THE HYDROGEOLOGY OF LANDFILL SITES IN WESTERN NEW YORK

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INTRODUCTION

Because existing state environmental regulations require extensive hydrogeologic reports for landfills, waste disposal sites provide a wealth of penetrative data that may be synthesized for characterization of regional surficial and bedrock geologic units. Access to penetrative data may be accomplished by filing a Freedom of Information request with the New York State Department of Environmental Conservation (NYSDEC).

Landfill siting and operation are governed by 6 NYCRR Part 360 regulations. This regulatory document contains a defacto table of contents for a comprehensive hydrogeologic investigation of landfill sites. Furthermore, the regulations require a literature search and analysis of broader, regional data in order to provide a context for definition of site-specific, hydrostratigraphic units. When properly completed, resultant hydrogeologic reports contain a plethora of penetrative and water quality data, as well as hydrogeologic interpretations, that academic researchers would find difficult to fund through grant-lending agencies. Consequently, in the course of local geologic or water resource investigations, hydrogeologic reports for landfill sites should not be ignored. When reconciled with data published by the U.S.G.S., U.S.D.A. Soil Conservation Service, NY State Geological Survey, and the academic community (e.g. in NYSGA guidebooks!), these hydrogeologic reports add considerable volumes of quantitative information to any geologic research database.

The purpose of this field trip is to provide an overview of the hydrogeologic aspects of the Part 360 regulations and to illustrate the diversity of hydrogeologic data collected for landfill sites. Furthermore, this article is intended to demonstrate how Part 360 data may be synthesized for characterization of geologic units in western New York. The field trip will also provide an opportunity for landfill operators to demonstrate how modern, secure facilities are planned, designed, operated and closed to minimize negative environmental impacts.

PART 360 LANDFILL SITING PROCESS

Landfill siting is a controversial and expensive proposition in New York State. The process had been particularly controversial for the private sector under previous versions of Part 360. One particular problem would commonly arise when a potential landfill site was selected, based upon economic and/or geographic characteristics, before performance of a formal Part 360 site selection study. Site selection studies, both under previous and current versions of Part 360, involve comparison of potential sites on the basis of hydrogeologic, engineering and socio-economic properties. Ideally, the site selection process provides a means to determine the "best" site out of many potential landfill locations. Prior to the October 9, 1993 revision to the Part 360 regulations, when a preferred site would be chosen before other candidate sites were identified, expensive siting studies would subsequently have to be "retrofitted" to produce the desired conclusion that the preferred site is the most appropriate location among other "strawman" candidate sites for the facility.

The New York State Department of Environmental Conservation apparently recognized the quandary in which project sponsors found themselves when the preferred, suitable site was identified prior to completion of the formal site selection study. Furthermore, the NYSDEC also apparently recognized that, because siting studies require analysis of non-hydrogeologic variables (e.g. transportation, population, utilities, etc.), less hydrogeologically suitable sites could potentially be promoted over sites with more desirable subsurface characteristics for reasons other than susceptibility to groundwater and surface water contamination. Apparently for these reasons, the NYSDEC recently revised the Part 360 siting process for project sponsors who identify sites that exceed minimum hydrogeologic and engineering criteria for landfill construction. Under certain specifically stated hydrogeologic conditions, an expensive site selection study may not be required to defend the obvious merits of a highly suitable site. The revised regulations ease the financial burden and the logistical difficulty in objective compliance with landfill siting requirements when specified hydrogeological conditions are met. By establishing standards which must be met in order to waive the requirement for a site selection study, the NYSDEC can still guarantee that landfills can be constructed and operated in a manner which minimizes the potential for negative impacts to humans, wildlife or the environment.

The following is a synopsis of the landfill siting regulations as stated in the October 9, 1993 revision to the Part 360 regulations:

Siting Prohibitions and Restrictions

1. Prime agricultural land, within an agricultural district formed pursuant to the Agricultural and Markets Law, is excluded from siting if the landfill site is proposed to be taken through the exercise of eminent domain.

2. Flood plains are excluded from siting unless provisions have been made to prevent encroachment of flood waters upon the facility and unless the facility will not pose a significant hazard to humans, wildlife, or land or water resources.

3. Critical habitat for endangered species is excluded from siting.

4. Regulated wetlands are excluded from siting.

5. No landfills may be constructed over principal or primary aquifers[1], or within the cone of a public depression water supply well.

6. Proximity of landfills to airports is a concern because of the hazards associated with bird/plane impacts. Therefore, no landfill containing putrescible waste may be constructed within 5,000 ft. from an airport runway used by piston-powered aircraft or within 10,000 ft. from an airport runway used by turbine-powered aircraft.

7. No landfills may be constructed over unstable areas. According to the Part 360 regulations, unstable areas are those susceptible to natural or human-induced events or forces capable of impacting any structural component of the landfill responsible for leachate containment. Lands suspectable to landslides or sink holes are examples of unstable areas.

8. No landfill may be located in an area that is unmonitorable or unremediable. For example, groundwater flow rates and directions must be predictable. Site conditions must permit the placement of groundwater monitoring wells both upgradient and downgradient of the facility. Furthermore, site conditions must not preclude the ability to remediate in the event of a contaminant release.

9. Landfills cannot be constructed within 200 ft. of a fault that has had displacement during Holocene time unless the owner or operator demonstrates that the facility will not suffer structural damage in the event of fault displacement.

10. Landfills must not be sited in seismic risk zones, unless the owner/operator demonstrates that the integral containment structures can resist the maximum horizontal ground acceleration. Seismic risk zones are areas where a 10 percent or higher probability exists that the maximum horizontal ground acceleration in lithified earth material, expressed as a percentage of earth's gravitational pull (g), will likely exceed 0.10 g in 250 years.

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[1] *Principal* and *primary* aquifers are NYSDEC designations. A *principal* aquifer is one which has potential for development but is not currently exploited. A *primary* aquifer is one which is presently utilized for municipal water supply.

Landfill Siting Requirements

A formal landfill siting study involving penetrative investigation of multiple candidate sites will not be required if a preferred site is identified which does not conflict with the preceding siting prohibitions and restrictions and also exhibits the following characteristics:

1) The site is not underlain by bedrock subject to rapid or unpredictable groundwater flow unless the project sponsor demonstrates that a failure of the facility's containment system would not result in contamination entering the bedrock system.

2) The site is not in close proximity to any mines, caves or other anamolous features that may alter groundwater flow.

3) The site must contain an unconsolidated overburden thickness of 20 ft. or greater beneath the constructed liner system.

4) More than 50 percent of the vertical section through the upper 20 ft. of overburden must consist of soils with a permeability of less than $5x10^{-6}$ cm/s with no appreciable, continuous deposits exhibiting a permeability greater than $5x10^{-4}$ cm/s. The top five ft. of soil beneath the constructed liner must be able to achieve a permeability of $5x10^{-6}$ cm/s or less (Figure 1).

New landfills may be located on parcels that do not exhibit the above characteristics if two conditions are met.

1. The proposed facility is identified in a NYSDEC-approved local solid waste management plan; and

2. A formal site selection study involving multiple candidate sites is performed.

Waiver of an expensive site selection study provides a prime motive to identify a preferred site that exhibits suitable hydrogeologic conditions for landfilling. Site selection studies are costly, comprehensive analyses that evaluate hydrogeologic, economic, technologic, and public safety factors. The site selection study must demonstrate that, in spite of not meeting the previously stated siting requirements, operation of a facility on the preferred site will have no adverse impacts on public health, safety, or welfare, the environment or natural resources and will be consistent with the provisions of the State Environmental Conservation Law.

