^{o}/_{oo} = [(R_x - R_s) / R_s] \times 1000$$

where x is the sample, s is the standard. The standard for oxygen and hydrogen isotopes is SMOW (standard mean ocean water). A negative del value indicates that the water is depleted or has fewer of the heavy isotopes relative to SMOW, and a positive value indicates that the water is enriched in the heavy isotopes relative to SMOW (Fontes, 1980).

The relationship between $\partial\, ^{18}O$ and latitude, which is temperature related, is indicated on Figure 3.2 from Dansgaard (1964). Summer precipitation is enriched in the heavier isotopes, due to the higher temperatures, while winter precipitation is depleted in the heavier isotopes. The groundwater takes on a dampened version of the atmospheric and meteoric isotopic conditions.

Oxygen -18 data from marl and cellulose materials indicate that there was a general cooling of the post-glacial climate, which provides a good marker for ^{18}O dating (Edwards and Fritz, 1988). The cellulose materials were carbon-14 dated to get an accurate date corresponding to the oxygen-18 data (Edwards and Fritz, 1988).

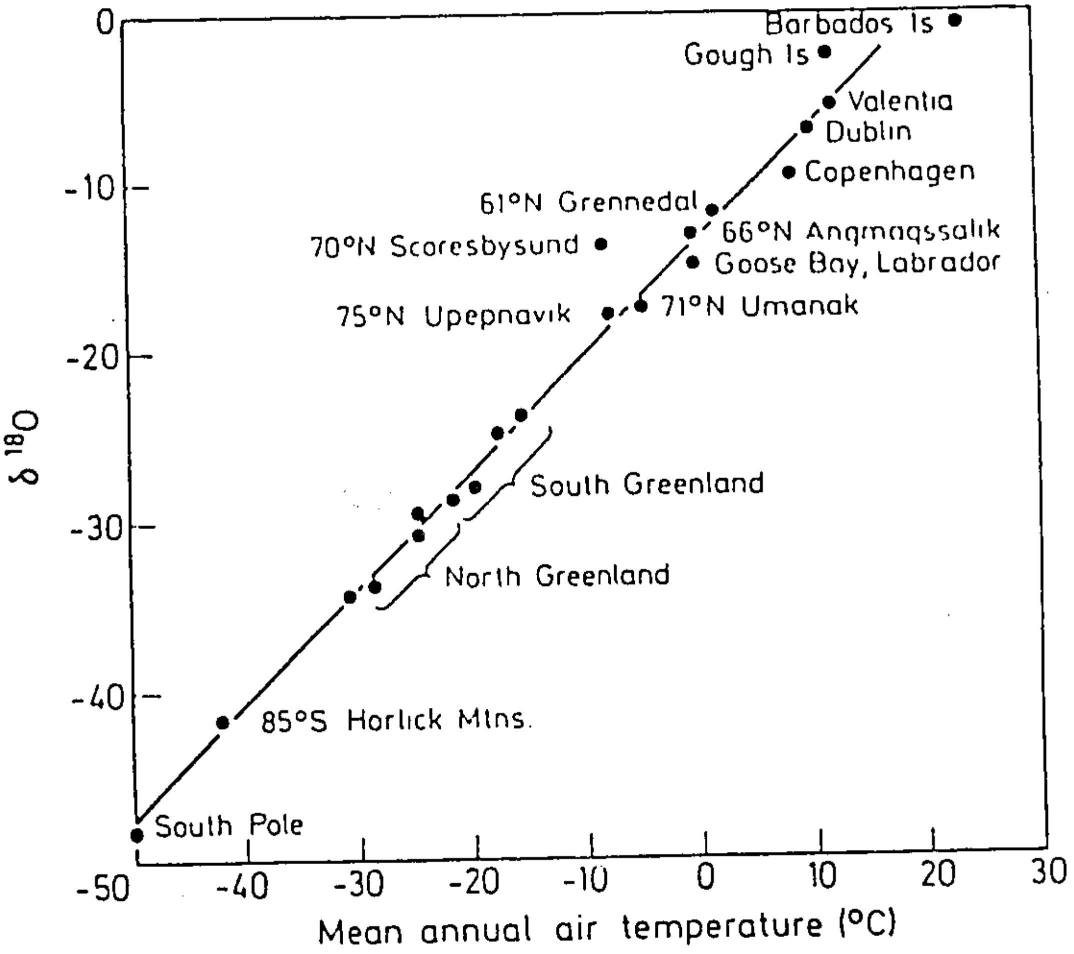

Figure 3.2 - Diagram of ∂ ^{18}O versus temperature (Dansgaard, 1964).

Tritium, a radioactive isotope of hydrogen, has a half life of 12.35 years (Egboka et al.,1983). Tritium is naturally produced when cosmic rays bombard nitrogen. Before 1953 the atmospheric tritium levels were approximately 15 TU in the Ottawa Valley (Brown, 1961). Any water that was recharged prior to 1953 will now be less than 2 TU because of radioactive decay.

Atmospheric nuclear tests were first conducted in 1953. These tests produced and injected large amounts of tritium into the atmosphere. The greatest number of tests per year were conducted in the years 1962 and 1958 (Egboka et al., 1983). By 1963 the maximum monthly levels of tritium in the atmosphere were close to 4000 TU in the region around Windsor (Egboka et al., 1983). Since 1963, after the ban on atmospheric nuclear tests, there has been a steady decline in the amount of tritium in the atmosphere. Figure 3.3 shows the tritium in precipitation profiles with time.

This anthropogenic or "bomb" tritium provides an excellent marker for recently recharged water and can also be used to indicate dispersion of the groundwater (Egboka et al., 1983). If water was recharged within the past 40 years then it contains relatively large quantities of tritium. The amount of tritium in the atmosphere will steadily decrease from the 1963 levels until the anthropogenic tritium is indistinguishable from naturally produced tritium.

Tritium can be measured by counting the radioactive decays on a scintillation counter. A more accurate count can be obtained by enriching the sample and then determining the tritium count.

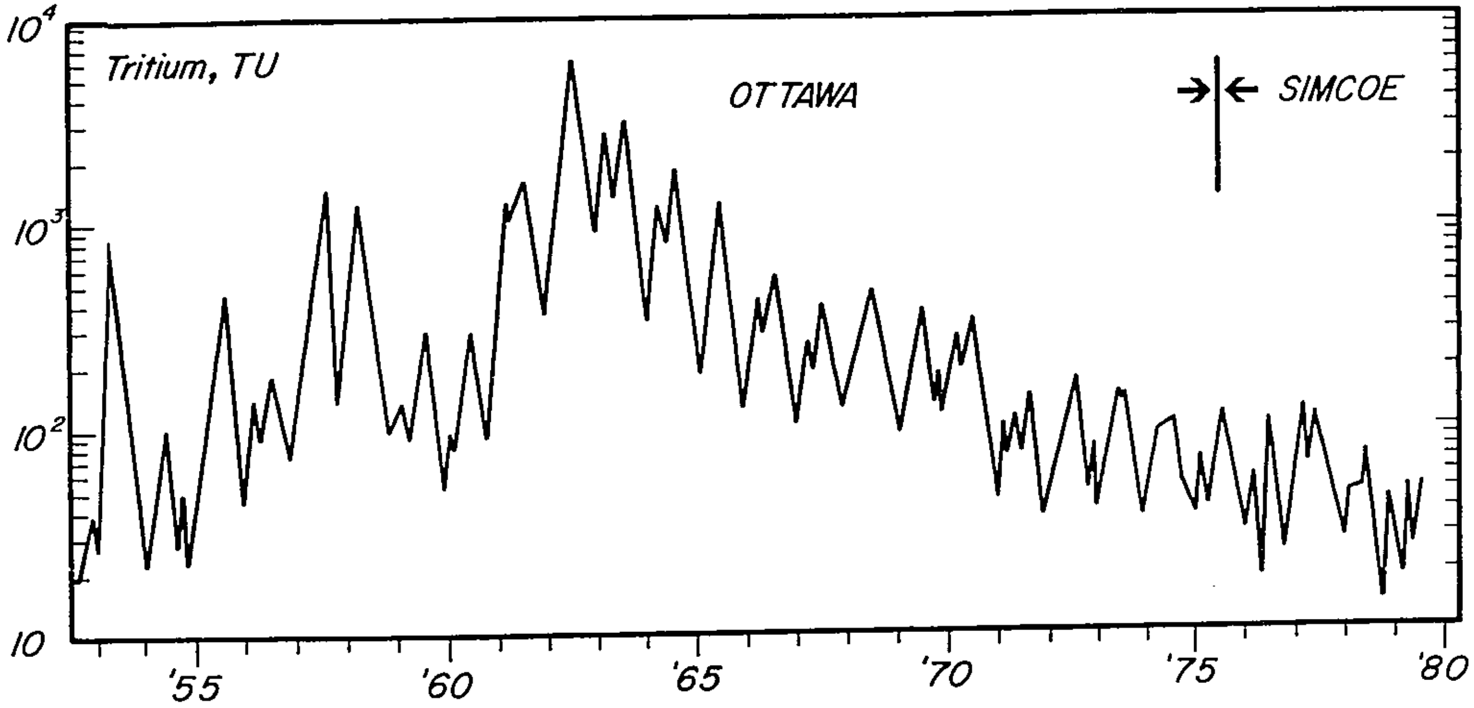

Figure 3.3 - Diagram of tritium versus time in the atmosphere

3.6.2 Soil Squeezing

Holes AMA-90-01, from Site #1, and AMA-90-04a, from Site #2 were sampled using Shelby tubes. Shelby samples were taken every 3 m throughout the entire length of the hole. The samples were sealed in the tubes with wax, until they were extracted using a Shelby tube extraction device (Figure 3.1) at Dominion Soil Investigations Inc. in Windsor. Samples were kept in a cool (15° C), dark room until they were squeezed. The isotopic content of the extracted porewater from each sample is representative of the water at this level. The measured $\partial\,^{18}O$ values gives an isotopic profile of the hole. The profile reflects the recharge history and reflects the vertical groundwater flow tale.

The samples were squeezed with a porewater extraction cell (Figure 3.4 , from Orpwood, 1984). The apparatus was made of a heavy duty stainless steel cylinder. On the bottom of the cylinder was a steel perforated drainage disk. Attached to the drainage disk was a stainless steel base with a drainage port. Both of these pieces fit snugly into the cylinder and were sealed using rubber "O" rings.

A 19 cm long section of core was cut from the main sample. This was quickly wrapped in a Whatman #1 filter at both ends. Two coffee filters were wrapped around each end so that all of the sample was covered. Any part of the sample that was not covered would allow sediment to get squeezed out with the pore water. The sample was then placed in the cylinder and capped with a small stainless steel disk that fit snugly inside the cylinder. A large plunger was placed on top of the lid and a 5 tonne hydraulic jack was placed between the plunger and a secured steel bar. The jack was pumped until the pressure gauge read 1.379×10^{7} Pa (2000 psi), which represents the minimum pressure required to get water out of the sample. The pressure of the jack forced the

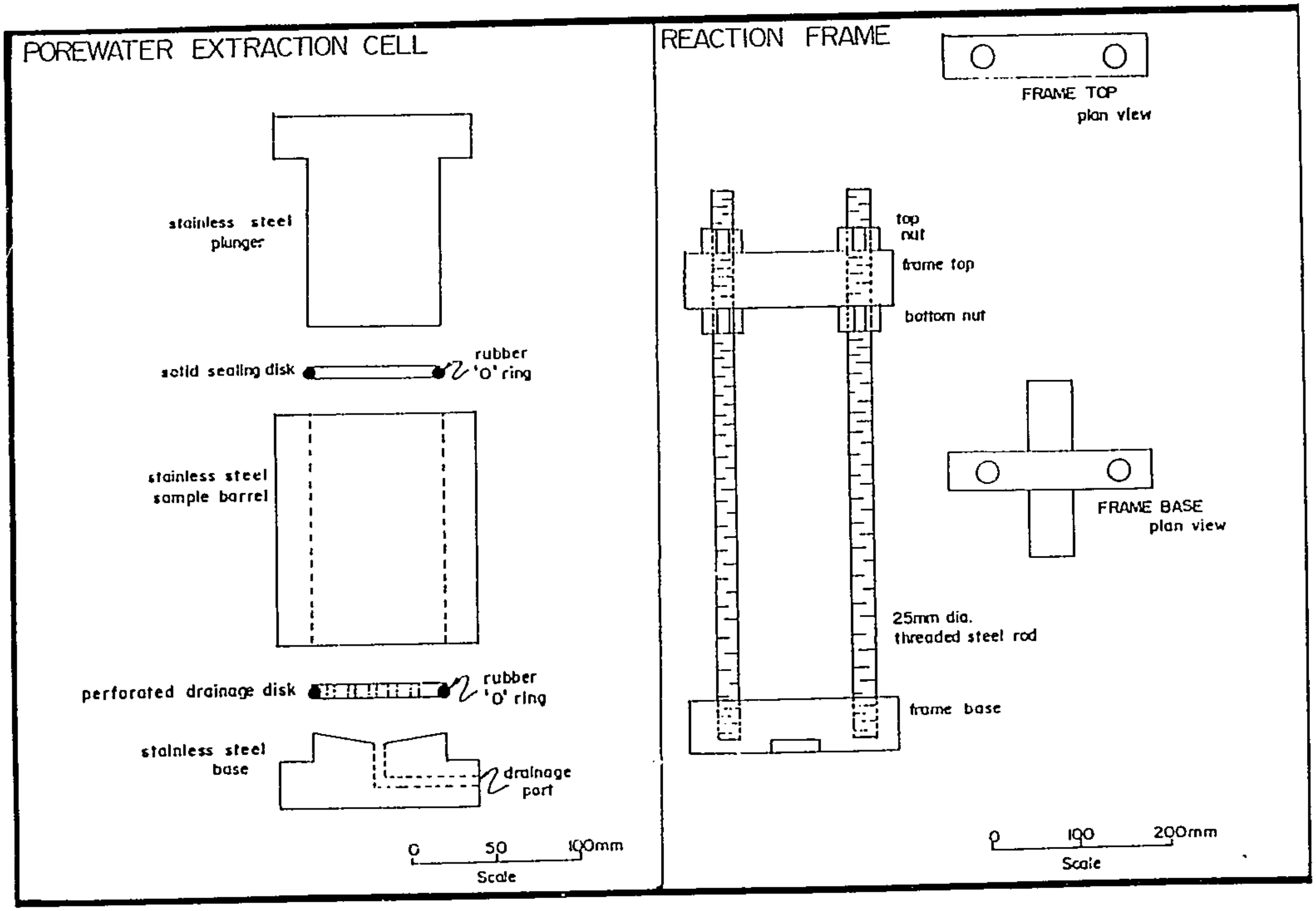

Figure 3.4 - Diagram of porewater extraction cell (Orpwood, 1984).

plunger down and squeezed the water out of the intergranular pore spaces.

When water started coming out of the drainage port, a pair of rubber tubes were attached to the spout. A larger tube fit directly onto the spout with a smaller tube attached to its other end. When the smaller tube was filled with water, a glass syringe was attached to it. The water sample was under enough pressure that it would fill the syringe and push out the glass plunger in the syringe. This method was used to minimize evaporation. Precautions were taken throughout the entire process to ensure a minimum of evaporation.

Pressure from the hydraulic jack was increased slowly to a maximum of 3.4475×10^{7} Pa (5000 psi). When the syringe was filled with approximately 20 mL of pore water, it was removed and the water was transferred into two 8 mL glass vials. The threads of the vials were wrapped in Teflon® tape and the vials were labelled. The tape made an effective seal and prevented evaporation of the sample.

Sometimes the squeezing of two or more sections of sample was required to produce an adequate amount of porewater. If this was necessary, the original sample was removed and the cylinder, screen, lid, and water collecting apparatus were thoroughly cleaned and dried before the next sample was inserted. The water samples were then prepared for $\partial^{18}O$ analysis.

3.6.3 Isotopic Investigations

Previous studies by Crnokrak (1987, 1991), and MacGregor (1985), have determined the distribution of ^{18}O and ^{3}H in the freshwater aquifer in Essex County. These studies have shown that the $\partial\,^{18}O$ values show a progressive depletion radiating northward from the Leamington area. Figure 3.5 shows a map of the results from the previous isotopic studies. The contours are based on data from 36 domestic wells.

Contour lines of equal $\partial\,^{18}O$ values tend to be parallel and trend in an east-west direction. In the middle of Essex County lies an area where the contours deviate northward. In this area, water is less depleted than one would expect. Crnokrak (1991) suggested that this water has been recharged from the surface more recently than the water in the surrounding area. This anomalously young water coincides with buried linear morphological features located by Morris (1989).

A tritium map, shown on Figure 3.6 from Crnokrak (1991), shows a pocket of tritiated water (eg. >20 TU) in the same area as the $\partial\,^{18}O$ anomaly. This tritiated water represents groundwater that has been recharged within the past 40 years.

One interpretation for this anomalously young water stems from the fact that all the data used by Crnokrak (1991) and MacGregor (1985) were collected from domestic wells. These wells may not have been sealed properly and meteoric water may be infiltrating down the annulus of the well. This hypothesis may be true but it is unlikely that all the wells in this area, which were drilled and completed by different drilling companies and drillers, were not sealed properly. Other wells in the county seem to be constructed and completed in an acceptable manner. However it may be possible that the geology of the area prevented a proper seal from being installed.