Site selection studies are expensive, because the process requires that alternative sites are evaluated to a comparable degree as the preferred site. Penetrative hydrogeologic investigations are required to determine depths to water and bedrock as well as the hydraulic conductivities of the various surficial and bedrock geologic units. The goal of the penetrative investigations is to ensure that the following siting criteria are satisfied:

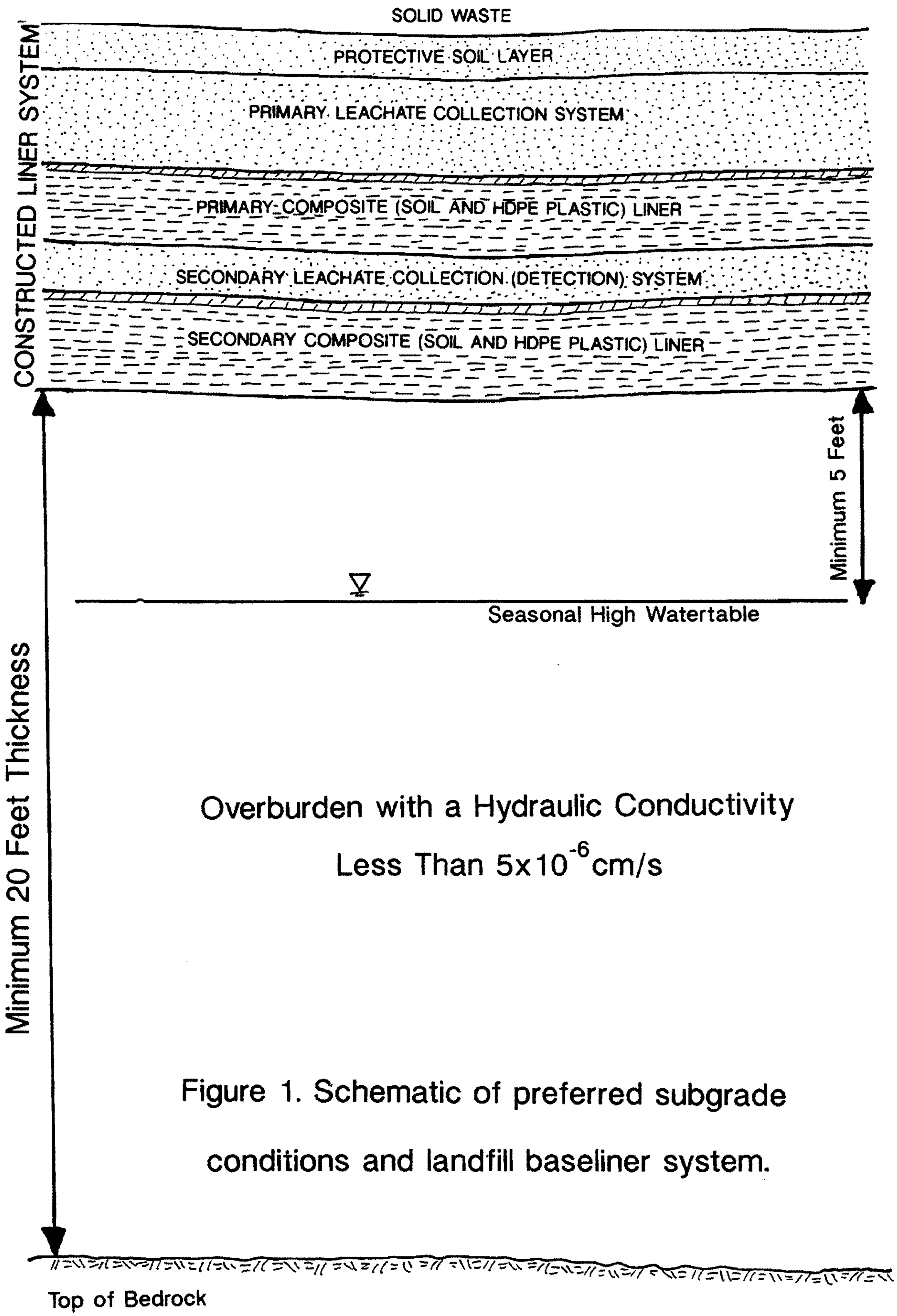


Figure 1. Schematic of preferred subgrade conditions and landfill baseliner system.

1) Candidate sites are those with the greatest possible thickness of unconsolidated deposits exhibiting hydraulic characteristics that permit them to serve as a barrier to migration of contaminants into rock.

2) Groundwater flow in bedrock must not be rapid or unpredictable unless it can be demonstrated that a designed containment system would not allow fugitive leachate to produce a contravention of groundwater quality standards.

3) Groundwater flow and quality must be such that containment failure would do the least environmental damage and could be easiest to correct.

4) Proximity and hydrogeologic relationship to water supply sources should be negligible.

5) Natural topography cannot be so steep that the engineered baseliner is unstable.

6) Relationship to mines, caves, or other anomalous hydrogeologic features that might alter groundwater flow should be negligible.

So, as can be discerned, if a project sponsor is going to promote a site as a possible host for a landfill, it is in his best interest to identify the site that truly meets the hydrogeologic standards necessary to avoid the requirement for a site selection study.

Waiver of the need for a site selection study does not, however, waive the requirements under the State Environmental Quality Review Act (SEQRA) for the project sponsor, the lead agency (usually the NYSDEC), and the concerned public to participate in an exhaustive analysis of environmental conditions, risks, impacts, and potential mitigation measures. The recent revisions to the Part 360 regulations save the project sponsor from unnecessarily consuming financial resources to defend the obvious merits of a highly suitable site so that appropriate emphasis can be placed on the SEQRA Environmental Impact Statement (EIS) and other engineering and hydrogeological documents required for the Part 360 permit application to construct and operate the facility.

Can Optimal Hydrogeologic Settings Be Defined?

The Part 360 process clearly promotes research to locate sites within hydrogeologic settings most likely to satisfy the stringent siting requirements. Recent efforts to place some geographic constraints on some of the hydrologic parameters necessary to streamline the siting process yielded a preliminary "terrain suitability map for landfill siting" (Goodman and others, 1992).

The map and its component "layers" (bedrock, surficial geology, aquifers and wetlands maps), that are based upon available published maps from the state and federal geologic surveys and agencies, can be used to determine regions (at the resolution of 1:250,000 scale data) that may exhibit characteristics unsuitable for landfill siting. Such characteristics that are discernible on the regional-scale maps include major limestone formations which could potentially exhibit karstic features, areas of exposed bedrock, faults, coarse-grained unconsolidated deposits, both documented and potential aquifers, and large-scale wetland areas (Figures 2A-D). Terrains possessing relatively unsuitable characteristics were shaded on the state-wide maps; conversely, relatively suitable areas were shown in white. When the layers are superimposed, a terrrain suitability map is the product (Figure 3). The map provides a degree of geographic tangibility to some of the hydrogeologic conditions which restrict or prohibit siting. This type of map may be useful for public awareness seminars, because the citizens of many low population regions of the state perceive that they are being "dumped on" by more populous areas. In actuality, there is a hydrogeologic rationale for prioritizing some areas of the state over others in the preliminary siting stage.

The results of the initial analysis suggest that, on the basis of hydrogeology alone, the Appalachian Plateau region contains the least sensitive and, therefore, most suitable terrains for landfill siting. The Erie-Ontario Plain also contains suitable hydrogeologic settings. Both of these physiographic provinces contain shale-rich bedrock units which are overlain by variably thick, fine-grained, glacial till and/or lacustrine deposits. It should be noted, however, that the terrain suitability map of Goodman and others (1992) was designed to address only hydrogeological siting criteria. Other demographic, economic, and transportation issues remain to be evaluated on a case-by-case basis.

The terrain suitability analysis may be useful for developing regional landfill siting strategies. Because of the generalized data used to construct it, however, the map does not serve as a substitute for site-specific hydrogeologic analysis (Cloyd and Concannon, 1993). In fact, key landfill construction requirements for bedrock and groundwater separation obviously cannot be evaluated using 1:250,000 scale data. Therefore, division of the major physiographic provinces into discrete hydrogeologic settings using all available maps and penetrative data is necessary to begin to produce "terrain suitability maps" at the appropriate scale for evaluation of local or site-specific conditions (Smith and others, 1993; Cole and others, 1993; Goodman and Stanwix, 1994). Only after evaluation of the compatibility of small-scale hydrogeologic settings with Part 360 siting and construction criteria can "optimal" subsurface conditions for landfill siting be mapped.

HYDROGEOLOGIC SETTINGS OF WESTERN NEW YORK

Western New York State is situated at the eastern limits of the Central Glaciated Groundwater Region of Health (1984). Aller and others (1987) have defined sixteen discrete hydrogeologic settings for the region (Table 1) as a foundation for

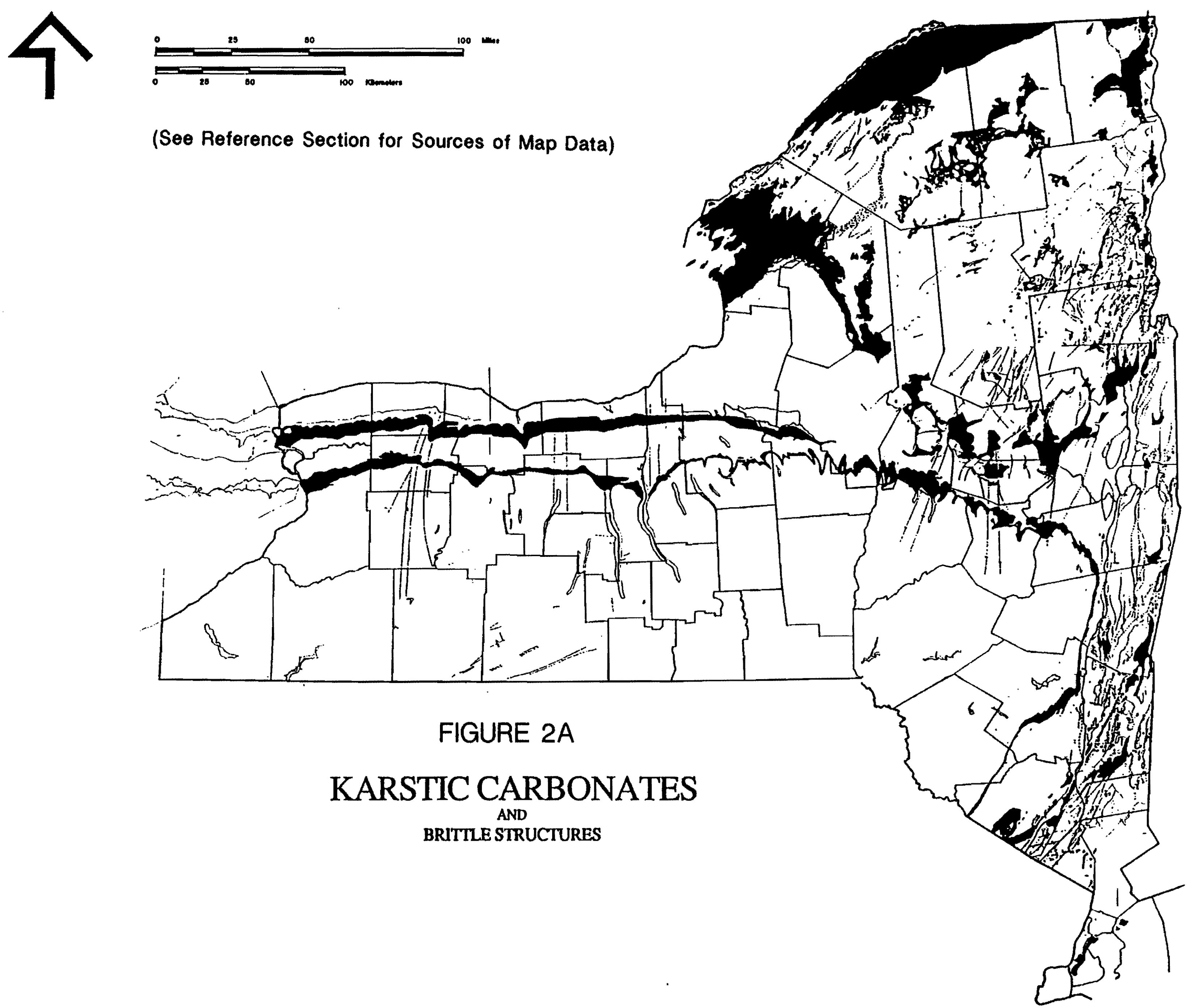
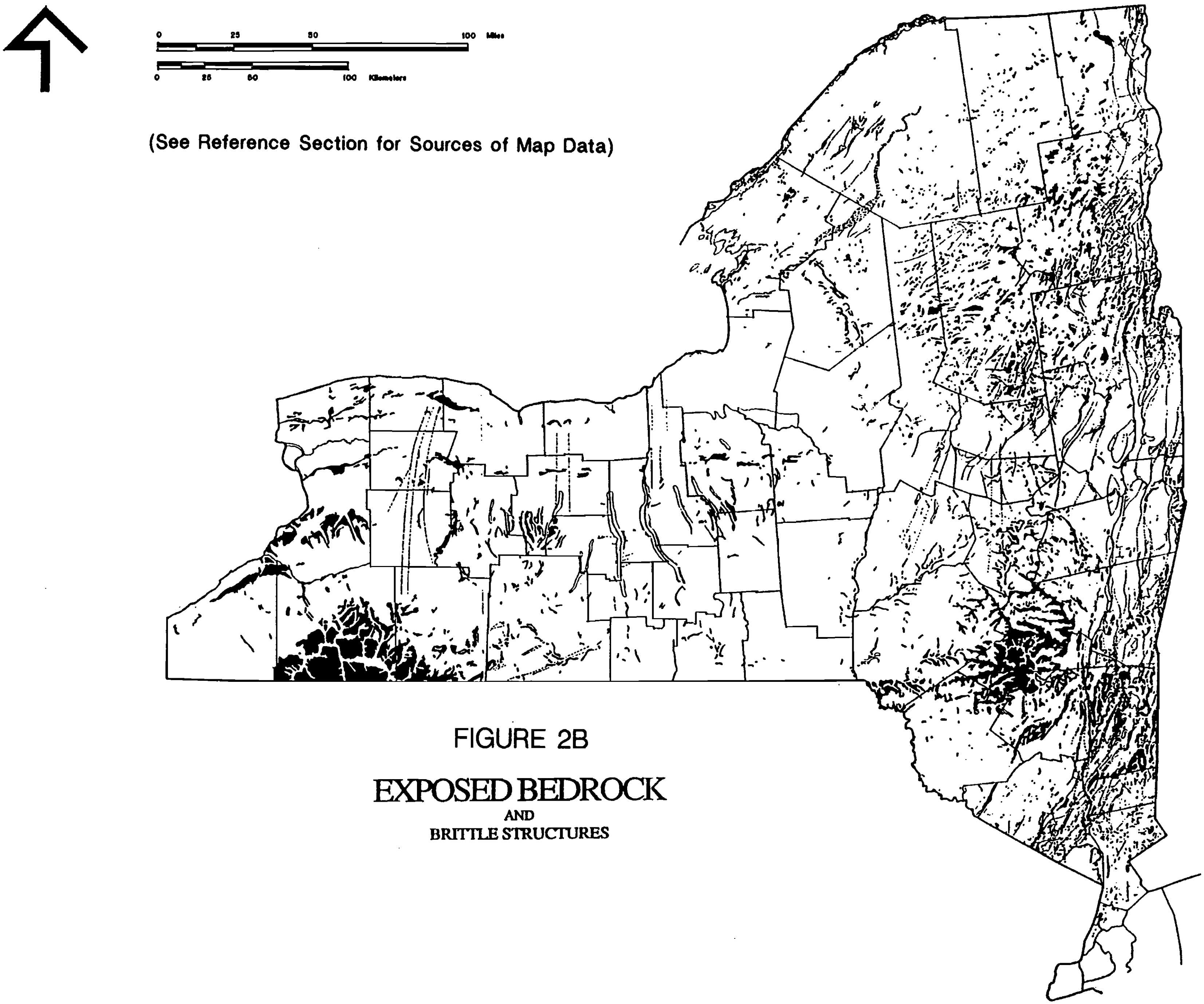


FIGURE 2A

KARSTIC CARBONATES
AND
BRITTLE STRUCTURES



(See Reference Section for Sources of Map Data)