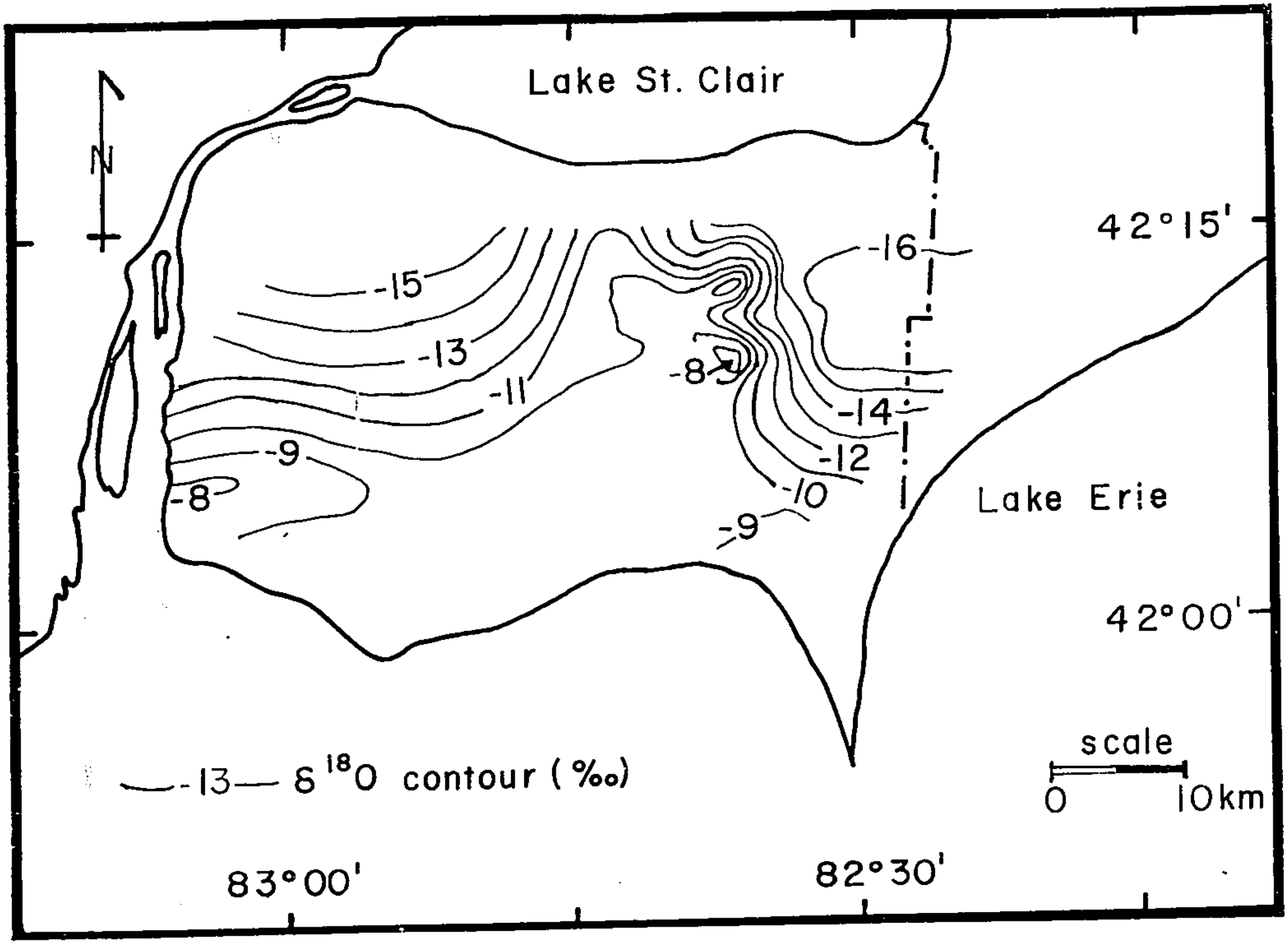

Figure 3.5 - Map of $\partial\ ^{18}O$ distribution in Essex County (Crnokrak, 1991).

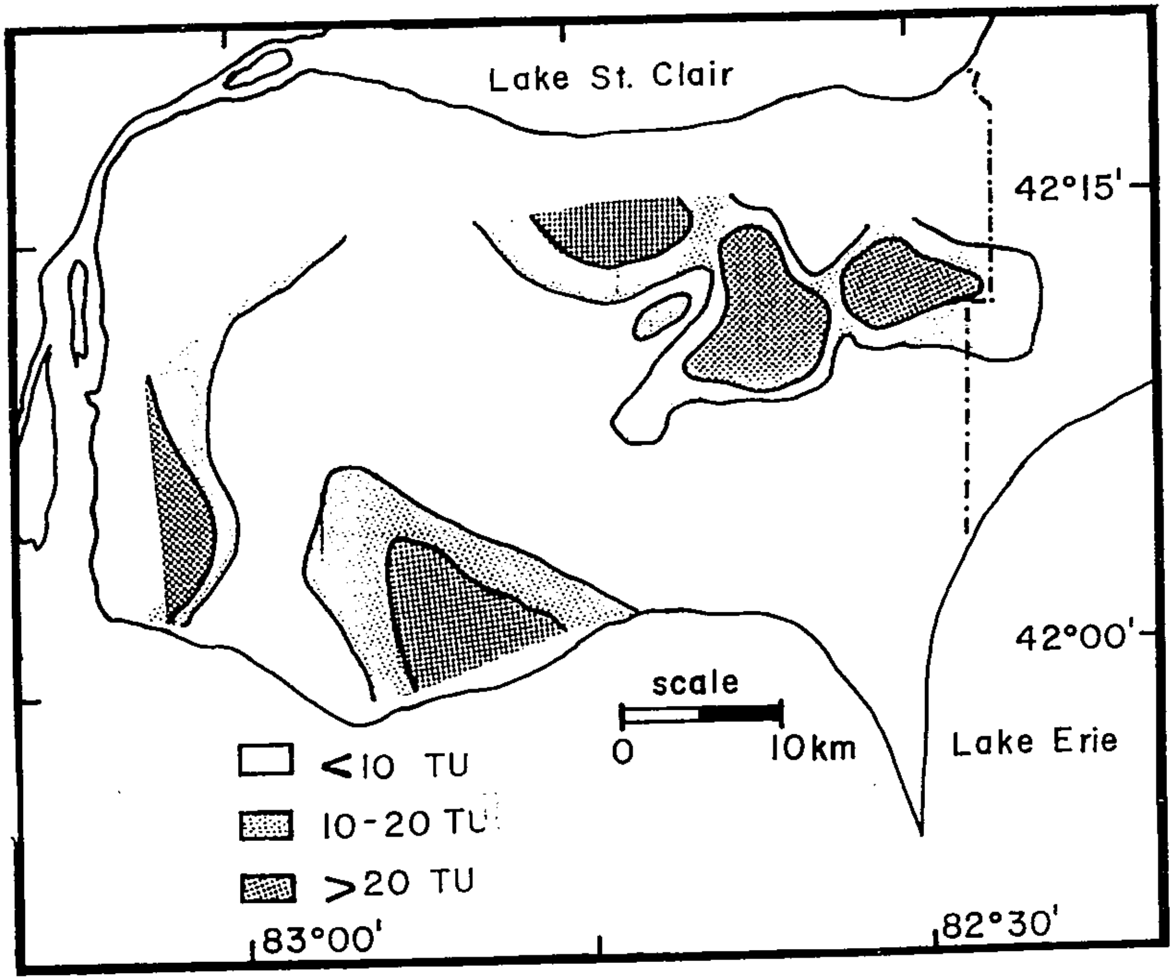

Figure 3.6 - Map of tritium distribution in Essex County (Crnokrak, 1991).

3.6.4 Sampling and Sample Preparation

Water samples from both the Series A and B wells were analyzed for ^{18}O. The Series A wells each had at least three well volumes of water removed prior to sampling. The wells were pumped with a motorized Wattera® pump. The samples were poured into 8 mL glass vials which were capped after wrapping the threads with Teflon® tape to prevent evaporation.

The Series B wells were usually connected to the plumbing inside the house. Only wells that drew water from the rock overburden interface, or from the shallow bedrock zones were selected. For the purposes of this study, water from these wells could not go through a water softener nor could it run through a pressure tank, if it could be avoided. The taps were run for ten to fifteen minutes before a sample was taken. These samples were put in 8 mL glass vials and sealed. In some locations, the pressure tanks were drained to get fresh water which would be representative of the aquifer. At AMA-B-08, the water was taken directly from the top of the well before it entered the plumbing system.

All samples were prepared for $\partial\, ^{18}O$ analysis in the isotope extraction lab at the University of Windsor using the extraction procedure described by Epstein and Mayeda (1953). They were reacted with carbon dioxide (CO_2), then sealed in 14 cm glass tubes, and sent to the University of Ottawa to be analyzed on a SIRA-12 Mass Spectrometer. Standards of known $\partial\, ^{18}O$ value were run on every tenth sample to check for procedure and equipment errors.

For the tritium samples, all the Series A wells were pumped as noted above. These samples were put in 1 L glass jars, sealed immediately, and sent for analysis. The samples from the Series A wells were analyzed using the enriched method for tritium on a liquid scintillation counter in the isotope lab at the University of Waterloo. This method is accurate within +/- 0.6 TU. The Series B well samples were put in 500 mL nalgene bottles and immediately sent for analysis using the direct tritium method on a liquid scintillation counter in the isotope lab at the University of Waterloo. This method has a precision of +/-8 TU.

3.7 Major Ions

All samples were filtered through Whatman #5 filters before any analysis was undertaken. All equipment used for filtration was acid washed. The filters were then wetted with a 10% nitric acid (HNO_2) solution and some of the sample was poured into a funnel through the filter into a container. The container was rinsed with the filtered sample and that portion of the sample was discarded. This was done to wash away possible contaminants that might have been in the filter paper, funnel and container. The remaining portion of sample was then filtered.

To prevent the ions from coming out of solution, 5 mL of concentrated nitric acid were added for every 1000 mL of sample. Two duplicate samples were prepared as above but without the acid to determine its effects.

The major cations calcium (Ca^{+}), sodium (Na^{+}), potassium (K^{+}), and magnesium (Mg+), were analyzed by atomic absorption on a Varian Model SP300 Atomic Absorption

Spectrometer in the Geochemistry Lab at the University of Windsor. A blank was analyzed first followed by the standards, from the lowest to the highest concentration. A standard was analyzed every ten samples to maintain a check on the precision of the analysis.

The sulfate anion (SO_4^-) was analyzed on a PYE UNICAM SP6-300 Spectrophotometer in the Geochemistry Lab at the University of Windsor. The method used is a combined method from the American Public Health Association (1976) and Hach Chemical Company (1975).

The bicarbonate anion (HCO_3^-) was measured using an acid titration technique in the field. The technique used is a standard one used in the Geochemistry Lab at the University of Windsor.

The chloride (Cl^-) ion was determined using an Orion Microprocessor Ionalyzer (Model #901), with a Chloride Electrode (Model # 94-17B), and a Double Junction Reference Electrode (Model # 90-02). These analyses were completed in the Department of Civil and Environmental Engineering at the University of Windsor. The method used is described in the manual for the ionalyzer (Orion, 1983).

The electrical conductivity, temperature, and pH of the samples were all measured in the field. The electrical conductivity and temperature were measured using a YSI Model 32 conductivity meter that automatically calibrates the readings to 25 ° C. The pH was determined using a Corning Model 103 pH Meter. The instrument was periodically calibrated using a buffer solution with a pH of 7.

4.0 RESULTS AND DISCUSSIONS

4.1 Location of Wells

The Series B wells were selected in a line approximately perpendicular to and intersecting the feature. A group of wells were also selected to be on top of or very close to the buried feature. A total of thirteen Series B wells were selected and sampled. The locations of the Series B wells and the Series A sites are shown on Figure 4.1. The NTS coordinates and geologic descriptions for all the Series B wells are found in Appendix II.

The Series A wells were drilled at two locations, Site #1 and Site #2. Site #1 is located on the Highway 401 right of way just south of the roadway and just west of Belle River Road at the Belle River Road exit on the 401. The locations of the wells AMA-90-01, AMA-90-02a, AMA-90-02b, and AMA-90-03 and their positions with respect to Highway 401 and Belle River Road are shown on Figure 4.2. Site #2 is located on the east side of the Rochester Township Concession Road #3 right of way. It is approximately 400 m north of Essex County Road #8. The locations of the wells AMA-90-04a, AMA-90-04b, AMA-90-04c, AMA-90-05 and AMA-90-06 and their positions with respect to Concession Road #3 are shown on Figure 4.3. Wells with a lower case letter after the number are members of a piezometric nest.

Data from a companion study (Ibrahim, personal communication) was also used. Five drilled wells, labelled OAI-01, OAI-2a, OAI-2b, OAI-02c, and OAI-03, were drilled at OAI Site #1. The site is on the Highway 401 right of way just south of the roadway and

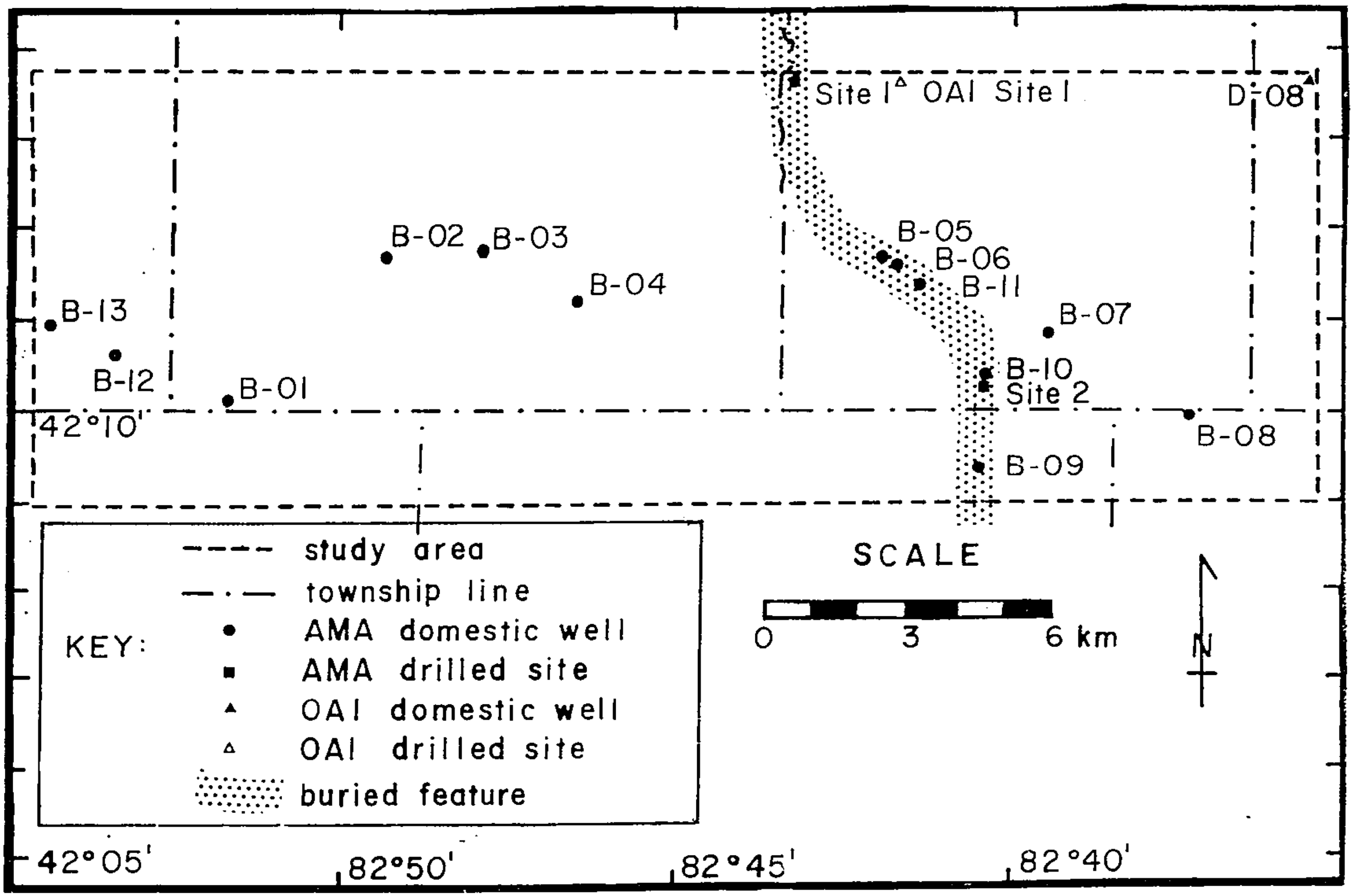

Figure 4.1- Location map of Series B wells and Series A sites, and location of buried linear morphological feature (Morris, personal communication).

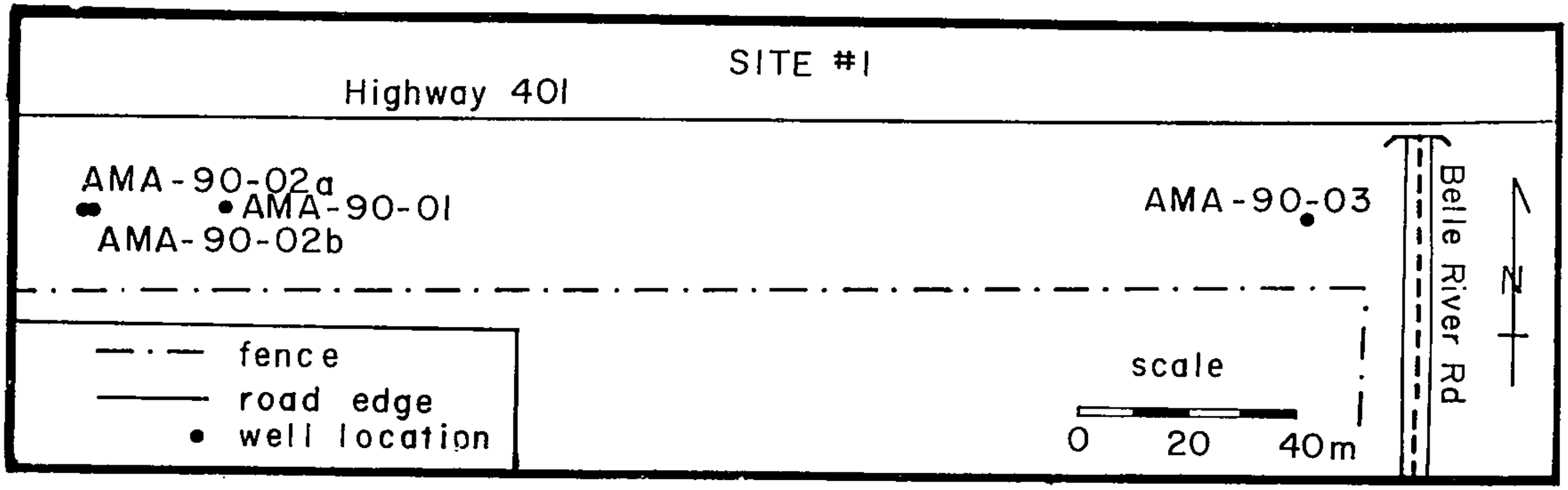

Figure 4.2 - Location map of Site #1 showing well locations with respect to Hwy. 401, and Belle River Road.

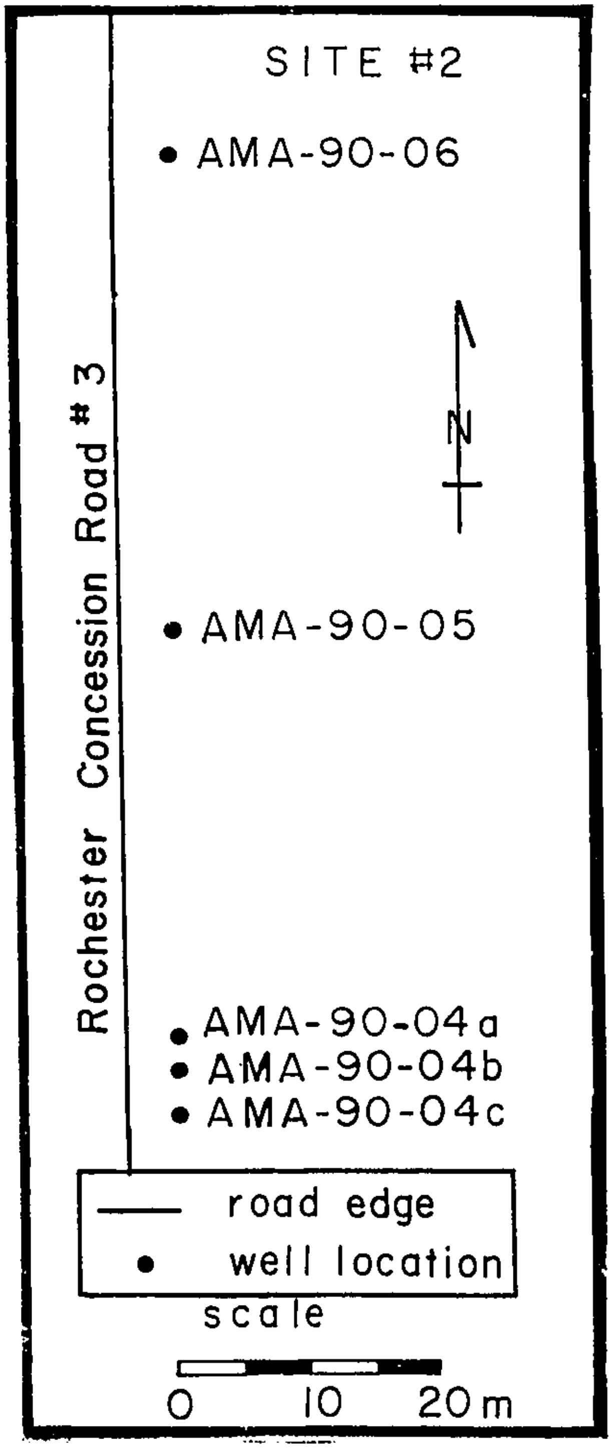

Figure 4.3 - Location map of Site #2 showing well locations with respect to Concession Road #3.

just east of the Rochester Township Concession Road #2 overpass. Also used from the Ibrahim study were two domestic wells, which were designated as OAI-D-08 and OAI-D-11. These well locations and the location of OAI Site #1 are shown on Figure 4.1. The locations of the wells and their positions with respect to Highway 401 and Rochester Concession Road #2 are shown on Figure 4.4.

4.2 Geological Cross-sections

The detailed logs of each hole are found in Appendix III. The geology is typically represented by a fractured brown clay till from the surface to a depth of usually less than 3 m. Below the brown clay till is a fractured grey clay till. These fractures were observed in split spoon samples in the top portion of the grey clay till. The fractures were indicated by oxidation halos or rust coloured, yellowish brown alteration rings around pebbles.

The grey clay contained varying amounts of pebble and sand sized grains. The actual breakdown of the grain sizes is given in Section 4.3. Desaulniers (1981) identifies this clay as a clay till. Thin, isolated, discontinuous, sand lenses are found within the till at various depths. These sand lenses appeared to have the same characteristics as the sand lenses at the surface that were described by Chapman and Putnam (1984) and Morris (1988, 1989). It is considered that the sand represents proglacial, subaquatic deposits. These may have taken the form of proglacial deltas (Morris, 1989) or shallow water sandbars in the proglacial lakes (Chapman and Putnam 1984). It is difficult to distinguish between sediments of glacial origin, or tills, and the lacustrine sediments, because much of the glacial sediments have been re-worked by the proglacial lakes.

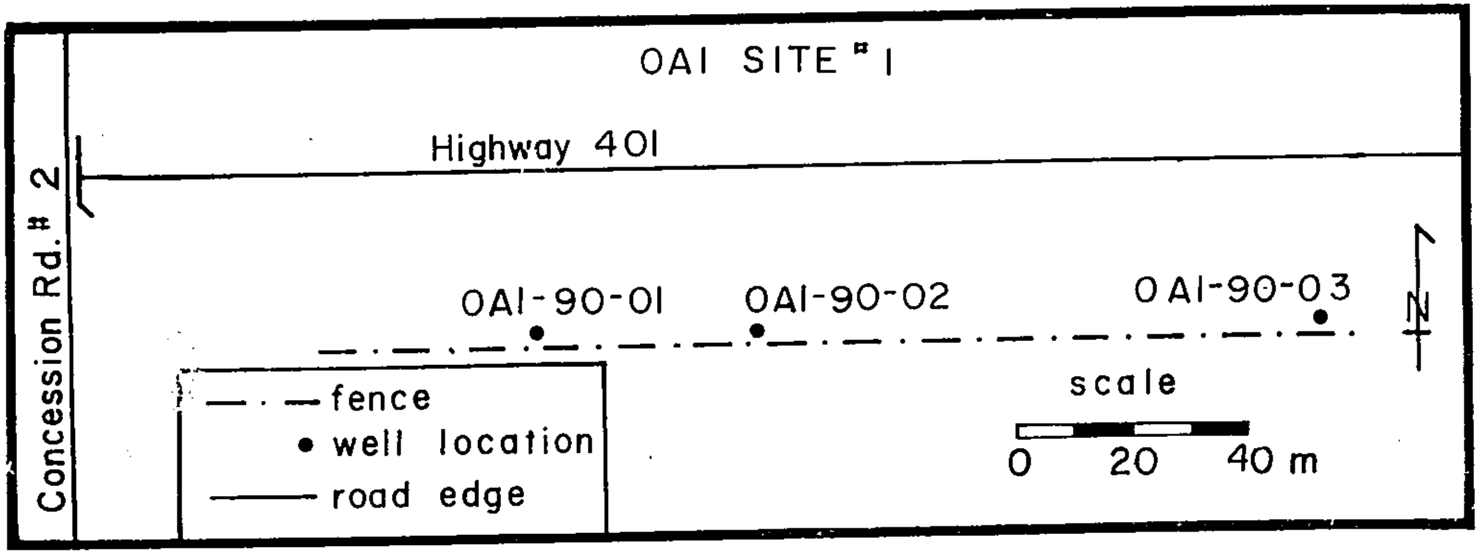

Figure 4.4 - Location map of OAI Site #1 showing well locations with respect to Hwy. 401 and Concession Road #2.

Below the thick deposits of grey clay till are sand deposits. This sand usually is very wet and under high hydraulic head. Underlying these beds are very dense sand and silt layers. In contrast, these layers appear to contain less water than the sand layers above. Underlying this dense layer is a layer of coarse sand and gravel. This layer also contains large volumes of water and represents the freshwater aquifer. Below this layer is the fractured bedrock.

The cross-section for Site#1 is shown on Figure 4.5. This figure has an exaggerated vertical scale to show the stratigraphy and shows that the top brown fractured clay can be correlated from hole to hole. The grey clay till can be roughly correlated. The bottom of this unit varies but can be correlated from the tops of the silty sand layers in holes AMA-90-02a and AMA-90-01 to the top of the fine sand layer in AMA-90-03. The sand lenses within the clay till can not be correlated with each other. Chaisson (personal communication) is trying to determine if the sand lenses located in the 6 to 9 m depth range are hydraulically connected on a regional basis. The sand in these units, and in other sand lenses, is typically fine grained. The sand contains grains of quartz, feldspar, mica, and some calcite. Other lithic fragments may occur as larger grains.

In the 25 m distance between AMA-90-02a and AMA-90-01 the silt layer at the 25-29 m depth pinches out. In hole AMA-90-02a it is 2.4 m thick while in hole AMA-90-01, the layer is 0.6 m thick. This layer is not present in AMA-90-03. Underlying the silty sand is a layer of fine sand. The intersection depth of this sand layer changes by 3 m between AMA-90-01 and AMA-90-02a. This sand has the same lithology as the sand lenses in the clay till. The coarse sand and gravel was found in

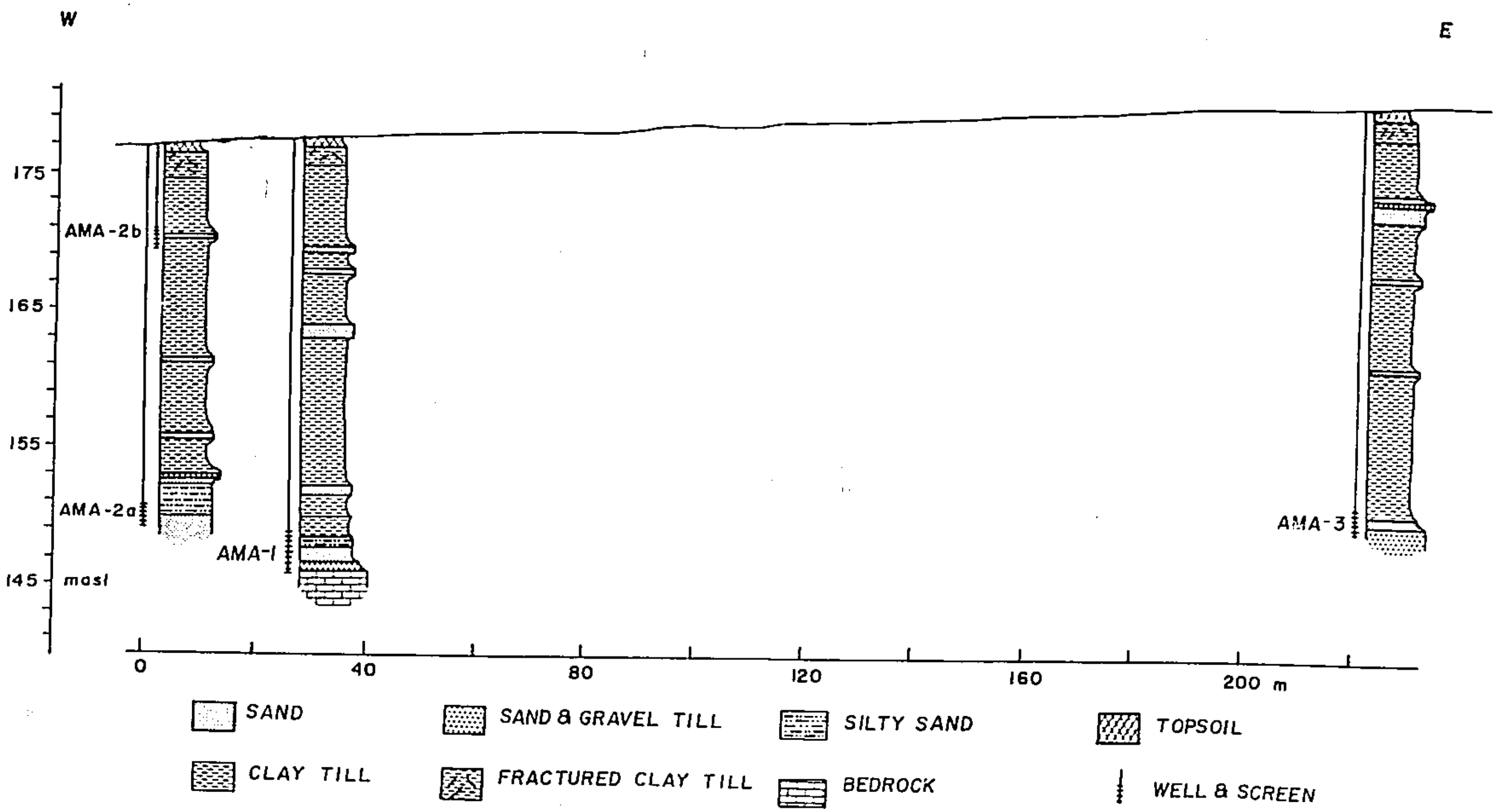

Figure 4.5 - Geologic cross section of Site #1

AMA-90-01 and AMA-90-03 but not in AMA-90-02a. The coarse sand found at the bottom of these holes is rounded to sub-angular and is polylithic. The gravel from this basal layer is made up of carbonates, shales, and erratics.

Figure 4.6 shows a cross section of Site # 2. This figure has the same vertical and horizontal scale as Figure 4.5. The brown fractured clay till at the top of the stratigraphic column and the underlying grey clay till unit can be correlated from hole to hole. Some of the grey till is also fractured at this site. In hole AMA-90-04a, fractures were observed extending into the grey clay till. The bottom portion of the clay till becomes less defined as many small sand and silty sand seams are present. The lithology underlying the grey clay till begins to be interbedded with various layers of sediment in the 21 to 24 m range. The silty sand and the underlying fine sand can be correlated in AMA-90-05 and AMA-90-04a.

Hole AMA-90-04a did not intersect sand until a depth of 22 m. At this depth silty coarse sand and gravel was encountered for 6 m. Below the sand and gravel was the layer of dense silty sand. Fine sand was intersected beneath the dense silty sand. Hole AMA-90-04b was drilled down to the top of the coarse sand and gravel and intersected the top of this zone almost 1 m deeper than at AMA-90-04a. Hole AMA-90-04b is only 2.5 m from AMA-90-04a. This probably represents the top of a ridge. The feature is probably a linear ridge or an isolated occurrence, because it does not show up in other holes. Since the feature is made up of silty sand and gravel, it may represent a buried esker.

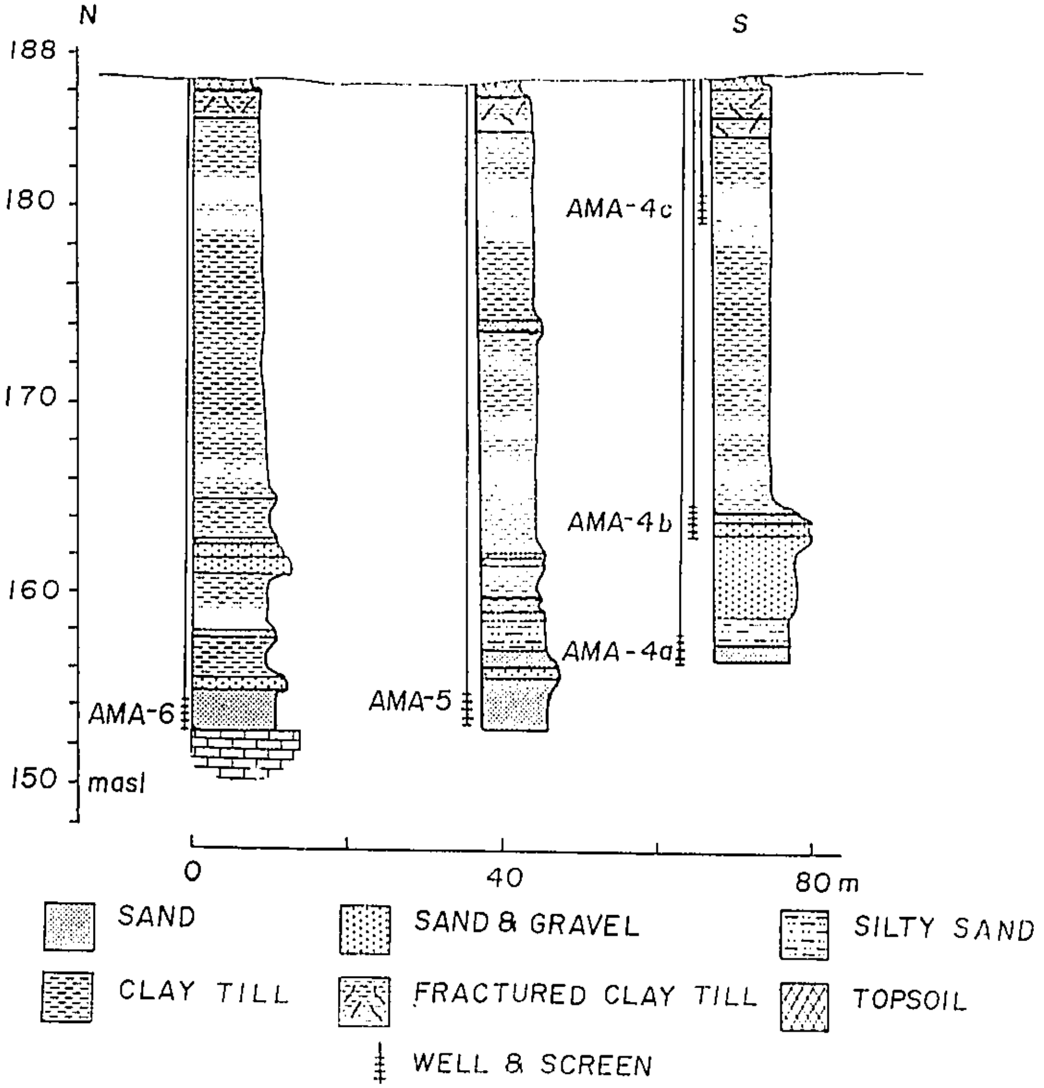

Figure 4.6 - Geologic Cross-section of Site #2 wells.

The linear morphological feature is considered to trend north-northwest at this location (Morris, personal communication). A domestic well, located to the north and on the west side of the Concession Road #3 and adjacent to AMA-B-10, intersects fine sand from approximately 14 m to 28 m with gravel underlying the sand. The sand and gravel found in this well may also represent the linear morphological feature. This is where the buried feature is estimated to be located. The estimated location of the buried linear morphological feature (Morris, personal communication) is shown on Figure 4.1.

The geology from the wells at OAI Site #1, described in detail by Ibrahim (1991), is similar to the general geology at AMA Site #1. Generally there is a thin layer of weathered and fractured brown clay till at the surface. This overlies the thick grey clay till. Fractures may extend into the grey clay till. The grey clay till has numerous sand seams in it. Underlying the clay till is a fine sand layer. Dense silty sand is below this fine sand. Underlying this unit is either the coarse sand and gravel or the bedrock.

4.3 Grain Size Distributions

Samples from boreholes AMA-90-01, AMA-90-03, AMA-90-04a, and AMA-90-05 were analyzed for grain size distributions. Table 4.1 gives the breakdown of the soil analysis. Figure 4.7 contains trilinear plots of all the samples, one plot for each hole sampled. There are three main groups where the samples concentrate. One cluster forms in the silty clay zone, and another occurs in the clayey silt zone. The freshwater aquifer samples all plot on the right side of the triangle in a silty sand group.

At Site #1, all the samples from holes AMA-90-01 and AMA-90-03 were analyzed to establish a profile of the grain distributions. The average distribution for the clay till

Table 4.1 : Grain size distribution results.