FIGURE 2B

EXPOSED BEDROCK
AND
BRITTLE STRUCTURES

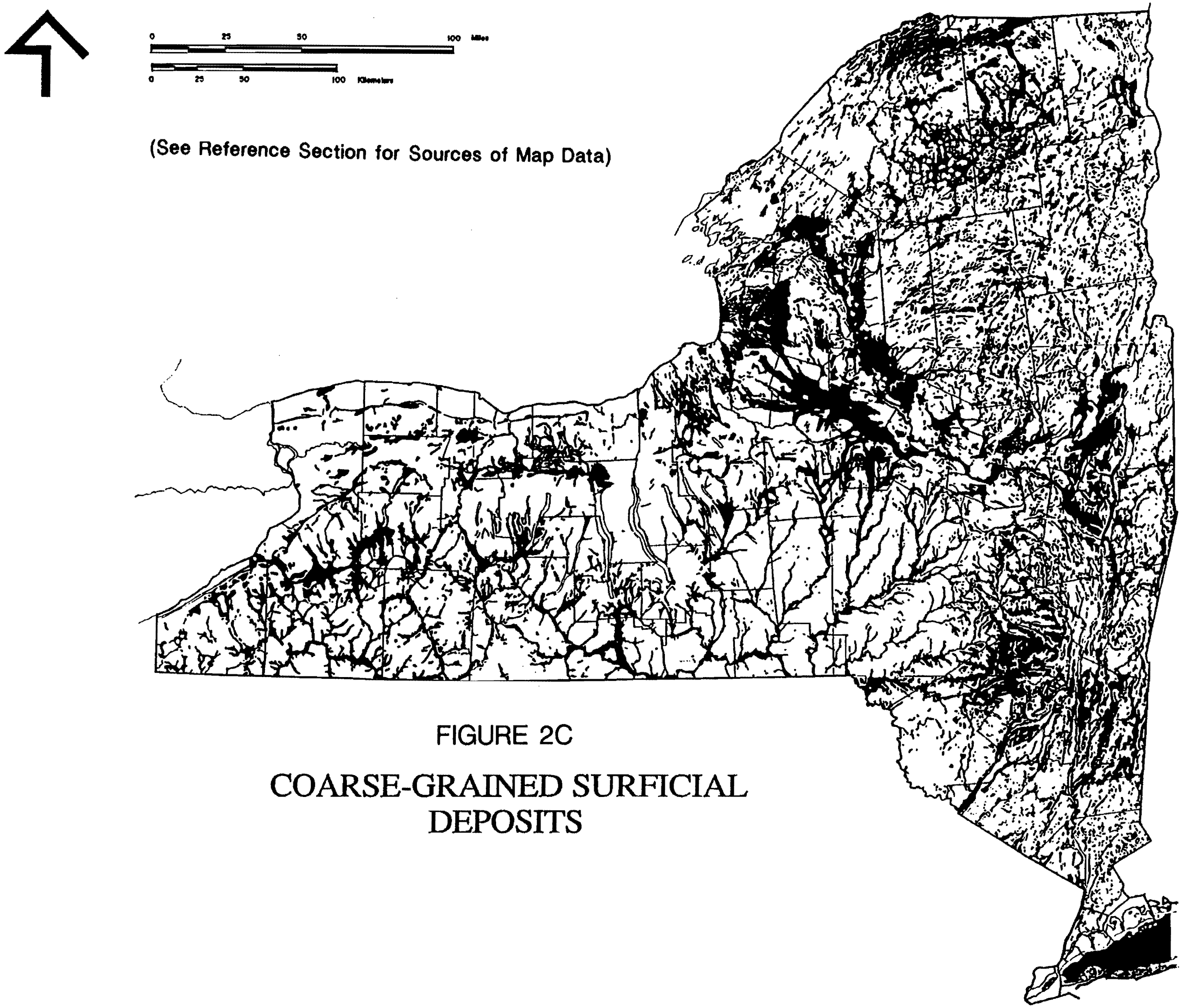
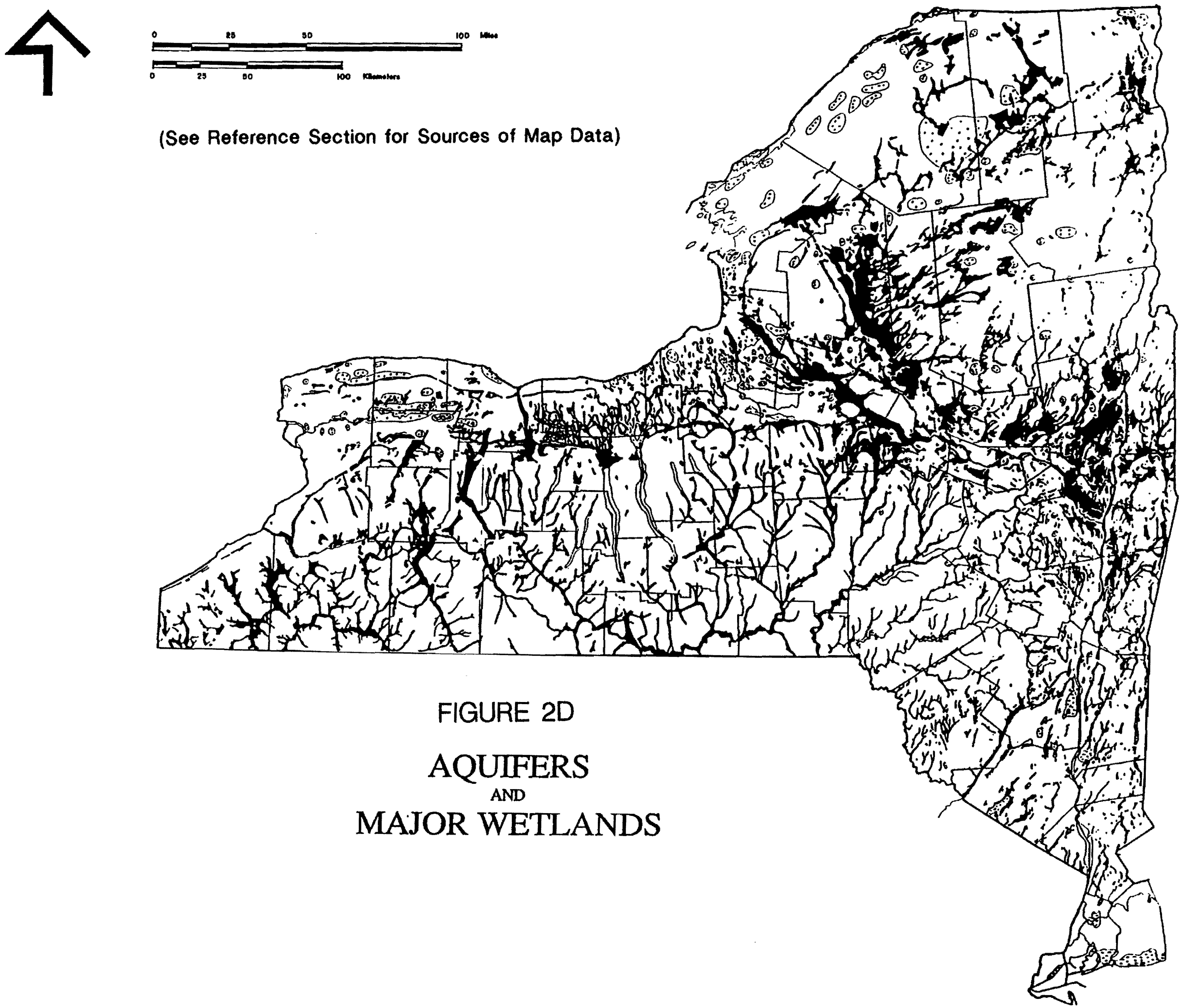


FIGURE 2C

COARSE-GRAINED SURFICIAL DEPOSITS



(See Reference Section for Sources of Map Data)

FIGURE 2D

AQUIFERS
AND
MAJOR WETLANDS

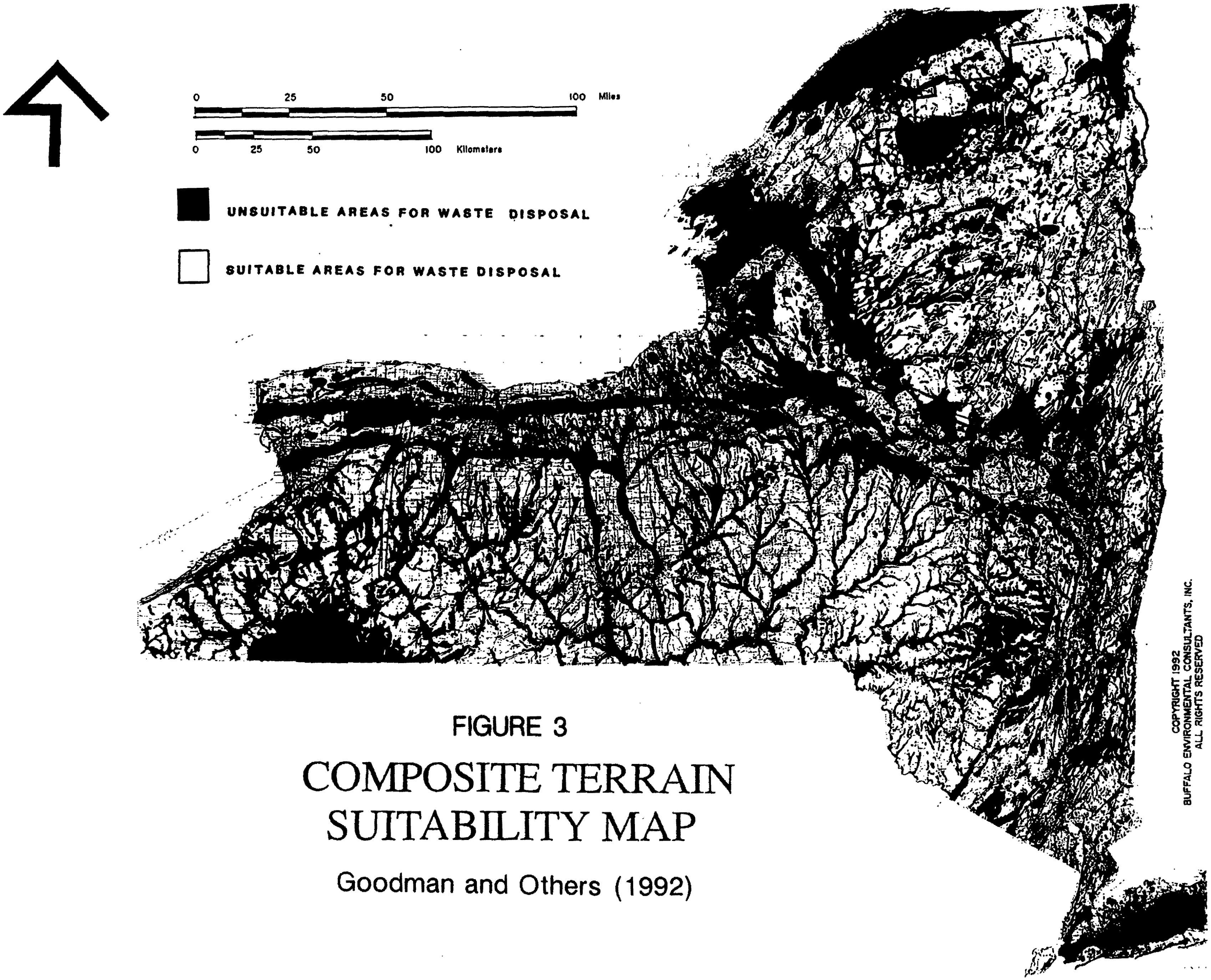


FIGURE 3

COMPOSITE TERRAIN SUITABILITY MAP

Goodman and Others (1992)