Sample #	**Depth (m)**	**Pebbles (%)**	**Sand (%)**	**Silt (%)**	**Clay (%)**	**D 60**	**D 10**	**Uniformity**	**Sed. Name**
AMA-1-1	3.05	1	10	40	49	0.004			silty clay
AMA-1-2	6.10	3	34	30	33	0.05			silty sandy clay
AMA-1-3	9.14	1	12	78	9	0.004	0.002	1.90	sandy silt
AMA-1-4	12.19	2	15	78	5	0.006	0.003	2.07	sandy silt
AMA-1-5	15.24	17	10	25	48	0.009			silty clay
AMA-1-6	18.29	2	15	79	4	0.007	0.003	2.25	sandy silt
AMA-1-7	21.34	8	8	39	45	0.006			silty clay
AMA-1-8	24.38	10	20	68	2	0.002	0.008	0.20	sandy silt
AMA-1-9	27.43	12	11	30	47	0.06			silty clay
AMA-1-10	30.48	21	37	42	0	0.38	0.005	76.00	sandy silt
Average		6.22	15.00	51.89	26.89				
AMA-3-1	3.05	3	16	77	4	0.006	0.003	1.65	(sandy) silt
AMA-3-2	6.10	2	13	72	13	0.006	0.002	3.33	sandy (clayey) silt
AMA-3-3	9.14	4	11	44	41	0.005	0.002	2.65	clayey silt
AMA-3-4	12.19	3	13	76	8	0.004	0.002	1.81	(sandy) silt
AMA-3-5	15.24	2	11	37	50	0.004	0.002	2.41	silty clay
AMA-3-6	18.29	2	12	39	47	0.005	0.002	2.94	silty clay
AMA-3-7	21.34	2	13	36	49	0.005	0.002	3.25	silty clay
AMA-3-8	24.38	1	12	66	21	0.003	0.002	1.56	clayey silt
AMA-3-9	27.43	4	18	71	7	0.004	0.002	1.87	(sandy) silt
AMA-3-10	30.48	9	77	14	0	0.65	0.015	43.33	coarse to med. sand
Average		2.56	13.22	57.56	26.67				

Sample #		**Sand (%)**	**Coarse Sand**	**Med. Sand**	**Fine Sand**
AMA-1-2	6.10	34	6	8	20
AMA-1-10	30.48	37	10	14	13
AMA-3-10	30.48	77	38	32	7

Table 4.1

Sample #	Depth (m)	Pebbles (%)	Sand (%)	Silt (%)	Clay (%)	D 60	D 10	Uniformity	Sed. Name
AMA-4-1	3.05	4	11	36	49	0.004			silty clay
AMA-4-2	6.10	6	12	39	43	0.007	0.002	4.67	silty clay
AMA-4-3	9.14	4	10	41	45	0.005			silty clay
AMA-4-4	12.19	2	11	40	47	0.005			silty clay
AMA-4-6	18.29	3	7	39	51	0.004			silty clay
AMA-4-7	21.34	6	24	70	0	0.015	0.004	3.95	sandy silt
Avg. w/o #7		3.80	10.20	39.00	47.00				silty clay
AMA-5-1	3.05	4	17	36	43	0.006	0.002	3.22	silty clay
AMA-5-2	6.10	4	12	38	46	0.005	0.002	2.94	silty clay
AMA-5-3	9.14	1	12	46	41	0.004	0.002	2.19	clayey silt
AMA-5-4	12.19	5	31	34	30	0.023			clayey sandy silt
AMA-5-5	15.24	1	15	20	64	0.002	0.001	1.64	(silty) clay
AMA-5-6	18.29	1	11	59	29	0.003	0.002	1.56	clayey silt
AMA-5-7	21.34	7	20	73	0	0.012	0.004	3.16	sandy silt
AMA-5-8	24.38	5	28	67	0	0.02	0.003	6.25	sandy silt
AMA-5-8(b)	24.50	10	68	22	0	0.35			silty fine to med. sand
AMA-5-9	27.43	2	39	59	0	0.062	0.012	5.17	sandy silt
AMA-5-10	30.48	31	44	25	0	1	0.01	102.04	(silty) pebbly sand
Avg. #1-#6		2.67	16.33	38.83	42.17				(sandy) silty clay
Avg. #7-#10		11.00	39.80	49.20	0.00				sandy silt

Sample #			Sand (%)	Coarse Sand	Med. Sand	Fine Sand
AMA-5-8(b)	24.5	10	68	7	34	27
AMA-5-10	30.48	31	44	12	16	16

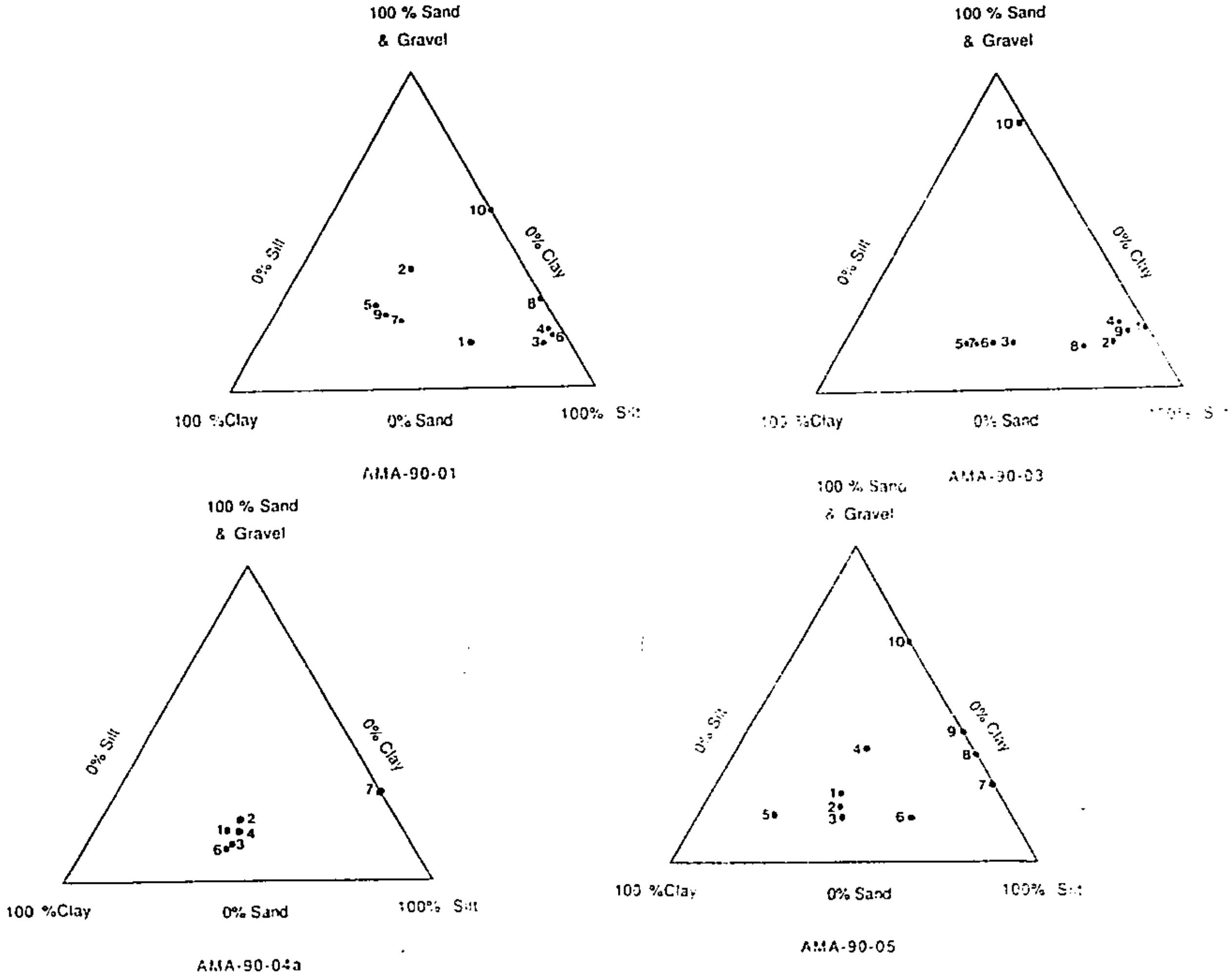

Figure 4.7 - Trilinear plots of grain size distribution
(sample numbers are plotted)

samples from AMA-90-01, which were taken approximately every 3 m, is: 6 % gravel,15 % sand, 52 % silt, and 27 % clay. The till is classified as a clayey silt. These numbers are similar to those reported in Desaulniers et al. (1981).

Gravel usually appeared as a few large stones. Many of the grains were rounded originally, but most of the grains were broken or ground into sub-angular to angular fragments.

The D_{60} value represents a grain diameter where 60% of the grains are finer. The D_{60} value is plotted versus the depth of the sample on Figure 4.8. The large increase at the 30 m depth represents the freshwater aquifer. The D_{10} represents the diameter of grains in suspension during a hydrometric test, for which only 10% of the sample particles are finer. The D_{60} value divided by the D_{10} value gives the uniformity of the sample. Values less than 2 are considered to be uniform. From the five samples assessed, AMA-1-3 and AMA-1-8 , retrieved from 9 and 24 m depths respectively had values less than 2, while AMA-1-4 (12 m) and AMA-1-6 (18 m) had values very close to 2.

The average distribution for the clay till in hole AMA-90-03 is 3 % gravel, 13 % sand, 57 % silt, and 27 % clay. This average would be classified as a clayey silt. This average was calculated without including the values from AMA-3-10. Sample AMA-3-10 was taken from the freshwater aquifer, and is classified as a coarse to medium grained sand. This sand was

sub-rounded to sub-angular and contained quartz, feldspar, mica, and calcite grains.

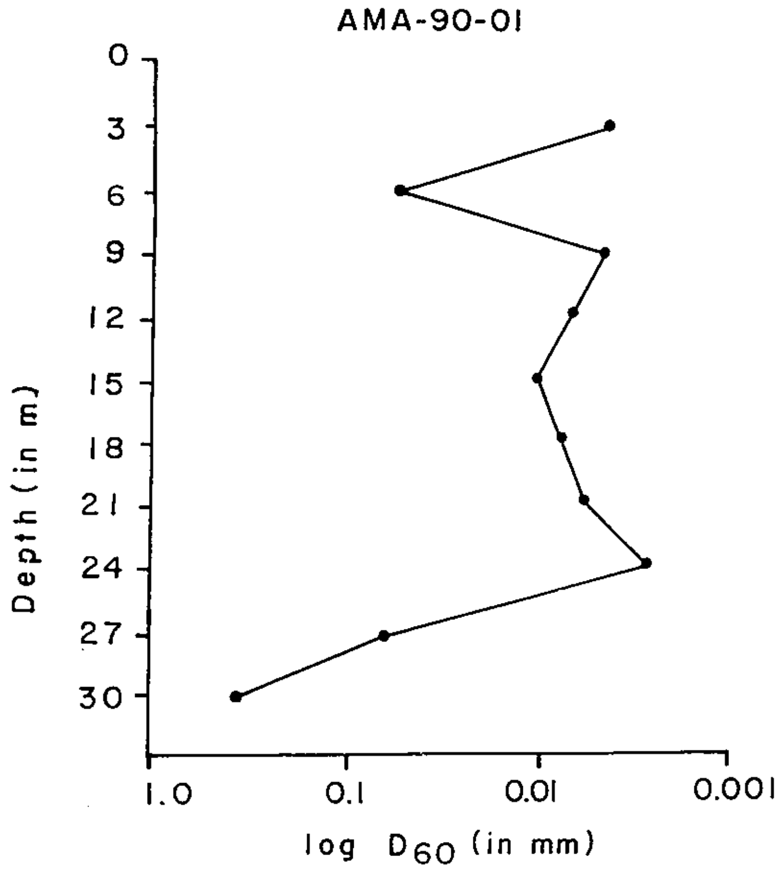

Figure 4.8 - Plot of grain size distribution for AMA-90-01 (D_{60} vs sample depth).

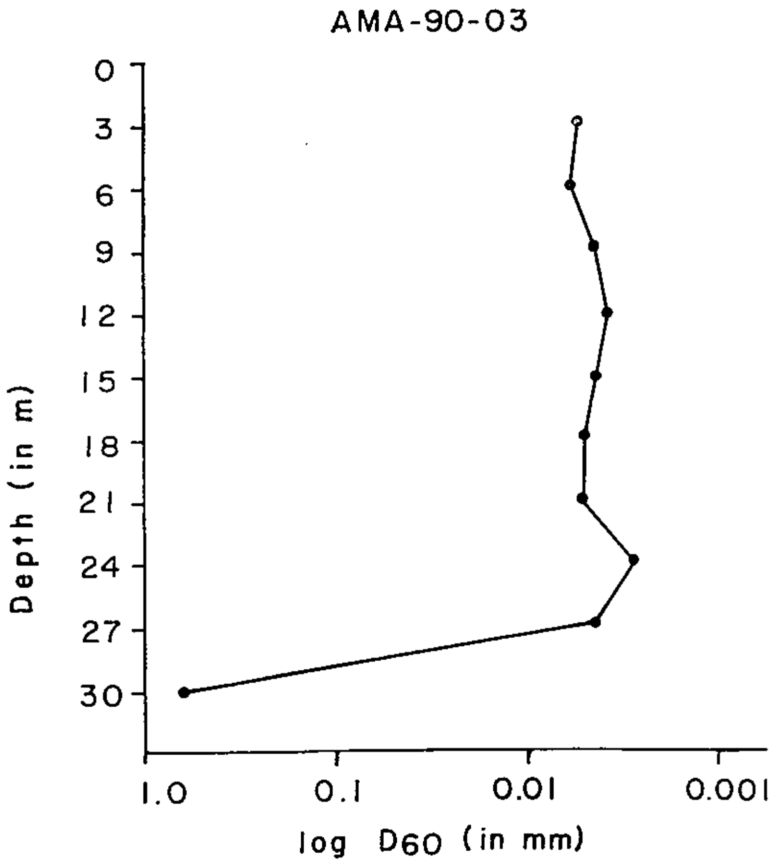

Figure 4.9 - Plot of grain size distribution for AMA-90-03 (D_{60} vs sample depth).

Some of the larger grains were shale, limestone, and erratics.

Figure 4.9 is a plot of D_{60} versus sample depth for AMA-90-03. The uniformity values represent material that is relatively uniform with four of the ten samples having a uniformity of less than 2, and five other samples have uniformity values of less than 4. Only the deepest sample is not uniform.

At Site #2, all of the samples at AMA-90-04a were classified as silty clays, except the last sample which was classified as a sandy silt. The last sample was taken just above the linear morphological feature. The average distribution of the silty clay till is 4 % gravel, 10 % sand, 39 % silt, and 47 % clay. This is classified as a silty clay.

Figure 4.10 shows the profile of D_{60} versus depth. The dotted line represents an approximation, due to a lack of a sample around the 15 m depth. The graph shows an increase for the basal sample. This represents the increased sand content immediately above the linear morphological feature. Samples AMA-4-2 and AMA-4-7 were relatively uniform, having uniformity values of less than 5.

Hole AMA-90-05 displays two distinct zones. The average grain size distribution for the top zone, represented by the first six samples, is 3 % gravel, 16 % sand, 40 % silt, and 42 % clay. These samples are classified as a silty clay. The average for the lower zone, represented by the remaining samples, is 11% gravel, 40 % sand, and 49 % silt. These samples are classified as sandy silts. The basal sample represents the freshwater aquifer. Figure 4.11 shows the profile of D_{60} versus depth. Of the nine samples for

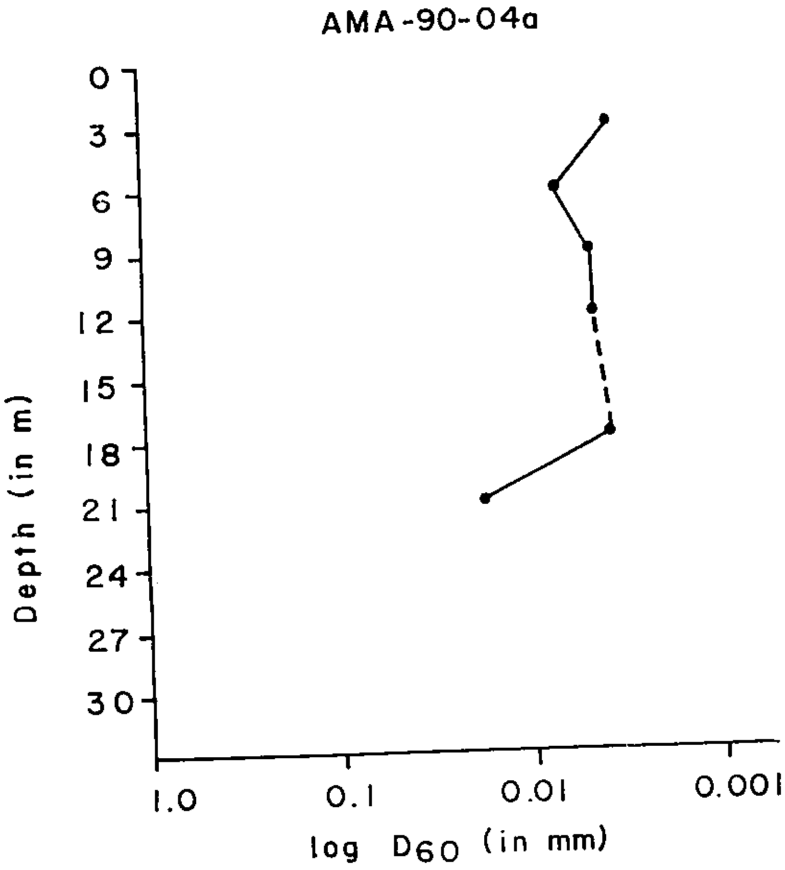

Figure 4.10 - Plot of grain size distribution for AMA-90-04a (D_{60} vs sample depth).