AFI ENVIRONMENTAL
6101 ROBINSON ROAD
LOCKPORT, NEW YORK 14094
(716) 625-3434

Table 1
Hydrogeologic Settings and Representative Drastic Indices[1] of the Central Glaciated Region
(Aller and others, 1987)

Setting	Drastic Index
Glacial Till over Bedded Sedimentary Rock	103
Glacial Till over Outwash	137
Glacial Till over Solution Limestone	139
Glacial Till over Sandstone	109
Glacial Till over Shale	88
Outwash	176
Outwash over Bedded Sedimentary Rock	156
Outwash over Solution Limestone	186
Moraine	135
Buried Valley	156
River Alluvium with Overbank Deposits	134
River Alluvium without Overbank Deposits	191
Glacial Lake Deposits	135
Thin Till over Bedded Sedimentary Rock	121
Beaches, Beach Ridges and Sand Dunes	202
Swamp, Marsh	160

[1] Drastic Indices provide a relative gauge of sensitivity to point sources of pollution. The higher the index, the higher the vulnerability of the hydrogeologic setting.

their DRASTIC model[2]. Each hydrogeologic setting has been assigned a representative DRASTIC index which is a relative gauge of the vulnerability of groundwater resources to contamination from point sources at ground surface. The higher the assigned DRASTIC index value is, the more vulnerable the hydrogeologic setting is to groundwater contamination.

Existing, operating landfills, proposed facilities and a limited number of closed facilities in Western New York (NYSDEC Regions 8 and 9) are shown in Figure 4. The sites, their hydrogeologic settings and key bedrock and surficial deposits are identified in Table 2. As can be discerned, the majority of landfill sites are situated in those hydrogeologic settings with low DRASTIC indices. For example, the majority of sites located in the Appalachian Plateau are situated in "Glacial Till Over Bedded Sedimentary Rock" hydrogeologic settings. The exception is CID Landfill which is situated on low permeability till and lacustrine deposits within the Valley Heads Moraine complex. Most sites located on the Erie-Ontario Plain occupy two hydrogeologic settings: "Glacial Till over Bedded Sedimentary Rock" and "Glacial Lake Deposits". The exceptions are the Schultz C&D Landfill ("River Alluvium with Overbank Deposits") and the Niagara County Landfill that is located in a limestone quarry in Lockport, N.Y. In the following sections, the hydrologic properties of the various key deposits comprising the most suitable hydrogeologic settings for landfill siting are presented in order to demonstrate their compatibility with Part 360 criteria as well as the nature and depth of data required for landfill siting and routine monitoring during operation and after closure.

APPALACHIAN PLATEAU

Based upon analysis of 9 landfill sites, a general model of the "Glacial Till Over Bedded Sedimentary Rock" hydrogeologic setting may be developed for the Appalachian Plateau of western New York (Fig. 5). Common elements among these sites include a bedrock hydrostratigraphy consisting of, in descending order, a glacitectonized rock aquitard, a fractured rock aquifer, and a competent rock aquitard. Other common elements include a low permeability surficial geologic profile consisting predominantly of lodgement and ablation till facies. A cross-cutting weathered zone, whose basal boundary is demarcated by a color change in tills and bedrock from brown above to gray below, probably reflects the slow, vertical migration of an oxidation front during the Holocene. The weathered zone cross-cuts glacigenic facies boundaries and also extends into bedrock beneath high elevation topographic divides that define local drainage basins. These common elements are described below.

Regional Bedrock Hydrostratigraphy

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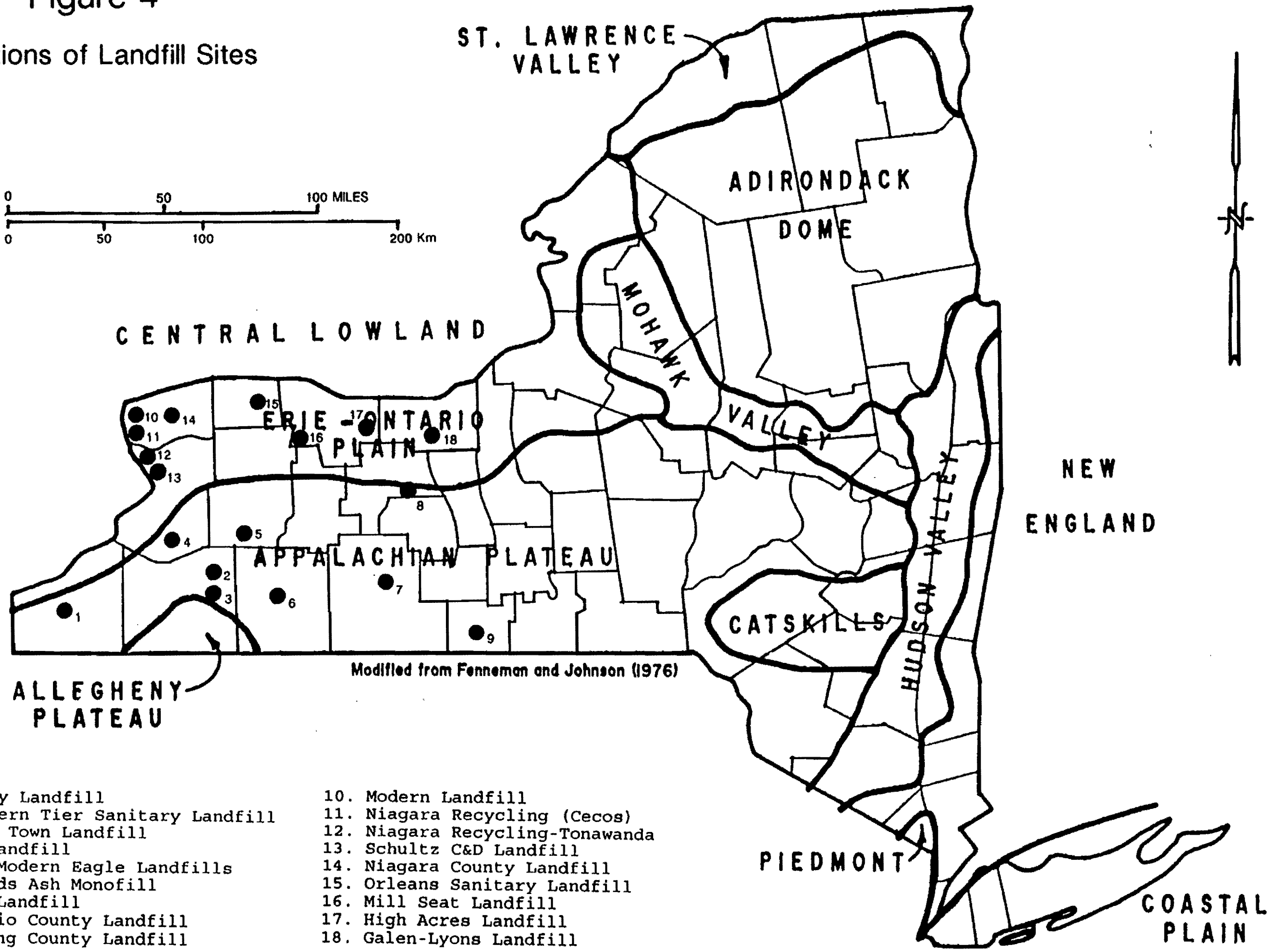
2 DRASTIC is an acronym for seven hydrogeologic parameters that influence the vulnerability of groundwater to pollution from point sources at ground surface. These variables are 1) depth to water (D); 2) recharge rate (R); 3) composition of the local aquifer medium (A); 4) soil type (S); 5) topographic slope (T); 6) influence of the vadose zone media (I); and 7) hydraulic conductivity of the local aquifer (C).

Figure 4

Locations of Landfill Sites



1. Ellery Landfill
2. Southern Tier Sanitary Landfill
3. Olean Town Landfill
4. CID Landfill
5. BFI, Modern Eagle Landfills
6. Hylands Ash Monofill
7. Bath Landfill
8. Ontario County Landfill
9. Chemung County Landfill
10. Modern Landfill
11. Niagara Recycling (Cecos)
12. Niagara Recycling-Tonawanda
13. Schultz C&D Landfill
14. Niagara County Landfill
15. Orleans Sanitary Landfill
16. Mill Seat Landfill
17. High Acres Landfill
18. Galen-Lyons Landfill

zones.