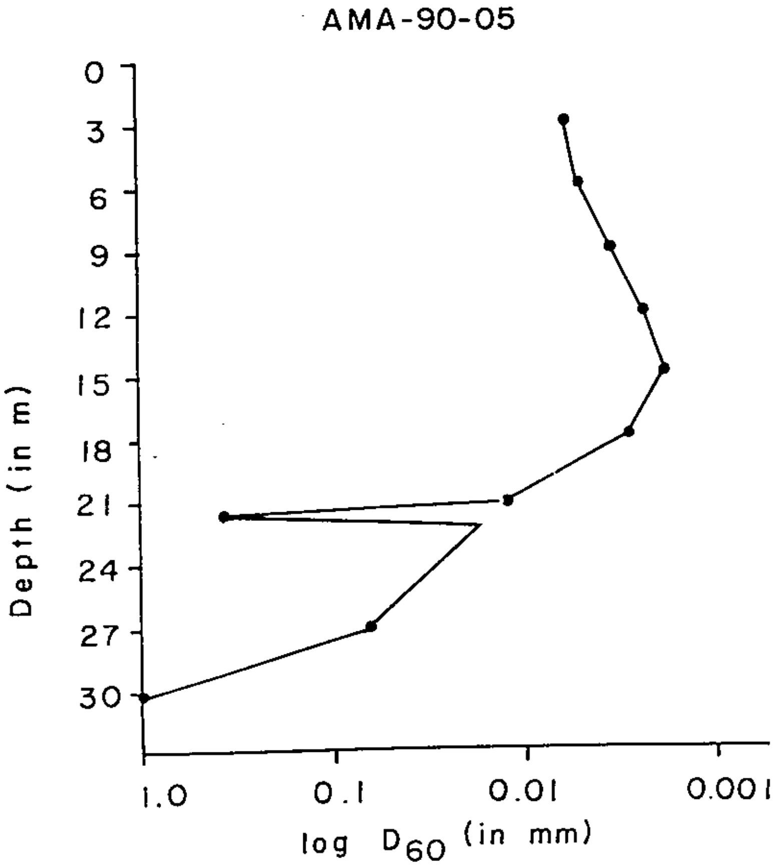

Figure 4.11 - Plot of grain size distribution for AMA-90-05 (D_{60} vs sample depth).

which uniformity was determined, only AMA-5-5 and AMA-5-6 have uniformity values less than 2. Four of the samples had uniformity values of less than 4.

All the D_{60} profiles indicate fairly constant grain size with depth, until just above the freshwater aquifer, where the grain size starts to increase. The freshwater aquifer contains the largest diameter grains. In hole AMA-90-05 the grain size increases, from 19 m in depth, steadily until the freshwater aquifer. Sample AMA-5-8b, a sand seam from the 24.5 m depth, was sampled separately and is indicated by the extension to the left on the profile. The sand seam contained mostly medium grained and fine grained sand.

It follows from the grain size distribution that the till is generally made up of silty clay with minor sand and gravel. This is consistent with the findings of Soderman and Kim (1970). The freshwater aquifer can range between coarse sand, medium sand, to a silty sand. Due to the silt content of the freshwater aquifer, Morris (personal communication) believes that this is the Catfish Creek Till.

4.4 Hydraulic Heads

The hydraulic head data from Crnokrak (1991) indicates that the main recharge zone for Essex County is in the Leamington area, as shown on Figure 2.6. The static water levels from the drilled wells and the domestic wells from this study indicate that the area around Site #2 may be a recharge area or is closer to one than previously expected.

The potentiometric level was measured from different wells and was then contoured to represent the potentiometric surface. Table 4.2 shows the elevation, the static water

Table 4.2 : Hydraulic heads of Series A and Series B wells.

Well#	Elevation (m asl)	Static Water Level (m from suface)	Hydraulic Head (m asl)
AMA-90-01	180.41	(+)2.5	182.91
AMA-90-02a	180.18	(+)1.45	181.63
AMA-90-02b	180.16	(+)0.09	180.25
AMA-90-03	181.72	(+)1.12	182.84
AMA-90-04a	187.37	1.18	186.19
AMA-90-04b	187.42	1.17	186.25
AMA-90-04c	187.45	1.94	185.51
AMA-90-05	187.28	1.05	186.23
AMA-90-06	187.33	1.16	186.17
AMA-B-01	193.24	11.58	181.66
AMA-B-02	192.02	8.23	183.79
AMA-B-03	188.98	10.05	178.93
AMA-B-04	188.98	4.27	184.71
AMA-B-05*	187.15	0.91	186.24
AMA-B-06*	187.15	0.91	186.24
AMA-B-07	187.45	1.52	185.93
AMA-B-08*	187.15	9.14	178.01
AMA-B-09	190.5	3.05	187.45
AMA-B-10	188.98	1.52	187.46
AMA-B-11*	187.15	0.91	186.24
AMA-B-12	193.24	11.58	181.66
AMA-B-13	192.02	9.75	182.27

* data taken from a nearby well

level, and the hydraulic head of each drilled and domestic well in the study area. The plus sign represents a static water level that was above the ground level. In several instances, the exact location of the domestic well, from which the water samples were taken, was not listed in the water well records (Ministry of the Environment, 1984). In those situations, the water level from a nearby well was used.

Figure 4.12 is a potentiometric level contour map of the Series B wells and the Series A sites. The potentiometric level is high in the area around wells AMA-B-05, AMA-B-06, AMA-B-11, AMA-B-10, and AMA-B-09. These wells are the closest to the linear morphological feature. The potentiometric levels are unknown on the eastern side of the feature due to a lack of data. Assumed contours through these unknown areas are indicated by dashed lines. On the western side of the feature, the contour lines are far apart, indicating that the potentiometric surface drops away from the feature gradually. The contours protrude towards the west. The explanation for this protrusion is unknown at this time. The contours tend to wrap around the feature. The cause of this may be that the linear feature affects the groundwater levels. The feature may induce an increased rate of vertical infiltration, which may explain why the water levels are higher over the feature. The pronounced effect of the buried feature on the contours disappears to the north of domestic wells AMA-B-05 and AMA-B-06.

From the geological description of the wells at AMA-B-03 and near AMA-B-08, (Ministry of the Environment, 1984) it is apparent that the wells were installed in a fine sand layer. This sand appears to be from the same sand layer that was intersected above the freshwater aquifer in the drilled wells of this study. These wells do not fully penetrate to the coarse sand and gravel and therefore can not be used to help define the

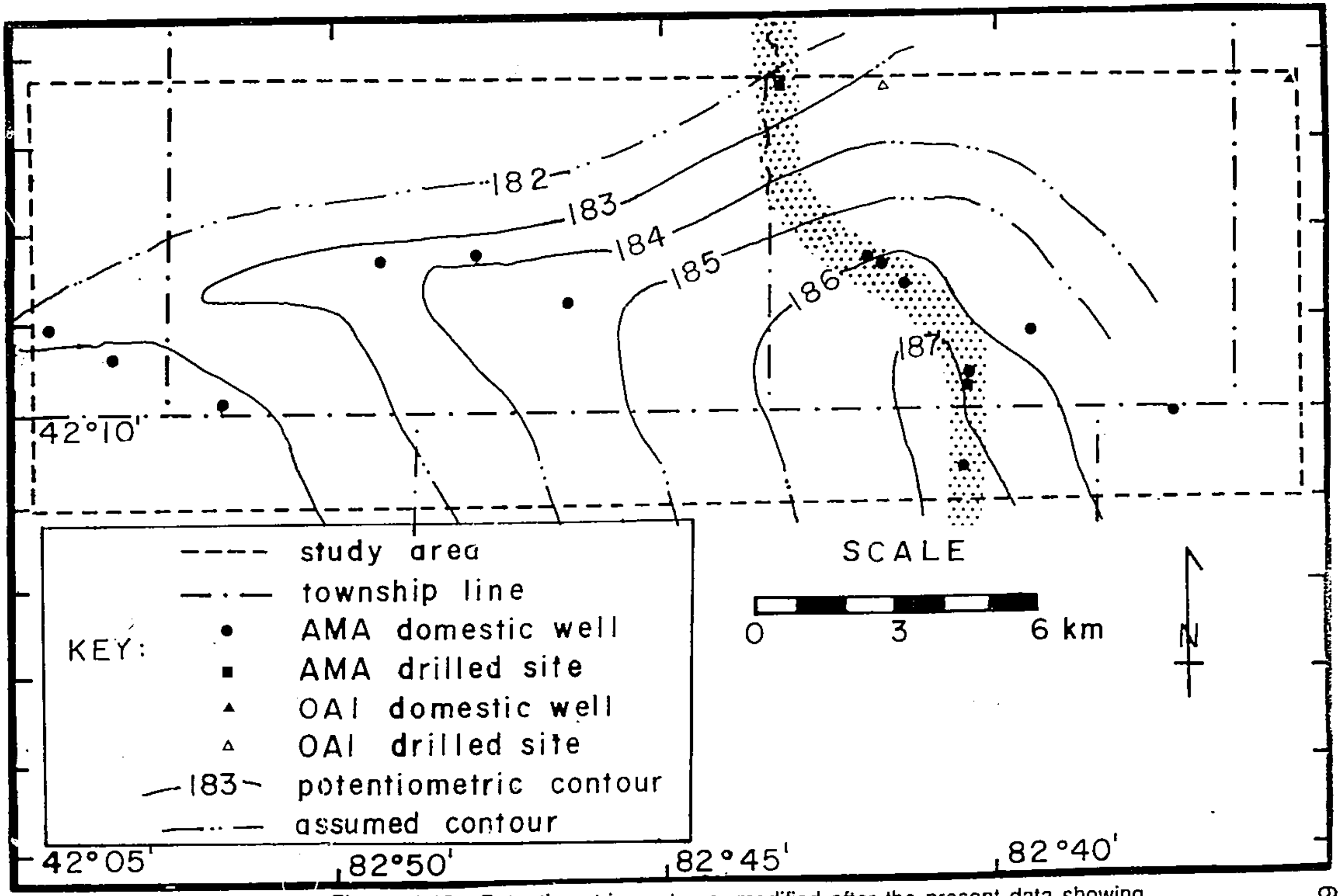

Figure 4.12 - Potentiometric contours- modified after the present data showing Series B wells and Series A sites.

potentiometric surface of the freshwater aquifer.

Static water level measurements were made in October 1990 and March 1991. At Site #1, AMA-90-01 had the highest hydraulic head of the three deep wells. The water in the freshwater aquifer apparently flows horizontally away from this well. Well AMA-90-02a is 25.44 m west of AMA-90-01 while AMA-90-03 is 196.4 m east of AMA-90-01. The hydraulic heads from the piezometric nest, AMA-90-02a and AMA-90-02b, indicate that water is rising from the freshwater aquifer and that this is a zone of discharge.

Wells AMA-90-01 and AMA-90-02a cannot be used to calculate the potentiometric surface because the screen in AMA-90-02a intersects the fine sand above the freshwater aquifer, which has a lower hydraulic conductivity than the freshwater aquifer. Wells AMA-90-01 and AMA-90-03 can be used for the potentiometric surface contours because the screens intersect the same stratigraphic unit. The hydraulic gradient between these two wells is insignificant.

At Site # 2, well AMA-90-04b has the highest hydraulic head. Wells AMA-90-04b, AMA-90-05, and AMA-90-06 all appear to be completed in similar material. The hydraulic heads at AMA-90-05 and AMA-90-06 indicate that the water is flowing away from

AMA-90-04b. The hydraulic gradient between AMA-90-04b and AMA-90-05 is over twice the average gradient of 0.0011 which was calculated by Crnokrak (1991). The gradient between AMA-90-05 and AMA-90-06 is very close to the average gradient. In the piezometric nest AMA-90-04b has the highest hydraulic head. The vertical gradient between AMA-90-04b and AMA-90-04a is downward at 0.008. The vertical gradient between AMA-90-04b and AMA-90-04c was upwards at 0.47. The overall vertical gradient between AMA-90-04a and AMA-90-04c was upwards at 0.03. The screen in well AMA-90-04b intersects coarse sand and gravel.

The screen for well AMA-90-04b intersects the coarsest material and therefore likely has the highest hydraulic conductivity. Well AMA-90-04c is shallow and the screen intersects the clay till. The fine sand intersected by the screen for well AMA-90-04a has a lower hydraulic conductivity, and therefore a lower rate of flow. This is represented by the lower hydraulic head. The water levels indicate the the water flows from the feature down into the finer sand. The water probably flows from the top of the feature into the overlying sediment, similar to that found at Site #1. In the fall, AMA-90-04c had not yet come up to the static water level. This explains the large difference between the spring and fall hydraulic heads.

The difference between the fall and spring water levels is an indication of the amount of water infiltrating into the aquifer. More water in the confined aquifer increases the hydraulic pressure. As the pressure increases the potentiometric surface rises (Freeze and Cherry, 1979).

4.5 Single Well Tests

Single well tests, using Hvorslev slug and bail methods, were conducted to determine the hydraulic conductivity of the freshwater aquifer. The evaluation for the single well tests is listed in Table 4.3. The detailed results are found in Appendix IV.

Table 4.3 : Single well test results.

Well #	To (sec)	r (cm)	R (cm)	L (cm)	K (cm/sec)
AMA-90-01	660	2.54	2.54	304.8	7.68E-05
AMA-90-02a	4050	2.54	10.25	152.4	1.41E-05
AMA-90-02b	16200	2.54	10.25	152.4	3.53E-06
AMA-90-03	630	1.59	1.59	152.4	5.99E-05
AMA-90-04a	5640	1.59	10.25	152.4	3.96E-06
AMA-90-04b	128	1.59	1.59	152.4	2.95E-04
AMA-90-04c	1202400	1.59	10.25	152.4	1.86E-08
AMA-90-05	195	2.54	2.54	152.4	4.44E-04
AMA-90-06	30	1.59	1.59	152.4	1.26E-03

To = time of recovery at initial rate

r = radius of casing

R = radius of screen

L = length of screen

K = Hydraulic conductivity

In wells AMA-90-02a, AMA-90-02b, AMA-90-04a, and AMA-90-04c, the radius of the screen was essentially the radius of the artificial sand pack which in turn represented the augered hole diameter. The artificial sand pack is much coarser than the surrounding sediment by its nature, and therefore water is able to flow easily through it. The sand pack acts like an extension of the screen. The length of the screen including the height of the sand pack, L, is listed on Table 4.3.

Although wells AMA-90-01 and AMA-90-03 are flowing, their hydraulic conductivity values are relatively low, with a 10^{-5} cm/s order of magnitude. These values are higher than the other deep well at this site, AMA-90-02a, which has a value of 1.4×10^{-5} cm/s. The coarse sand and gravel zone intersected by the screens of wells AMA-90-01 and AMA-90-03, may be clogged with silt. This was demonstrated in Section 4.3, Grain Size Distribution, where the freshwater aquifer samples from wells AMA-90-01 and AMA-90-03 were noted to contain 43 and 14% silt respectively. The fine sand intersected by the screen of well AMA-90-02a, may also be clogged with silt. Freeze and Cherry (1979) indicate that hydraulic conductivity values of this magnitude are representative of silty sands.

The shallow well at Site #1, AMA-90-02b, has a hydraulic conductivity of 3.5×10^{-6} cm/s. This unusually high value for a till can be attributed to the intersection of a fine sand layer above the screen. It is possible that the screen and the sand layer are hydraulically connected.

At Site #2 the hydraulic conductivity values are generally lower, except for wells AMA-90-04a and AMA-90-04c. The former has a value of 3.9×10^{-6} cm/s, while the latter has a value of 1.8 x 10^{-8} cm/s. This last value is reasonable for a clayey glacial till, which is what its screen intersects.

Well AMA-90-04a was drilled through the feature and it's screen intersects a fine sand layer below the coarse sand and gravel. This sand layer is considered to be very silty and the silt may be clogging the screen. Hydraulic conductivity values of these magnitudes are representative of glacial till by Freeze and Cherry (1979).

AMA-90-04b and AMA-90-05 both have hydraulic conductivity values of approximately 10^{-4} cm/s order of magnitude. Well AMA-90-04b intersects the top of the feature while the screen in well AMA-90-05 intersects what may be the apron of the feature. These hydraulic conductivity values are approaching values representative of a clean sand, but are still in the silty sand range. The grain size distribution for well AMA-90-05, indicates that the screen intersects a zone of (silty) pebbly sand. Well AMA-90-06 has a hydraulic conductivity of 1.2 x 10^{-3} cm/s, which is representative of a clean sand according to Freeze and Cherry (1979).

The single well tests indicate that the hydraulic conductivity of the freshwater aquifer is low due to the quantity of silt in this zone. The hydraulic conductivities for the clay till are similar to the values reported by Desaulniers (1981). The hydraulic conductivity for the feature is lower than the freshwater aquifer.

4.6 Isotopic Investigations

The results of the isotopic investigations are listed in Table 4.4 and discussed below.

Table 4.4 : Isotopic results.

Hole #	**Tritium (TU)**	**Oxygen -18 (per mille)**
AMA-90-01	<0.8	-12.2
AMA-90-02a	<0.8	-11.0
AMA-90-02b	<0.8	-12.2
AMA-90-03	<0.8	-11.9
AMA-90-04a	<0.8	lost
AMA-90-04b	2.6	-7.5
AMA-90-04c	2.3	-9.2
AMA-90-05	<0.8	-9.6
AMA-90-06	5.2 4.9	-8.8
AMA-B-01	<6.0	-13.3
AMA-B-02	10.0	-14.3
AMA-B-03	16.0	-10.7
AMA-B-04	<6.0	-16.1
AMA-B-05	15.0	-8.3
AMA-B-06	21.0	-8.0
AMA-B-07	<6.0	-9.7
AMA-B-08	<6.0	-11.1
AMA-B-09	<6.0	-9.7
AMA-B-10	14.0	-9.4
AMA-B-11	<6.0	-9.6
AMA-B-12	<6.0	-13.0
AMA-B-13	<6.0	-9.6

Squeeze Samples

Hole #	**Depth (m)**	**Oxygen -18 (per mille)**
AMA-90-01	3.05	-12.0
	6.10	-12.3
	9.14	-12.4
	12.19	-12.4
	15.24	-12.3
	18.29	-13.0
	21.34	-12.6
	24.38	-12.5
	27.43	-12.3
	30.48	-11.5
AMA-90-04a	3.05	-6.9
	6.10	-6.7
	9.14	-7.1
	12.19	-7.0
	18.29	-8.2
	21.34	-7.0
OAI-02a	3.05	-8.7
	6.10	-9.1
	9.14	-10.7
	12.19	-11.7
	15.24	-11.9
	21.34	-14.9
	24.38	-14.5
	27.43	-14.8
	30.48	-12.6

4.6.1 Oxygen - 18

The study area is shown in Figure 4.13, with a plot of the $\partial^{18}O$ contours for all the Series B wells and the Series A sites. The ^{18}O values for the deep holes at each Series A site were averaged to get a value which could be contoured at this scale. The dashed lines represent approximations due to a lack of data in those areas.

The deep wells at both Series A sites are relatively enriched in ^{18}O compared to the surrounding area. The deep wells at Site #1 have $\partial\ ^{18}O$ values ranging between -11.0 and -12.2 $^o/_{oo}$. The deep wells at Site #2 have values ranging between -7.5 and -9.6 $^o/_{oo}$. The more depleted values at the northern site indicate that groundwater is flowing along the feature. The Series B wells close to the feature, AMA-B-05, 06, 07, 09, 10, and 11, all had values between -7.9 and -9.7 $^o/_{oo}$.

Farther away from the feature, the ^{18}O values decrease. Except for AMA-B-03 and AMA-B-13 all the other locations have values ranging between -11.0 and -16.1 $^o/_{oo}$. The values from Site #1 are more depleted than at Site #2. The effect of the feature on the isotopic contours is less pronounced at the north end of the feature as shown by a greater contour spacing.

According to Edwards (as found in Crnokrak, 1991), modern water, which has recharged within 1000 yrs, for the Windsor area has $\partial^{18}O$ values of

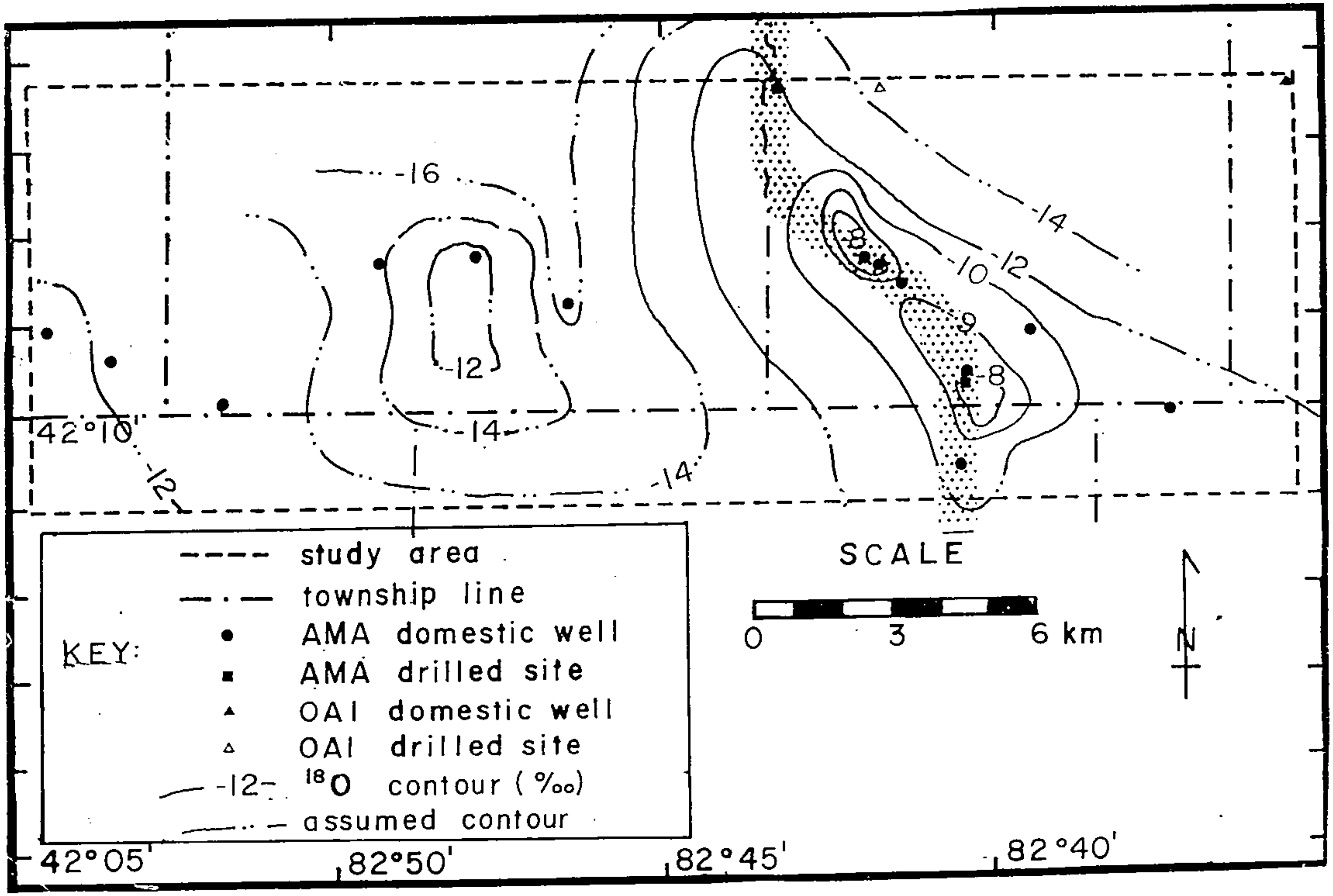

Figure 4.13 - ^{18}O contours, modified after the present data showing Series B wells and Series A sites.

-10.1 $^{o}/_{oo}$ (±0.7$^{o}/_{oo}$). With increasing depth, the values then increase until they reach -7.9 $^{o}/_{oo}$ (±0.7 $^{o}/_{oo}$). These values represent an estimated recharge age of 6300 years before present. With greater depths , the $\partial^{18}O$ values decrease, with minor fluctuations, to -14.2 $^{o}/_{oo}$ (±0.38 $^{o}/_{oo}$). These values represent an approximate recharge age of 11450 years before present. Water recharged before this time present will be even more depleted. These approximate ages were determined by comparing $\partial^{18}O$ data from marl with $\partial\,^{18}O$ data from wood cellulose, which could also be carbon-14 dated (Edwards and Fritz, 1988).

With this information it is possible to determine the approximate time when the water was recharged into the groundwater system. Assuming piston flow and the $\partial\,^{18}O$ values of precipitation from Crnokrak (1991), the $\partial\,^{18}O$ values close to the feature represent approximate ages of 6300 to 7700 years before present. The values at Site #1 have approximate ages between 8700 and 9550 years before present.

Water from the squeezed samples was tested to establish isotopic profiles for selected holes. Holes AMA-90-01 and AMA-90-04a were sampled by Shelby tube every 3.0 m. These samples were squeezed and the pore water was analyzed for $\partial\,^{18}O$. The results are listed in Table 4.4.

Samples from a companion study (Ibrahim, 1991) and the results from other studies, (Desaulniers et al.,1981, and Orpwood, 1984) are used for comparison. Five profiles are found on Figure 4.14 with the $\partial\ ^{18}O$ values plotted against the depth of the top of the sample. The profile of OAI-02a, from Ibrahim (1991), is similar to the Woodslee profiles from Desaulniers et al. (1981) and Orpwood (1984). In these cases, the $\partial\ ^{18}O$ values become progressively more depleted with depth. This indicates that the age of the water increases with depth. However, for the profiles at Site #1 and Site #2, the $\partial\ ^{18}O$ values remain approximately constant with depth.

At approximately the 18 m depth, all of the profiles from this and the companion study, trend slightly towards more depleted values. This could indicate that this water was recharged during a relatively cold period.

There tends to be a relative enrichment of the $\partial\ ^{18}O$ at the freshwater aquifer. Although the profile at Site #2 does not extend into the feature, there may be mixing of the enriched water from the freshwater aquifer and the feature with the depleted water of the clayey silt above. This represents an overall enrichment of the $\partial\ ^{18}O$ values above the aquifer.

The very enriched values for AMA-90-04a may indicate that the water has been evaporated. This can be proven if deuterium was analyzed. This could have occurred during the sampling procedure, but this is considered unlikely since none of the other analyzed samples, which used an identical sampling procedure, were evaporated. This is not a well installation problem because the water was squeezed from the sediments. It is considered that the water was evaporated before it infiltrated the soil. One of the sources of the water could be the ditch at the side of the road. Meteoric water collects in

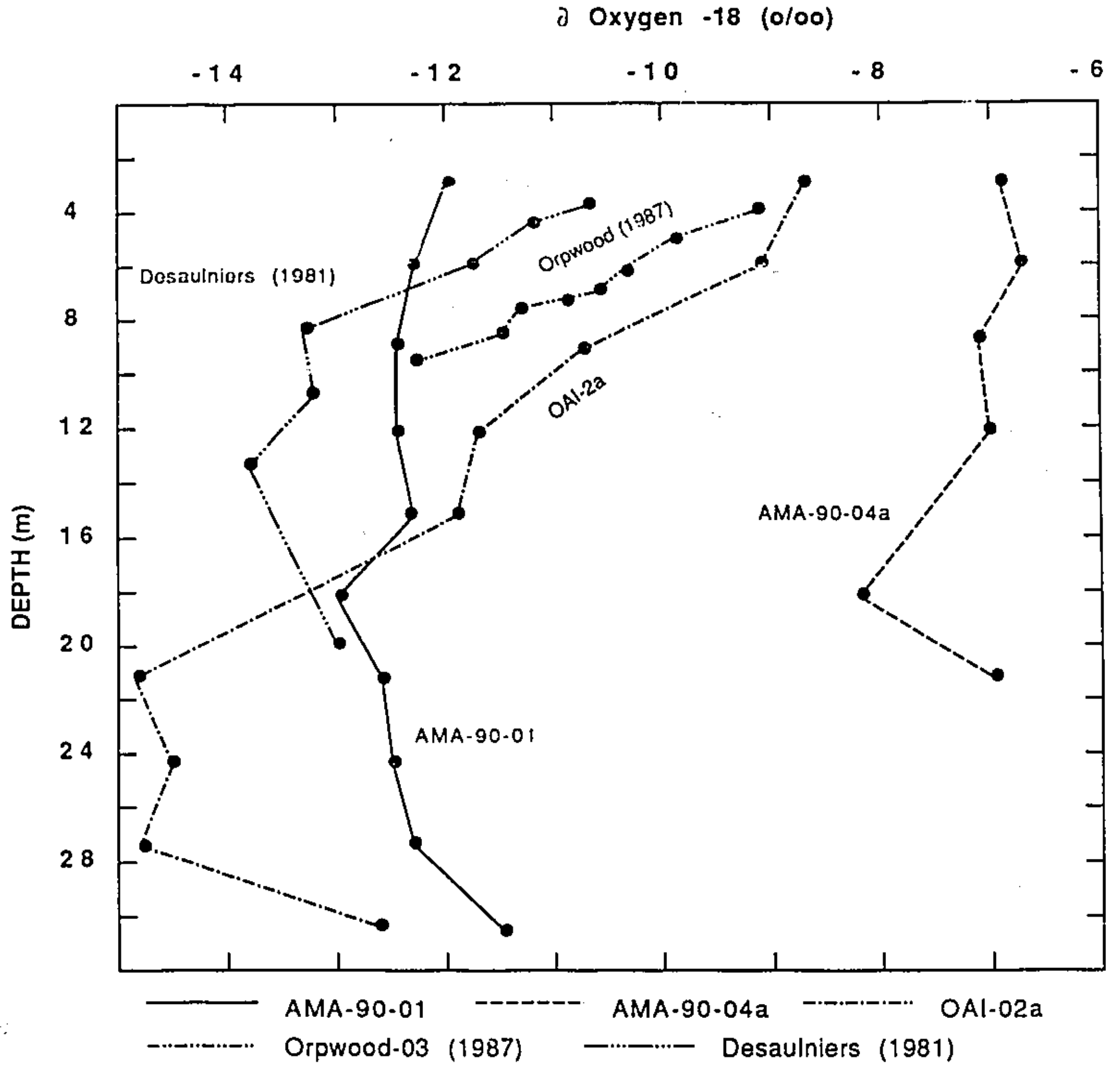

Figure 4.14 - ^{18}O profiles versus depth for AMA-90-01, AMA-90-04a, OAI-2a, Orpwood #4, (1987), and Desaulniers (1981)

the ditch and does not drain away because of poor ditch construction. The water that sits in the ditch, evaporates, and becomes progressively enriched with ^{18}O. Several days after the rain event, most of this water may have evaporated, but some may infiltrate through fractures to the feature and the freshwater aquifer.

4.6.2 Tritium

Groundwater from all the Series B wells was analyzed for tritium (T) content using the direct tritium method. The direct tritium method has a precision of ± 8.0 TU. The precision depends on the counting time and the TU level. Egboka et al. (1983) suggest that values of less than 15 TU determined by the direct method almost always have less than 1-2 TU when analyzed by the more accurate enriched method. Similarly, values between 15 and 20 TU by the direct method commonly have values of less than 1-2 TU when analyzed by the enriched method.

Well AMA-B-05 produced the only sample that had a value greater than 20 TU. Wells AMA-B-06 and AMA-B-03 were above 15 TU. Well AMA-B-10 was close to 15 TU with a value of 14 TU. Groundwater samples from AMA-B-05, 06, and 10 were taken from the target or close to it. The relatively tritiated water suggest that the groundwater must have been recharged within the past 40 years.

The enriched tritium method has an accuracy of ±0.7 TU. Results using this method indicate that only samples from Site #2, specifically wells AMA-90-04c, 04b, and 06, contain measurable amounts of tritium. The water from these wells was recharged less than 40 years ago and indicates that the water has infiltrated vertically. Well AMA-90-04c is a shallow well which was completed in the silty clay at a depth of 7 m.

It is possible that fractures extend down to that level and the water therefore is recharged relatively quickly.

Well AMA-90-04b was completed in the top of the feature. This indicates that the water in the feature either mixes with very young water or all of the water in the feature is tritiated and was recharged very recently. All Site #1 wells contain water that is not tritiated and therefore was recharged more than 40 years ago.

4.7 Major Ions

An assessment of major ion content was done to provide additional information about the water samples. The major ion results are listed in Table 4.5 and Appendix V.

Theoretically, for a balanced charge, the sum of the cation epm should equal the sum of the anion epm for each sample. Table 4.5 shows some discrepancies. Only in samples AMA-B-01, 02, 06, 07, 08, 09, and 10 are the values within 10 % of each other. These differences may imply a missing cation, or as in six of the samples where the cation sum is greater than the anion sum, a missing anion that is an important constituent of the chemistry, but was not analyzed.

A general rule of thumb about the quantity of certain anions present gives a rough determination of the relative age of the water. A method using the quantities of bicarbonate (HCO_3^-), sulfate (SO_4^-), and chloride (Cl^-) was proposed by Chebotarev (1955, as found in Freeze and Cherry, 1979). The method determines that water rich in bicarbonate, containing little or no sulfate, is the youngest water in the system. With increasing age, the water becomes more sulfate enriched, while the amount of

Table 4.5 : Geochemical results

Hole #	Bicarb. (epm)	Ca (epm)	K (epm)	Mg (epm)	Na (epm)	Cl (epm)	Sulfate (epm)	E. C. uS/cm	Sum (epm) Cations	Sum (epm) Anions
AMA-90-01	3.95	0.53	0.23	7.90	9.08	12.55	10.83	1650	17.74	27.33
AMA-09-02a	1.39	5.15	0.22	7.98	9.63	13.59	12.91	1793	22.98	27.89
AMA-90-02b	2.94	9.82	0.22	8.04	12.77	4.687	16.15	2221	30.85	23.78
AMA-90-03	4.4	2.66	0.14	4.57	7.52	6.01	8.12	1432	14.89	18.53
AMA-90-04a	4.24	1.24	0.15	1.08	1.94	1.79	0.46	343	4.41	6.49
AMA-90-04b	3.91	2.25	0.13	1.07	0.73	1.55	0.83	318	4.18	6.29
AMA-90-04c	5.14	1.59	0.12	1.48	2.65	0.9	1.10	563	5.84	7.11
AMA-90-05	4.32	0.65	0.13	1.05	1.97	1.93		294	3.80	6.25
AMA-90-06	8.07	1.80	0.14	0.76	0.38	1.45	0.96	371	3.08	10.48
AMA-B-01	4.04	0.83	0.08	0.81	3.31	1.11		718	5.03	5.15
AMA-B-02	2.45	1.01	0.09	1.17	4.84	2.96	2.50	605	7.11	7.91
AMA-B-03	2.28	2.83	0.26	3.35	3.79	4.64	5.41	1026	10.23	12.33
AMA-B-04	1.47	11.66	0.23	14.41	8.46	13.38	34.98	2200	34.76	49.83
AMA-B-05	6.28	3.29	0.08	2.72	3.06	1.45	3.33	796	9.15	11.06
AMA-B-06	4.08	2.37	0.16	1.83	1.85	0.7	1.77	476	6.21	6.55
AMA-B-07	3.26	0.63	0.12	0.92	3.83	1.8		465	5.50	5.02
AMA-B-08	na	1.99	0.15	3.45	9.21	14.53		1530	14.80	14.53
AMA-B-09	218.9	0.79	0.09	1.61	1.61	0.58		470	4.10	219.48
AMA-B-10	213.93	1.25	0.10	1.55	1.27	0.43		467	4.17	214.36
AMA-B-11	194.03	0.57	0.11	0.65	3.51	0.63		354	4.84	194.66
AMA-B-12	149.25	0.47	0.04	0.55	4.79	0.61	1.67	448	5.85	151.53
AMA-B-13	79.6	3.96	0.10	4.59	6.03	0.26	18.74	1502	14.68	98.60

bicarbonate decreases and the amount of chloride increases. The oldest water in the system contains mostly chloride with little sulfate and no bicarbonate. Domenico (1972, as found in Freeze and Cherry) classified this sequence into three zones: the upper zone, which is relatively younger, the intermediate zone, and the lower zone, which is relatively older. Each zone was characterized by the predominance of one of the compounds.

All of the wells from Site #2 have relatively high concentrations of bicarbonate and low concentrations of sulfate and chloride. The Series B wells AMA-B-01, 05, 06, 07, 09, 10, 11, and 12 all have relatively high bicarbonate concentrations with low sulfate and chloride concentrations. Wells AMA-B-05, 06, 09, and 10 are either directly on top of the feature or very close to it. Wells AMA-B-07 and AMA-B-11 are within 2 km of the feature. This indicates the water is relatively young in this area and is actively flowing in the groundwater system.

The wells at the first site have approximately the same concentrations of bicarbonate and chloride, but have very high concentrations of sulfate. This represents water from the intermediate zone which is relatively older. The water from wells AMA-B-04 and 08 have high concentrations of sulfate and chloride. These values would place these wells in the lower intermediate zone. Cation concentration is not a useful indicator in determining relative ages. Greater concentrations of chloride are associated with greater concentrations of sodium (Na^+) and potassium (K^+) ions. A greater concentration of sulfate ions is loosely associated with a greater concentration of magnesium (Mg^{+2})ions.

Figures 4.15 and 4.16 are contour maps of chloride concentration and electrical conductivity respectively. The dashed lines represent the assumed positions of the contours where data is lacking. The contours appear to be affected by the feature, but the effect of the feature disappears just north of the study area. The water samples with the lowest chloride concentrations come from close to the feature or directly on top of it.