Glacitectonized Bedrock Zone

Glacitectonized bedrock forms as stress imposed by moving ice deforms underlying bedrock units (Boulton and Paul, 1976; McGown and Derbyshire, 1977). Glacitectonized bedrock may commonly include small-scale, local folds and low-angle detachments. The competence of bedrock units (e.g. competent sandstone vs. incompetent shale) is the predominant determining factor controlling the degree of bedrock deformation beneath glacial ice. Less competent units tend to deform in a ductile, fold-forming fashion. More competent units tend to deform in a brittle fashion and, in some cases, form large, detached blocks (bedrock rafts) within poorly-sorted, variably comminuted matrix. Bedrock rafts render definition of local depth to bedrock (a key regulatory requirement) extremely difficult on landfill sites in the Appalachian Plateau of western New York.

Incorporation of significant volumes of till matrix between rotated bedrock rafts renders the glacitectionized bedrock zone readily identifiable. In areas where shale bedrock formations subcrop, the glacitectonized zone may be sampled using standard penetration tests with a split spoon sampler through hollow stem augers. Spoon samples will usually yield "disks" of weathered shale mixed with till.

In areas underlain by harder sandstone, the interval is more clearly observable in drill cores. Cores exhibit alternating zones of till matrix containing gravel-size, angular rock fragments and large, detached and rotated blocks of bedrock.

Generally, the glacitectonized bedrock zone is treated as the base of the lodgement till profile by most consultants because of the dislocation of the large bedrock rafts and the till matrix. The regulatory community, however, may prefer to use a more conservative definition of this interval as the top of the bedrock profile in order to insure that a minimum of ten feet of unequivocally defined, low permeability overburden is maintained beneath the constructed baseliner.

Given the gradational boundaries of the glacitectonized bedrock zone with the overlying lodgement till and underlying fractured bedrock aquifer, few sites contain wells that are screened discretely in this interval from which hydraulic conductivity values may be derived. At the Bath Landfill, however, six wells are screened in the zone and yield a range of K values between 2.8×10^{-6} cm/s and 2.2×10^{-5} cm/s and a geometric mean K value of 8.3×10^{-6} cm/s (Malcom Pirnie, 1994).

Seven wells are screened in the glacitectonized bedrock zone at the Southern Tier Sanitary Landfill site. These wells yield a range of K values between 1.9×10^{-5} and 5.0×10^{-4} cm/s and a geometric mean K value of 9.3×10^{-5} cm/s (AFI Environmental, 1992a).

Although thin till seams along bedding planes have been observed on some sites to depths of nearly 200 feet below ground surface, till injections into vertical fractures generally decrease progressively through the upper 30 feet of rock section and a gradual transition occurs from the till-choked, glacitectonized zone to the more permeable, fractured bedrock aquifer.

Fractured Bedrock Zone

The fractured bedrock zone is informally defined as the interval between the glacitectonized and competent bedrock zones. The interval is characterized by open, vertical fractures and numerous bedding parallel partings that may locally contain glacial detritus. Vertical fractures commonly are weathered indicating variations (probably seasonal) in degree of saturation. These fractures are also commonly lined by manganese oxides that, in conjunction with dissolution of calcareous fossils, render a blackened, decayed appearance to the joints.

On sites where the fractured and underlying competent bedrock zones are defined discretely, RQD data commonly reflect the differences in rock competency (Table 3). These data indicate that the RQD of a formation whose upper surface lies within the bedrock fracture zone may possess only 30% or less of the RQD value representative of the formation in the competent bedrock zone. The low RQD values of the aquifer zone reflect the numerous, bedding-parallel fractures that probably developed during unloading of glacially compressed bedrock. The combination of localized, differential slippage along bedding planes, perhaps induced in part by anomalously high subglacial hydrostatic pressure, and formation of unloading joints during stress relief, imposes a high secondary porosity on the top 10 to 30 feet of relatively till-free bedrock beneath most sites in the Appalachian Plateau. Consequently the hydraulic conductivity of the fractured bedrock zone is generally higher than corresponding values for the overlying glacitectonized zone and the underlying competent bedrock zone (Table 4).

Competent Bedrock Zone

In the competent bedrock zone, drill core samples are well-preserved, and strata retain their original gray tone colors, whereas the overlying glacitectonized and fractured aquifer zones may be oxidized to brown hues. Calcareous fossils remain intact and vertical fractures are tight and contain much less of the manganese oxide coating and fewer injected till seams that also are characteristic of the overlying horizons.

The hydraulic conductivity of the competent bedrock zone is slightly lower than that of the overlying bedrock hydrostratigraphic units (Table 4). Most sites possess a competent bedrock profile exhibiting a geometric mean K value in the low to mid 10^{-5} cm/s range although stratigraphic control on permeabilities at some sites may result in slightly higher mean values.

Table 3
RQD Values of Formations in the Fractured and Competent Bedrock Zones
Appalachian Plateau

Site	Depth of Fractured Zone (ft.)	Ave RQD in Fractured Zone	Ave RQD in Competent Zone
Olean Landfill[1]			
Machias Shale	24	23%	46%
Cuba Sandstone	12	11%	46%
Wellsville Shale	12	0%	37%
Hylands Ash Monofill[2]			
Machias Shale	24	17%	53%
Cuba Sandstone	12	12%	65%
Wellsville	35	8%	65%

Notes:
(1) Earth Investigations LTD. (1990a)
(2) Earth Investigations LTD. (1990b)

Table 4. Hydraulic conductivity (cm/sec) of formations in the fractured and competent bedrock zones for the Appalachian Plateau.

Site Formations	Fractured Zone Mean	Max	Min	N	Competent Zone Mean	Max	Min	N
Bath Landfill[1] Wiscoy, Caneadea	1.4 x 10^{-4}	1.0 x 10^{-3}	6.0 x 10^{-5}	9	4.3 x 10^{-5}	2.3 x 10^{-4}	1.4 x 10^{-5}	7
Hylands Ash MonoFill[2] Machias, Cuba, Wellsville	5.6 x 10^{-5}	3.7 x 10^{-4}	3.3 x 10^{-6}	9	1.7 x 10^{-5}	2.3 x 10^{-4}	1.2 x 10^{-6}	16
Olean Landfill[3] Cuba, Wellsville	2.6 x 10^{-5}	5.1 x 10^{-4}	9.6 x 10^{-6}	4	2.5 x 10^{-4}	1.2 x 10^{-3}	5.5 x 10^{-6}	20
Southern Tier Saniitary Landfill[4] Lower and Upper Canadaway Group	--	--	--	--	5.8 x 10^{-5}	9.1 x 10^{-3}	3.4 x 10^{-9}	77
Ellery Landfill[5] Ellicott Group	3.5 x 10^{-4}	2.0 x 10^{-4}	6.7 x 10^{-5}	10	2.4 x 10^{-4}	4.3 x 10^{-4}	3.5 x 10^{-5}	26
Modern-Eagle[6] Lower Canadaway Group	--	2.5 x 10^{-3}	8.4 x 10^{-5}	--	--	--	--	--

[1]Malcolm-Pirnie (1994b)
[2]Earth Investigations LTD (1990b)
[3]Earth Investigations LTD (1990a)
[4]AFI Environmental (1992a)
[5]Dunn Geoscience (1988)
[6]Malcolm-Pirnie (1994a)

Regional Surficial Hydrostratigraphy

Surficial geologic maps covering the study area are provided by Tessmer (1975), Muller (1977), and Cadwell (1988). The general distribution of glacial deposits in the Appalachian Plateau is such that hills supported by Upper Devonian sedimentary bedrock are covered by sheets of poorly-sorted, low permeability, glacial till and intervening valleys are filled by up to 500 feet of mixed glacial till, outwash and stream alluvium (Muller, 1977; LaFleur, 1979; Prudic, 1982). Stream valleys are typically occupied by perennial streams and can contain alluvium consisting of permeable sand and gravel (Crain, 1966; Miller, 1988). The northeast orientation of many of the stream valleys suggests that they reflect preglacial fluvial drainages that were subsequently deepened and widened by continental valley glaciation (Calkin, 1982; Prudic, 1986).

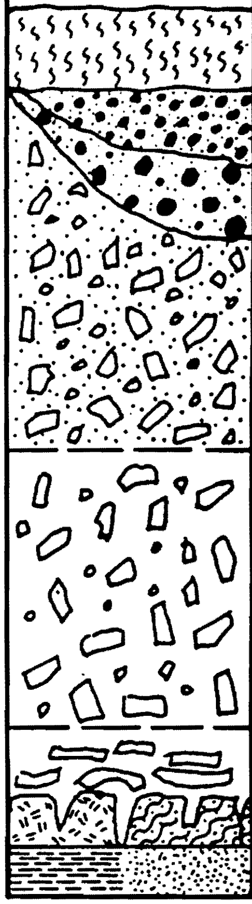
The stratigraphy and general properties of glacial deposits that cover landfill sites in the Appalachian Plateau of southwestern New York may be evaluated within the context of a continental glacial facies model. The importance and relevance of developing depositional models to understand the stratigraphic and geotechnical properties of glacial deposits in land-use evaluations (e.g. landfill siting analyses) is emphasized by Boulton and Paul (1976), Eyles and Sladen (1981), and Eyles (1983).