The shape of the contours in Figure 4.16 closely resemble the contours of Figure 4.15, and the $\partial^{18}O$ contours found on Figure 4.13. The contours of higher electrical conductivity indicate that the ion concentration is higher away from the feature and farther north along the feature.

The northern part of the feature, represented by the Series A wells at Site #1, contains the highest concentrations of chloride and the greatest electrical conductivities of all the groundwater samples taken from or very close to the feature. This suggests that water is flowing north and becoming more concentrated along its path. The contours also suggest that the groundwater very close to the feature is less concentrated than the surrounding water from the freshwater aquifer. This suggests that less chemically concentrated water , which may represent relatively younger water, is flowing northward along the feature.

The major ion composition of the freshwater aquifer gives further indications the water close to the feature is less chemically evolved. The water contains higher chemical concentrations away from the feature but also farther north of Site #2, along the feature. This indicates relatively older water in these areas.

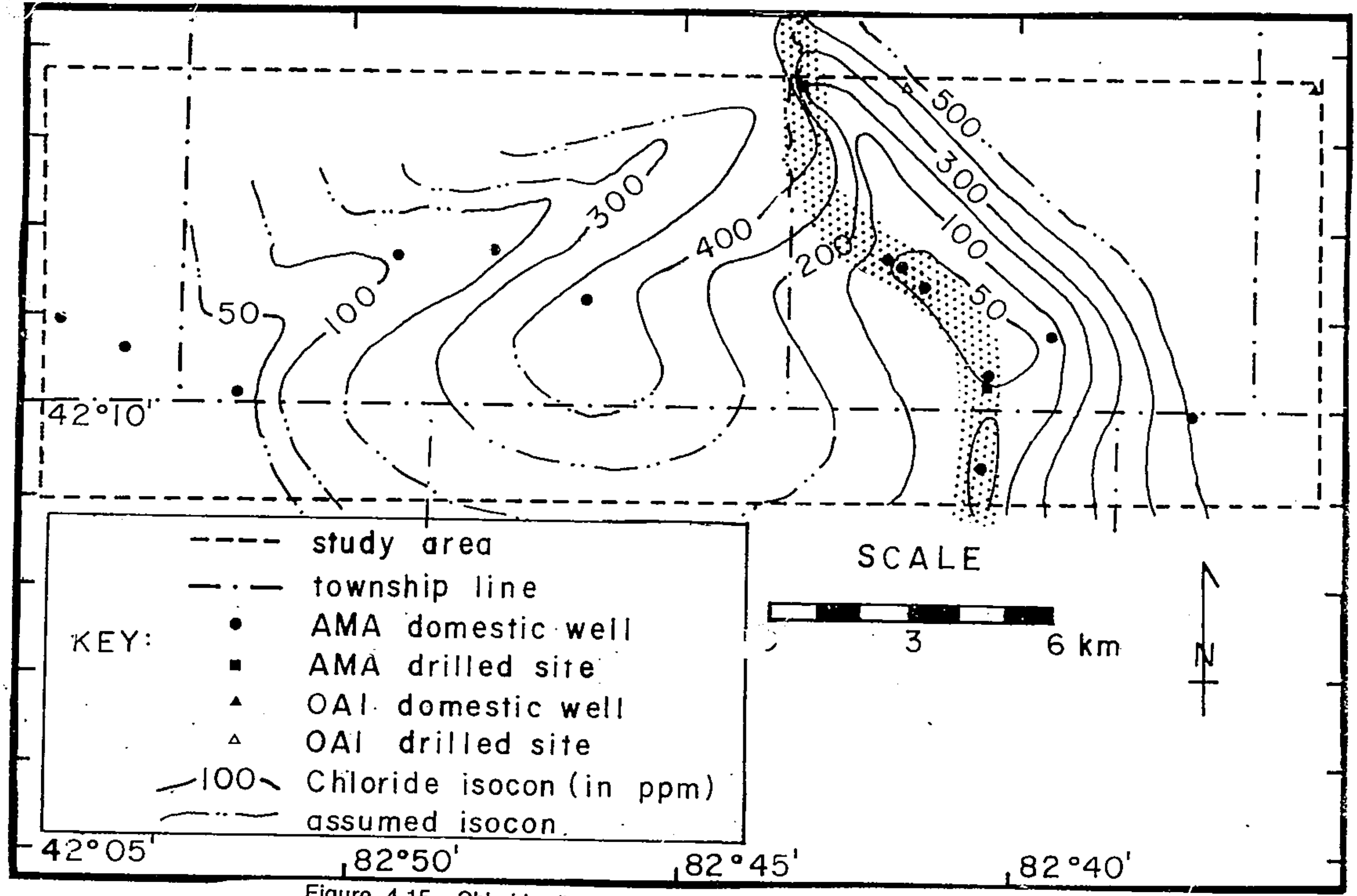

Figure 4.15 - Chloride distribution map of the study area showing Series B wells and Series A sites.

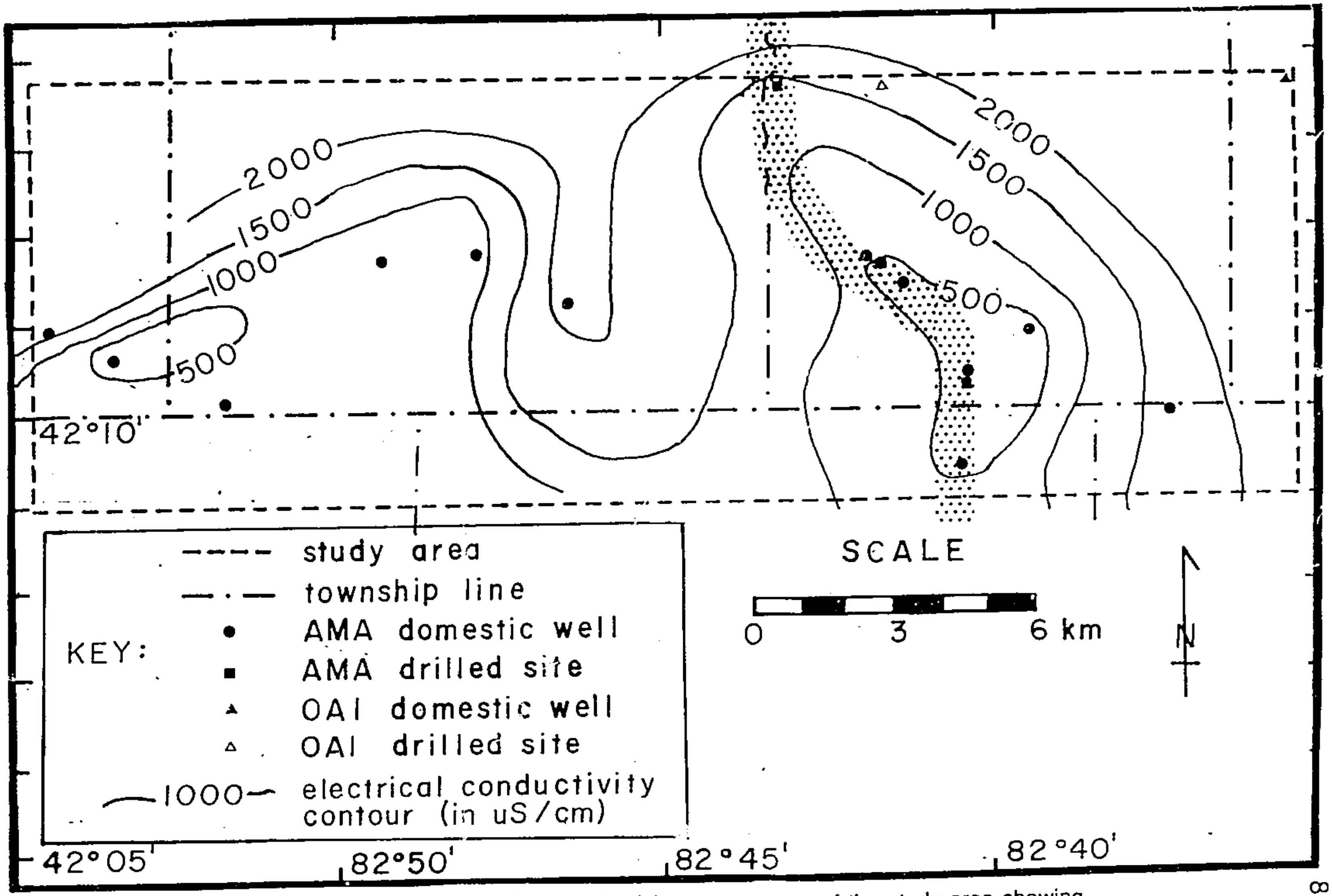

Figure 4.16 - Electrical conductivity contour map of the study area showing Series B wells and Series A sites.

4.9 Summary of Findings

A narrow, 6 m high ridge of coarse sand and gravel was encountered above the freshwater aquifer at Site #2. This feature was not intersected in any other holes, although the apron of the feature may have been intersected in other holes at this site. This feature may be an esker. At Site #1 coarse sand and gravel was not encountered, however, in the 25 m distance between two drilled wells, the fine sand layer ascended 3 m. This could represent part of the same linear morphological feature complex.

The grain size distributions indicate that the till is either a silty clay or clayey silt. There are minor discontinuous sand seams distributed throughout the till. The freshwater aquifer is a silty sand and gravel, containing up to 20% silt. The grain size profiles in the till remain relatively constant with depth, but the D_{60} size increases just above the freshwater aquifer.

The hydraulic heads for the Series B wells indicate that there is a potentiometric high over the target. In the northern part of the study area the effect is less pronounced. The potentiometric surface decreases in elevation laterally away from the feature. The hydraulic heads at Site #1 indicate that the potentiometric surface has a very low hydraulic gradient between AMA-90-01 and AMA-90-03. The hydraulic gradient between the well completed in the linear morphological feature and one completed in the apron of the feature at Site #2 is more than double the average for the county. This suggests that the water is flowing away from the feature. The piezometric nests from each Series A site, indicate that water is discharging from the freshwater aquifer into the overlying strata.

The hydraulic conductivities determined by the single well tests indicate that Site #2 has the highest values. The wells intersecting the feature have values in the order of 10^{-4} cm/s magnitude. Well AMA-90-06 has the highest hydraulic conductivity at 1.3×10^{-3} cm/s. The hydraulic conductivities for the deep wells at Site #1 are reasonable [illegible] silty sands. The silty clays have hydraulic conductivities in the order of 10^{-8} cm/s magnitude.

Young water in the area around the feature is identified by the isotopic data. Groundwater samples from the wells at Site # 2 are tritiated, indicating recharge within the past 40 years. This also indicates that vertical recharge has likely occurred for there is not an apparent source of recharge nearby. The Series B wells close to the feature were also tritiated. The ^{18}O testing indicates that the samples from the Series B wells close to the feature and the wells at Site #2 are relatively enriched, compared to the samples farther away from the feature. The depletion of the ^{18}O concentration is proportional to the distance along the feature north of Site #2 . This may indicate that water may also travel along the feature or there is local recharge present.

The major ion concentrations indicate the influence of the feature and that values are more concentrated away from the feature. They also give an indication of the relative age of the water samples. The electrical conductivity illustrates the same shape of the feature as was determined by the ^{18}O and potentiometric contours. The electrical conductivity increases away from the feature and along the feature in the northern parts of the study area.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The oxygen-18, and tritium data confirm the presence of anomalously young water in Rochester Township at Site #2. This confirms the data by MacGregor (1985) and Crnokrak (1987,1991). The geochemical data is consistent with the relatively young groundwater compared to other groundwater in Essex County.

Oxygen-18, potentiometric level, electrical conductivity, and chloride contours are all coincident with the linear morphological feature identified by Morris (1989). This suggests that the young groundwater and the location of the feature coincide. The drilling results, stratigraphic correlation, single well test data, and the hydraulic head data support the possibility that the linear morphological feature in question may be a buried esker.

The enriched tritium data indicate that some of the water in the feature is the result of vertical infiltration from above. The oxygen-18, electrical conductivity, chloride, and hydraulic head data indicate that there is also some lateral flow along the linear morphological feature. The hydraulic heads also indicate that the groundwater flows horizontally away from the feature. Groundwater discharges vertically from the feature into the overlying units at one site and appears to discharge into both the overlying and underlying units at the second site.

5.2 Recommendations

It is recommended that another site of drilled wells be installed between Site #1 and Site #2 to further define the linear extent of the feature. This would fill in the missing data and give a more complete picture of the effect the linear morphological feature has on the flow of groundwater.

More holes around the linear morphological feature at Site #2 should be drilled to identify the lateral extent of the linear morphological feature. Holes should be drilled directly west and east of AMA-90-04a to further define the dimensions of the linear morphological feature.

Angled drilling or the digging of trenches in the vicinity of Site #2 should be undertaken to identify where and how vertical infiltration is taking place, and also to verify the existence of the vertical infiltration.

A deuterium analysis compared to the oxygen-18 analysis would indicate whether water infiltrating around Site #2 is evaporated. This may also indicate the source of water infiltrating in this area.

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APPENDIX I

Stratigraphic Column of Bedrock in Essex County

System	Formation	
Devonian and Mississipian?	Port Lambton	
	Kettle Point	
Devonian	Hamilton	Ipperwash
		Petrolia
		Widder
		Olentangy
	Dundee	
	Detroit River Group	
	Bois Blanc	
Silurian	Bass Island	
	Salina	
	Guelph	
	Lockport	
	Clinton Group	Rochester
		Irondequoit - Reynales
	Cataract Group	Cabot head
		Manitioulin
Ordovician	Queenston	
	Meaford	
	Dundas	
	Billings	
	Trenton and Black River Groups	
Ordovician and Cambrian	Basal beds	
Precambrian		

Appendix I : Stratigraphic Column of Bedrock in Essex County (from Sanford and Brady, 1955)

APPENDIX II

Locations and Stratigraphy of Series B Wells

Hole#	Location Easting	Northing	Elevation (m)	Water found (m)	Static Water Level
AMA-B-01	346426	4671488	193.24	36	11.58
AMA-B-02	349520	467070	192.02	33.83	8.23
AMA-B-03	352050	4673880	188.98	33.53 38.4	10.05
AMA-B-04	356600	4672760	188.98	39.01	4.27
AMA-B-05	not found				
nearby well	360760	4673240	187.15	37.19	0.91
AMA-B-06	not found				
AMA-B-07	363400	467100	187.45	36.97	1.52
AMA-B-08	not found				
nearby well	365650	4669775	187.15	2.44	9.14
AMA-B-09	361875	4668875	190.5	30.48	3.05
AMA-B-10	not found				
nearby well	362130	4670893	188.98	14.63	1.52
AMA-B-11	not found				
nearby well	same as wells 5 and 6				
AMA-B-12	344200	4672310	193.24	35.97	11.58
AMA-B-13	342840	4673160	192.02	28.96 30.78	9.75

Hole#	Geology Description
AMA-B-01	yellow clay- 3.35, grey clay-38.40, sand shale - 39.32
AMA-B-02	clay - 32.92, medium sand- 111, rock
AMA-B-03	blue clay - 30.48, fine sand - 33.53, grey limestone - 38.40
AMA-B-04	black topsoil - 0.30, yellow clay - 4.27, blue clay - 32.00, grey sand - 35.05, grey sand clay - 38.40, brown limestone - 39.01
AMA-B-05 nearby well	clay - 31.09, hardpan - 37.19, gravel - 39.01
AMA-B-06	(coarse sand at 37.2), limestone @ 39.01
AMA-B-07	clay - 30.48, stones, hardpan - 34.75, limestone - 36.27
AMA-B-08 nearby well	clay - 29.57, hardpan - 30.48, sand - 31.09
AMA-B-09	yellow clay -4.27, blue clay - 25.60, medium sand and gravel clay - 27.43, blue clay - 29.57,
AMA-B-10	medium sand - 30.48, gravel - 31.09
nearby well	clay - 13.41, hardpan - 14.63, sand and gravel 14.93, fine sand - 28.35, gravel - 28.96
AMA-B-11 nearby well	
AMA-B-12	black topsoil - 0.30, grey clay - 12.19, grey clay - 27.43, black clay - 35.36, black sand - 35.97
AMA-B-13	black topsoil clay - 3.05, brown clay -3.35 grey clay - 28.04, blue hard pan - 29.26, grey sand - 29.87, grey sand - 30.78.

APPENDIX III

Series A Borehole Logs

Date: June 20, 1990
Hole #: AMA-90-01
Location: 217.1 m W of centerline @ Belle
River Rd
Time: 9:50 am
- 401 right of way

Depth	Description
0-10' (0-3.05 m)	-0-2'(0.61 m) - topsoil, 2-7'(2.13 m) - brown clay, fractured
10-12' (3.66 m)	-grey pebbly clay with fine grit
10-20' (6.10 m)	
20-22' (6.71 m)	-grey pebbly clay
20-30' (9.14 m)	-@27' (8.23 m) really wet clay, sand seam
30-32' (9.75 m)	-grey pebbly clay, sand seam @32' (9.75 m)
30-40' (12.19 m)	-out of really wet clay
40-42' (12.80 m)	-grey pebbly clay, minor silt
40-50' (15.24 m)	-45-48' (13.72-14.63 m)- sand seam surrounded by wet clay
50-52' (15.85 m)	-grey pebbly clay, minor grit
50-60' (18.29 m)	
60-62' (18.90 m)	-grey clay, minor silt, minor pebbles
60-70' (21.34 m)	
70-72' (21.95 m)	-grey clay, small pebbles, minor grit
70-80' (24.38 m)	
80-82' (24.99 m)	-grey clay - small green patches, very hard, very dense
80-90' (27.43 m)	-@ 84' (25.60 m) thin (approx 2 ft, or 0.61 m) sand seam
90-92' (28.04 m)	-grey clay, minor pebbles, some sand
90-100' (30.48 m)	-@ 91' (27.74 m) boulder struck with drill -96-98' (29.26-29.87 m) very dense silt layer
100-102' (31.09 m)	-very fine wet grey sand, qtz. feldspar, mica
100-110' (33.53 m)	-@102' (31.09 m) sandy gravel -@104' (31.70 m) bedrock, end of hole (EOH).