As indicated on surficial geologic maps, glacial tills are the most prevalent deposits in the high elevation terrains of the region. A genetic definition for glacial till is "an aggregate whose particles have been brought into contact by the direct agency of glacier ice and which, though it may have undergone glacially-induced flow, has not been significantly disaggregated" (Eyles, 1983, p. 11). Several types of till are encountered on many of the landfill sites. A typical stratigraphy of glacial tills is illustrated in Figure 7. Subglacial deposits include the deformation tills previously discussed as part of the bedrock hydrostratigraphy and overlying, densely-compacted lodgement tills. Englacial and supraglacial deposits include ablation and flow tills that contain discontinous lenses of water-sorted deposits, and a thin, mottled silt capping layer of uncertain origin.

A model for the distribution of subglacial deposits over a bedrock substrate is illustrated in Figures 8a and 8b. The subglacial tills found overlying glacitectonized bedrock at sites in Allegany and Cattaraugus Counties are generally interpreted in most hydrogeologic reports as lodgement tills. Further division into deformation till, comminution till, and lodgement till (sensu stricto) horizons may be possible, but these refinements are difficult to achieve because of the limited diameter and disturbance of deep till samples available from split spoons.

Lodgement Till

As observed in split spoon samples, the tills overlying glacitectonized bedrock are generally poorly sorted, gray to brown, silt- and clay-rich, channery deposits. As would be expected, the tills consist of detritus ranging is size from clay to boulders (Fig. 9). A typical till may contain roughly 25% gravel, 22% sand,



UNIT		AVERAGE GRAIN SIZE % Fines/% Sand/ % Gravel	FABRIC/STRUCTURES
SOIL		20/65/15	Massive silt loams
MOTTLED SILT		75/20/5	Massive silt with scattered sand and few pebbles
FLOW TILL	MUDDY FLOW TILL	55/10/35	Mud and silt-rich sand and gravel.
	DIAMICTIC FLOW TILL	15/30/55	Sandy and silty gravel, minor mud
BROWN LODGEMENT TILL		50/30/20	Massive to weak normal-grading. Many elongate bedrock rafts aligned parallel to bedding
GRAY LODGEMENT TILL		50/30/20	Same as brown lodgement till, but more cohesive and more compacted
DEFORMATION TILL			Elongate bedrock rafts that are folded and/or faulted
DECOMPOSED BEDROCK			Highly fractured bedrock with till injections; rafts in silt/clay matrix
FRACTURED BEDROCK			Massive to thin beds, cross-bedded sandstones, fissile shales

Figure 7.

Generalized Till Stratigraphy of the Landfill Sites in the Appalachian Plateau. Ablation Till is a common substitution for flow till. (after AFI Environmental, 1992b)

SCALE: NONE

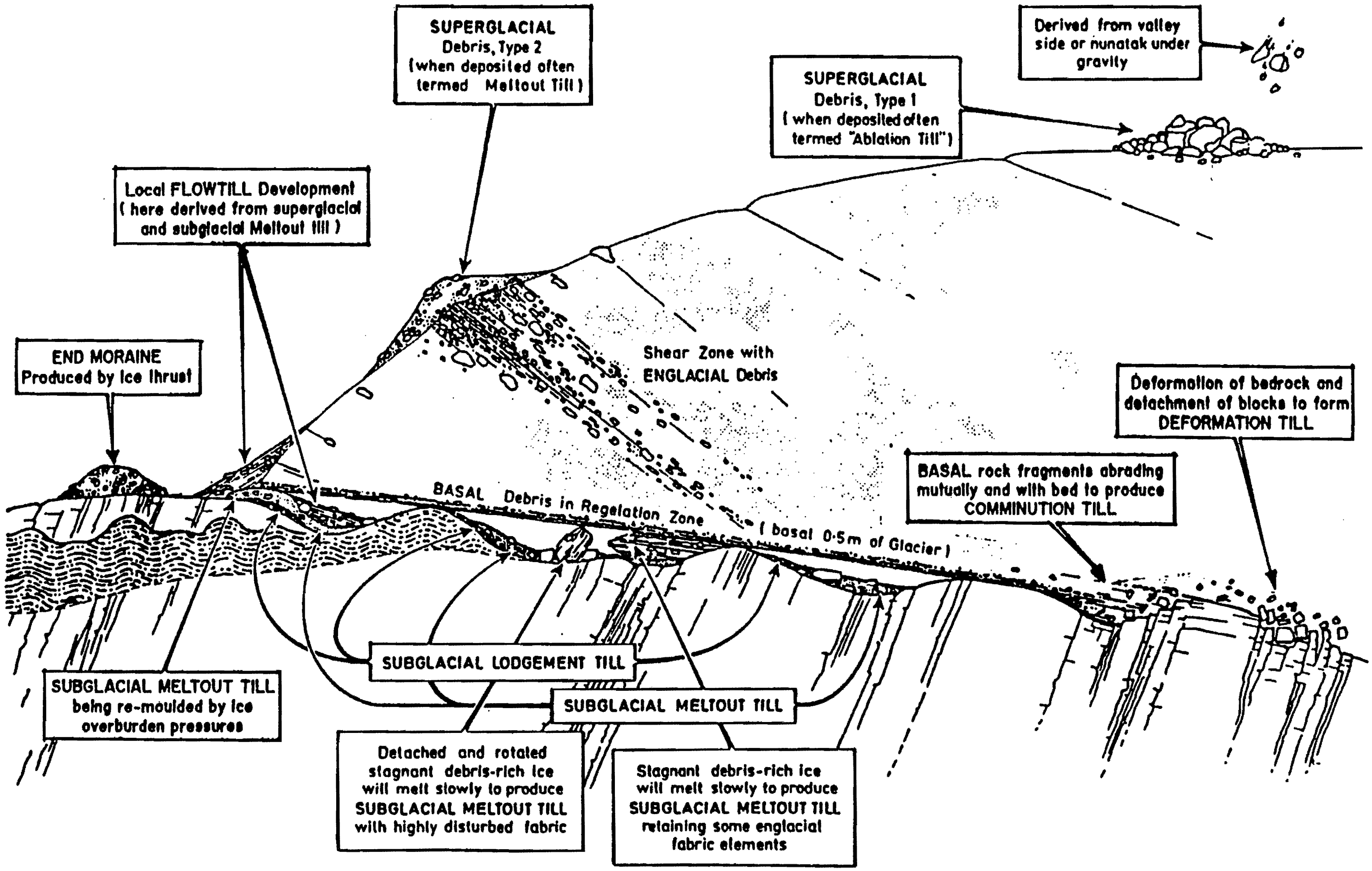
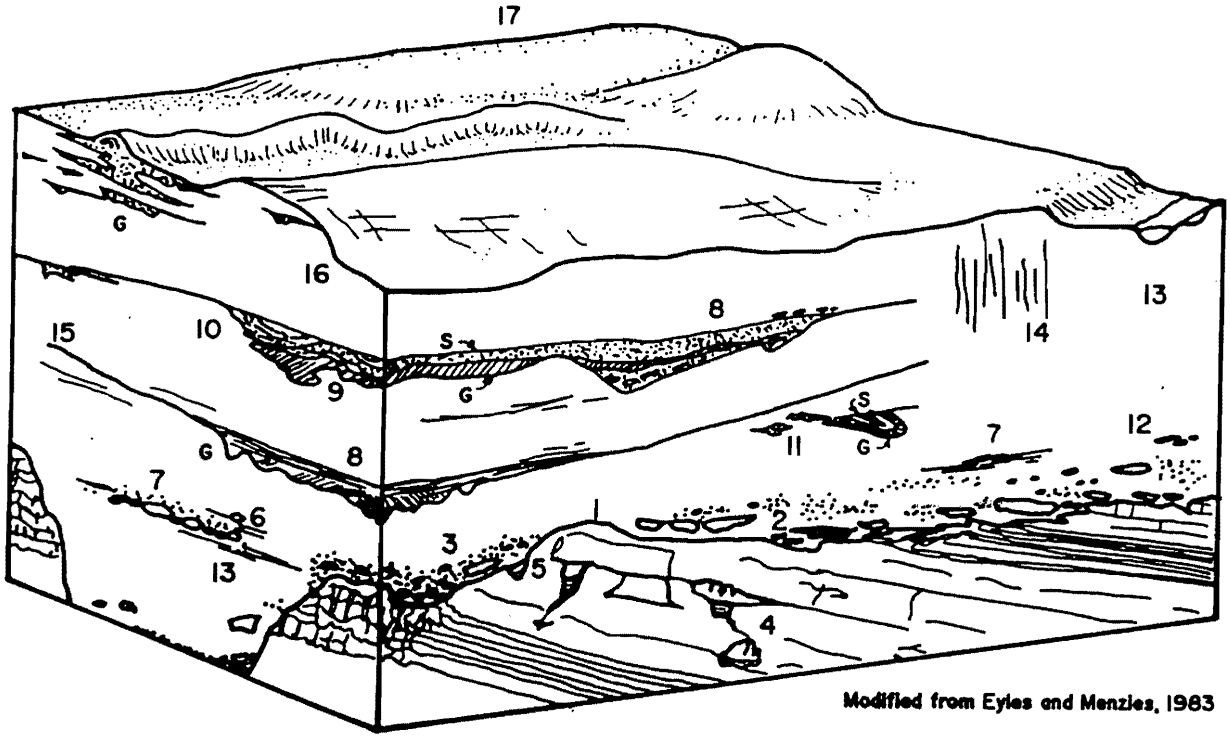
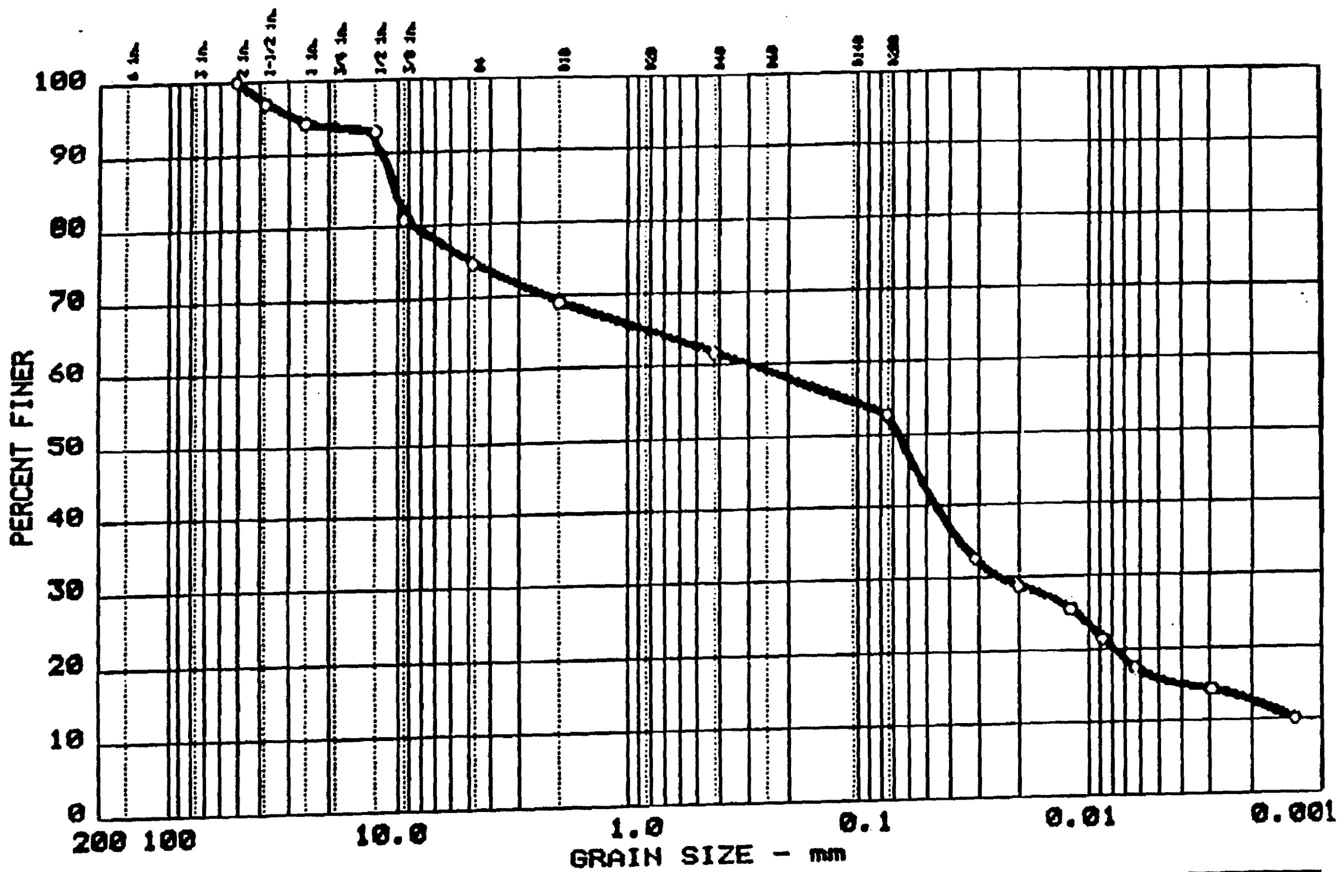