Date: June 21, 1990   Hole #: AMA-90-02a   Location:25.44 m W of #1
Time: 2:00 pm   401 @ Belle River Rd
Exit

Depth	Description
0-10' (3.05 m)	-0-2' (0.61 m) - topsoil, 2-8' (2.44 m) - brown clay, fractured
10-12' (3.66 m)	-grey pebbly clay with fine grit
10-20' (6.10 m)	
20-22' (6.71 m)	-grey pebbly silty clay, minor fine sand seams
20-30' (9.14 m)	-silty grey clay, pebbles
30-32' (9.75 m)	-grey pebbly clay, less silt but still small amounts of grit
30-40' (12.19 m)	
40-42' (12.80 m)	-grey pebbly clay, minor silt, oxidized pebbles, oxidation trails
40-50' (15.24 m)	
50-52' (15.85 m)	-@ 51' (15.54 m) sand lens, fine to med grained sand and silt -back to grey pebbly clay, minor grit
50-60' (18.29 m)	
60-62' (18.90 m)	-grey clay, minor silt, minor pebbles
60-70' (21.34 m)	
70-72' (21.95 m)	-minor wet sand seam, wet silty clay, pebbles,
70-80' (24.38 m)	
80-82' (24.99 m)	-sandy (silty) pebbly clay - more gravel- sand seam at 81.5' (24.84 m)
80-90' (27.43 m)	
90-92' (28.04 m)	-sand, fine to med. grained, clayey, some pebbles -@ 92' (28.04 m) EOH.

Date: July 10, 1990
of #1
Time: 2:00 pm
Exit

Hole #: AMA-90-02b

Location: 23.79 m W
401 @ Belle River Rd

Depth	Description
0-10' (3.05 m)	-0-2 (0.61 m)' - topsoil, 2-8 (2.44 m)' - brown clay, fractured
10-12' (3.66 m)	-grey pebbly clay with fine grit
10-20' (6.10 m)	
22.5-25' (6.86 - 7.62 m)	-grey pebbly silty clay
20-30' (9.14 m)	-@25' (7.62 m) end of hole.

Date: July 10, 1990
Aug. 15,1990
Time: 10:30 am

Hole #: AMA-90-03

Location: 20.7 m W of centerline @ Belle River Rd - 401 right of way

Depth	Description
0-10' (3.05 m)	
10-12' (3.66 m)	-grey dense clay with angular pebbles
10-20' (6.10 m)	
20-22' (6.71 m)	-grey clay, minor angular pebbles, minor sand lenses, and minor occasional fracture.
20-30' (9.14 m)	-20-27' (8.23 m) wet sand seam - @ 22' (6.71 m) up to 1' (0.30 m) cobble layer
30-32' (9.75 m)	-grey clay, angular pebbles
30-40' (12.19 m)	
40-42' (12.80 m)	-wet grey clay, minor small pebbles, minor small sand seam @40' (12.19 m)
40-50' (15.24 m)	
50-52' (15.85)	-grey clay, with angular pebbles and minor grit
50-60' (18.29 m)	
60-62' (18.90 m)	-grey clay, with angular pebbles
60-70' (21.34 m)	-62-63' (19.20 m) wet sand seam
70-72' (21.95 m)	-grey clay, fewer pebbles, slightly more sand
70-80' (24.38 m)	
80-82' (24.99 m)	-grey clay, with pebbles
80-90' (27.43 m)	
90-92' (28.04 m)	-grey clay, angular pebbles, minor fine sand
90-100' (30.48 m)	-@ 98' (29.87 m) very wet fine sand seam
100-102' (31.09 m)	-coarse sand, rounded, poorly sorted, poorly to slightly graded, polylithic
100-110' (33.53 m)	-@102' (31.09 m) well installed, EOH.

Date: Aug. 23, 1990
Hole #: AMA-90-04a
Location: 452.3 m N of centerline of Essex Co. Rd.#8 - Conc. Rd. #3, Rochester Twp.

Time: 11:30 am

Depth	Description
0-10' (3.05 m)	
10-11' (3.35 m)	-grey fractured clay with angular pebbles
10-20' (6.10 m)	
20-21' (6.40 m)	-grey clay, with sand and angular gravel grains
20-30' (9.14 m)	
30-32' (9.75 m)	-grey clay, fine grit and occasional angular gravel grains
30-40' (12.19 m)	
40-42' (12.80 m)	-grey clay, occasional angular gravel grain
40-50' (15.24 m)	-wet soft grey clay
50-52' (15.85 m)	-no sample taken
50-60' (18.29 m)	-@60' (18.29 m) clay is drier, harder
60-62' (18.90 m)	-grey clay, minor sand, occasional small angular gravel and pebbles
60-70' (21.34 m)	
70-72' (21.95 m)	-grey sandy clay, more gravel
70-80' (24.38 m)	-@73' (22.25 m) very gravelly clay - 76-76.5' (23.16 m) layer of stones- @78' (23.77 m) small layer of stones
80-82' (24.99 m)	-no shelby sample taken- material too stony and gravelly
80-90' (27.43 m)	
90-92' (28.04 m)	
90-100' (30.48 m)	-93-97' (28.35-29.57 m) dense layer of silty material -@97' (29.57 m) fine sand
100-102' (31.09 m)	
100-110' (33.53 m)	-@100' (30.48 m) well installed, EOH.

Date: Aug. 23, 1990 Hole #: AMA-90-04b Location: 449.6 m N of centerline of Essex Co. Rd. #8 - Conc. Rd. #3, Rochester Twp.

Time: 4:30 pm

Depth	Description
0-10' (3.05 m)	
10-11' (3.35 m)	-straight solid stem augering to 77 (23.47 m) feet, no sampling
10-20' (6.01 m)	
20-21' (6.40 m)	
20-30' (9.14 m)	
30-32' (9.75 m)	
30-40' (12.19 m)	
40-42' (12.80 m)	
40-50' (15.24 m)	
50-52' (15.85 m)	
50-60' (18.29 m)	
60-62' (18.90 m)	
60-70' (21.34 m)	
70-72' (21.95 m)	
70-80' (24.38 m)	-@76' (23.16 m) very gravelly clay - @77' (23.47 m)well installed, EOH.

Date: Aug. 23, 1990 Hole #: AMA-90-04c Location: 446 m N of centerline of Essex Co. Rd. #8 - Conc. Rd. #3, Rochester Twp.

Time: 11:30 am

Depth Description

0-10' (3.05 m)
10-12' (3.66 m) -no sampling until 23'
10-20' (9.14 m)
23-25'(7.01-7.62 m) -grey clay, minor grit, angular gravel grains
20-30' (12.19 m) -@25' (7.62 m) well installed EOH.

Date: Aug. 17, 1990 Hole #: AMA-90-05 Location: 483.3 m N of centerline of Essex Co. Rd. #8 - Conc. Rd. #3, Rochester Twp.

Time: 11:20 am

Depth	Description
0-10' (3.05 m)	-brown silty weathered clay- hard up to 8' (2.44 m) -@ 8' (2.44 m) natural water table, or softer grey clay
10-12' (3.66 m)	-dense brownish grey clay with rare angular pebbles sample may appear to be dense due to compression of sample.
10-20' (6.10 m)	
20-22' (6.71 m)	-moist grey clay, few angular pebbles, occasional large pebbles
20-30' (9.14 m)	
30-32' (9.75 m)	-moist grey clay, increase in angular gravel grains or pebbles
30-40' (12.19 m)	
40-42' (12.80 m)	-40-41' (12.19-12.50 m) wet sand, medium grained, rounded, 41-41.5' (12.50-12.65 m) wet sandy clay, 41.5-42' (12.65-12.80 m) grey clay.
40-50' (15.24 m)	
50-52' (15.85 m)	-moist grey clay, angular pebbles, gravel and sand
50-60' (18.29 m)	
60-62' (18.90 m)	-moist grey clay, angular pebbles, gravel and sand grains
60-70' (21.34 m)	
70-72' (21.95 m)	-moist grey clay, angular sand and gravel grains
70-80' (24.38 m)	
80-82' (24.99 m)	-80-81' (24.38-24.69 m) grey sandy clay, 81-82' (24.69-24.99 m) fine to medium sand, rounded, not well sorted.
80-90' (27.43 m)	-@ 83' (25.30 m) hard till, possibly 5' (1.52 m) of sand - interlayered sand and clay
90-92' (28.04 m)	-90-91' (27.43-27.74 m) fine sand, 91-92' (27.74-28.04 m) dense silt and fine sand.
90-100' (30.48 m)	-approximately 97-98' (29.57-29.87 m) dense silt changed to coarse sand and gravel.
100-102' (31.09 m)	-100-101' (30.78 m) fine to medium grained sand, -101-102' (30.78-31.09 m) coarse sand and gravel, very wet, poorly sorted, grains sub-rounded.
100-110' (33.53 m)	-sand and gravel seams, with dense silt @110' 6" (33.68 m) EOH

Date: Aug. 20, 1990

Hole #: AMA-90-06

Location: 519.7 m N of centerline of Essex Co. Rd. #8 - Conc. Rd. #3, Rochester Twp.

Time: 9:30 am

Depth	Description
0-10' (3.05 m)	-drillers started this one while we were not there- went down to 75' (22.86 m)- no sampling
10-12' (3.66 m)	
10-20' (6.10 m)	
20-22' (6.71 m)	
20-30' (9.14 m)	
30-32' (9.75 m)	
30-40' (12.19 m)	
40-42' (12.80 m)	
40-50' (15.24 m)	
50-52' (15.85 m)	
50-60' (18.29 m)	
60-62' (18.90 m)	
60-70' (21.34 m)	
70-72' (21.95 m)	-auger sample - grey, pebbly , gravelly, till - pebbles, clay, sand and gravel.
70-80' (24.38 m)	-@ 79' (24.08 m) small layer of sand
80-82' (24.99 m)	-auger sample - gravelly sandy till, increase in sand
80-90' (27.43 m)	-@ 82-85' (24.99-25.91 m) cobble layer, denser material, silty till - 85' (25.91 m) grey clay
90-92' (28.04 m)	-auger sample - dense silty till
90-100' (30.48 m)	-95-96' (28.96-29.26 m) stiffer drilling, layer of sand.
100-102' (31.09 m)	-auger sample - sandy till, sand with some clay, some gravel
103-105' (31.39-32.00)	-split spoon sample- gravel and coarse sand, some pebbles-oily smell.
100-110' (33.53 m)	-@106' (32.31 m) fine sand - @111.5-112' (34.00-34.14 m) bedrock - EOH.

APPENDIX IV

Single Well Test Results

	AMA-90-01	masl	H-h	H-initial head	Unrecovered head/ initial head diff.
Elevation		180.41			
Height of casing	0.43	180.84			
tatic water leve	2.5	182.91			
nitial water leve	3.9	176.94	5.97	5.97	1.00
Time @ 0					
.5 min	3.57	177.27	5.64		0.94
1	3.48	177.36	5.55		0.93
2	2.9	177.94	4.97		0.83
3	2.46	178.38	4.53		0.76
4	2.06	178.78	4.13		0.69
6	1.37	179.47	3.44		0.58
8	0.77	180.07	2.84		0.48
10	0.35	180.49	2.42		0.41
15	TOC@ 11:09				

	AMA-90-03	masl	H-h	H-initial head	Unrecovered head/ initial head diff.
Elevation		181.72			
Height of casing	0.04	181.76			
tatic water leve	1.12	182.84			
nitial water leve	5.1	176.66	6.18	6.18	1.00
Time @ 0					
2	3.94	177.78	5.06		0.82
4	2.88	178.84	4.00		0.65
6	2.31	179.41	3.43		0.56
8	1.72	180.00	2.84		0.46
10	1.23	180.49	2.35		0.38
15	0.34	181.38	1.46		0.24
20	TOC @17:52				

	AMA-90-04a	masl	H-h	H-initial head	Unrecovered head/ initial head diff.
Elevation		187.37			
tatic water leve	1.13	186.24			
nitial water leve	3.77	183.60	2.64	2.64	1.00
Time @ 0	13:37				
.5 min	3.73	183.64	2.60		0.98
1	3.71	183.66	2.58		0.98
6	3.51	183.86	2.38		0.90
8	3.45	183.92	2.32		0.88
10	3.39	183.98	2.26		0.86
15	3.25	184.12	2.12		0.80
20	3.12	184.25	1.99		0.75
25	3.00	184.37	1.87		0.71
30	2.89	184.48	1.76		0.67
45	2.58	184.79	1.45		0.55
60	2.37	185.00	1.24		0.47
90	2.12	185.25	0.99		0.38

	AMA-90-04b	masl	H-h	H-initial head	Unrecovered head/ initial head diff.
Elevation		187.42			
Static water leve	0.85	186.57			
nitial water leve	3.3	184.12	2.45	2.45	1.00
Time @ 0					
.5 min	2.76	184.66	1.91		0.78
1	2.41	185.01	1.56		0.64
2	1.93	185.49	1.08		0.44
3	1.69	185.73	0.84		0.34
4	1.53	185.89	0.68		0.28
6	1.36	186.06	0.51		0.21
8	1.31	186.11	0.46		0.19
10	1.3	186.12	0.45		0.18
15	1.25	186.17	0.40		0.16
20	1.24	186.18	0.39		0.16
25	1.24	186.18	0.39		0.16
30	1.24	186.18	0.39		0.16

	AMA-90-05	masl	H-h	H-initial head	Unrecovered head/ initial head diff.
Elevation		187.28			
Height of casing	0.38	187.66			
Static water leve	1.38	186.28			
nitial water leve	3.71	183.95	2.33	2.33	1.00
Time @ 0	14:15				
.5 min	3.40	184.26	2.02		0.87
1	3.10	184.56	1.72		0.74
2	2.64	185.02	1.26		0.54
3	2.30	185.36	0.92		0.39
4	2.07	185.59	0.69		0.30
6	1.78	185.88	0.40		0.17
8	1.62	186.04	0.24		0.10
10	1.55	186.11	0.17		0.07
15	1.46	186.20	0.08		0.03
20	1.44	186.22	0.06		0.03
25	1.41	186.25	0.03		0.01
30	1.41	186.25	0.03		0.01
45	1.40	186.26	0.02		0.01
60	1.40	186.26	0.02		0.01

	AMA-90-06	masl	H-h	H-initial head	Unrecovered head/ initial head diff.
Elevation		187.33			
Static water leve	1.10	186.23			
nitial water leve	1.18	186.15	0.08	0.08	1.00
.5 min	1.13	186.20	0.03		0.37
1	1.12	186.21	0.02		0.25
2	1.12	186.21	0.02		0.25
3 minutes	1.115	186.215	0.015		0.19
4	1.115	186.215	0.015		0.19
6	1.110	186.220	0.010		0.12
8	1.105	186.225	0.005		0.06
10	1.105	186.225	0.005		0.06
15	1.105	186.225	0.005		0.06
20	1.105	186.225	0.005		0.06

Well	Elevation (masl)	H	H (masl)	Initial head (masl)	Date	t=0	time	Elapsed time (h)	Elapsed time (m)	h (m) (below casing)
AMA-90-4c	187.45	1.94	185.51	182.8	4/12/91	15:13	15:13	0.00	0	4.650
							15:40	0.45	27	4.620
							16:20	1.12	67	4.600
					4/13/91		10:47	19.57	1174	4.390
					4/15/91		13:12	69.98	4199	3.890
					4/16/91		19:00	123.78	7427	3.870
					4/18/91		14:29	143.27	8596	3.650
AMA-09-2a	180.16	1.75	181.91	175.08	4/12/91	11:27	11:27	0.00	0	5.080
							11:30	0.05	3	5.065
							11:34	0.12	7	5.050
							11:39	0.20	12	5.040
							11:45	0.30	18	5.030
							11:49	0.37	22	5.025
							11:54	0.45	27	5.020
							11:59	0.53	32	5.010
							12:09	0.70	42	5.000
							12:19	0.87	52	4.980
							12:29	1.03	62	4.970
							13:24	1.95	117	4.880
							13:59	2.53	152	4.830
					4/13/91		10:22	22.95	1377	3.210
					4/15/91		11:30	72.05	4323	0.630
					4/16/91		18:32	103.08	6185	0.550

Well	h (masl)	H-h	H- Ho	unrecovered head /Initial Head Diff.
AMA-90-4c	182.80	2.71	2.71	1
	182.83	2.68		0.99
	182.85	2.66		0.98
	183.06	2.45		0.90
	183.56	1.95		0.72
	183.58	1.93		0.71
	133.80	1.71		0.63
AMA-09-2a	175.08	6.83	6.83	1.000
	175.10	6.82	6.83	0.998
	175.11	6.8	6.83	0.996
	175.12	6.79	6.83	0.994
	175.13	6.78	6.83	0.993
	175.14	6.78	6.83	0.992
	175.14	6.77	6.83	0.991
	175.15	6.76	6.83	0.990
	175.16	6.75	6.83	0.988
	175.18	6.73	6.83	0.985
	175.19	6.72	6.83	0.984
	175.28	6.63	6.83	0.971
	175.33	6.58	6.83	0.963
	176.95	4.96	6.83	0.726
	179.53	2.38	6.83	0.348
	179.61	2.3	6.83	0.337

Well	Elevation (masl)	H	H (masl)	Initial head (masl)	Date	t=0	time	Elapsed time (h)	Elapsed time (m)	h (m) (below casing)
AMA-90-02b	180.18	0.09	180.27	175.04	4/12/91	11:19	11:19	0.00		5.14
							11:33	0.23	14	4.76
							11:38	0.32	19	4.64
							11:46	0.45	27	4.49
							11:48	0.48	29	4.44
							11:53	0.57	34	4.35
							11:58	0.65	39	4.27
							12:08	0.82	49	4.10
							12:18	0.98	59	3.95
							12:28	1.15	69	3.81
							13:23	2.07	124	3.21
							13:59	2.67	160	2.67
					4/13/91		10:18	22.98	1379	0.61

Well	**h (masl)**	**H-h**	**H- Ho**	**unrecovered head /Initial Head Diff.**
AMA-90-02b	175.04	5.23	5.23	1
	175.42	4.85	5.23	0.93
	175.54	4.73	5.23	0.90
	175.69	4.58	5.23	0.88
	175.74	4.53	5.23	0.87
	175.83	4.44	5.23	0.85
	175.91	4.36	5.23	0.83
	176.08	4.19	5.23	0.80
	176.23	4.04	5.23	0.77
	176.37	3.9	5.23	0.75
	176.97	3.3	5.23	0.63
	177.51	2.76	5.23	0.53
	179.57	0.7	5.23	0.13

APPENDIX V

Chemical Results (in ppm)

Table of major ions

VITA AUCTORIS

NAME:	Andrew MacTavish Ainslie
PLACE OF BIRTH:	Niagara Falls, Ontario
YEAR OF BIRTH:	1963
EDUCATION: Ontario	Stamford Collegiate Vocational Institute, Niagara Falls, 1977-1982
	Brock University, St. Catharines, Ontario 1982- 1986, Honours B. Sc. in Geology
	University of Windsor, Windsor, Ontario 1989-1991, M.Sc. in Geology