Figure 8A. Glacial processes and resultant till types (modified from McGown and Derbyshire, 1977).



1) Striated rockhead surface locally overdeepened below sea-level by subglacial erosion.
2) Rock "rafts", glacitectonized rockhead and deformation till.
3) Bouldery unit of scree-like debris filling lee-side cavities in rockhead.
4) "Cold water" karst from enhanced solution of limestones by subglacial meltwaters.
5) Intrusion of till into joints in rockhead.
6) Preferentially oriented clasts (long axes parallel to flow direction).
7) Distinct flat-iron shaping of fine-grained lithologies; coarse-grained lithologies produce faceted clasts of higher sphericity, frequently found as boulder pavements.
8) "Cut and fill" fluvial sediments deposited as sand (S) and gravel (G) in interconnected subglacial channels or as laminated clays in subglacial ponds. Often contain coherent debris masses dropped from ice roof.
9) Till masses diapirically intruded up into the base of fluvial channels.
10) Lenses of resedimented till extending into channel fills resulting from sidewall erosion and collapse.
11) Upper surfaces of cut and fill channels partially eroded by ice flow and resulting in deformed and folded inclusions in overlying till. Smaller channels folded.
12) Shear lamination caused by shearing out of soft, incompetent bedrock lithologies ("smudges").
13) Slickensided bedding plane shears resulting from subglacial shear.
14) Near vertical en echelon joints systematically oriented with respect to glacier flow direction or joint pattern in underlying bedrock.
15) Base of till units may be fluted; orientation of clasts with long axes parallel to flow direction.
16) Post-depositional sheared upper surface, frequently redeposited by solifluction.
17) Drumlinized, streamlined low relief surface; where rockhead is close to surface, rock-cored drumlins and "crag and tall" forms can be mapped. Subglacially engorged eskers are frequently related to the "cut and fill" sequences of (8) at depth.

Figure 8B. Typical till stratigraphy over a glacitectonized bedrock substrate.



% +3"	% GRAVEL	% SAND	% SILT	% CLAY
0.0	25.5	21.6	37.2	15.7

LL	PI	D_{85}	D_{60}	D_{50}	D_{30}	D_{15}	D_{10}	C_c	C_u
23	8	10.52	0.30	0.07	0.025	0.0040	0.003		

Figure 9. Representative grain-size distribution for lodgement tills of the Appalachian Plateau.

43% silt and 10% clay (Table 5). The large clasts are often flat channers of local sandstone. In test pits, the channers in lodgement till are typically aligned with long axes parallel to depositional surfaces. Most of the large clasts are derived from local Devonian formations, although a small percentage of transported Silurian Medina Sandstone and Precambrian metaplutonic clasts are present (Muller, 1977; Prudic, 1986). Bulk x-ray analysis of till deposits at the West Valley nuclear repository indicate that quartz, illite and chlorite are the major mineralic constituents of the fine-grained till matrix (Prudic, 1986).

The lodgement tills of the landfill sites in the Appalachian Plateau are densely compacted. Average N-values based upon standard penetration tests are approximately 68 blows per foot for the gray, unaltered till and approximately 52 blows per foot for the brown, weathered till (Table 6). Seismic velocities for the lodgement tills range between 5000 and 7000 feet per second (fps) for the unaltered till and between 3500 and 7000 fps for the weathered till (Harding Lawson Associates, 1992; Kick, 1992; Gartner Lee, 1993a, b).

Given these physical properties, the lodgement tills form low permeability aquitards (Table 7). Reported values for the gray, unaltered till range between 3.2×10^{-9} cm/s and 8.5×10^{-5} cm/s and average approximately 6.6×10^{-6} cm/s. Reported values for the brown, weathered till range between 3.4×10^{-9} cm/s and 2.9×10^{-4} cm/s and average 2.3×10^{-5} cm/s.

Ablation Till

The lodgement tills within the study area may be overlain by less densely compacted till that on some sites contains discontinous lenses of glaciofluvial deposits up to 6 feet thick. These variably textured deposits are likely to be ablation tills. Ablation till, a type of melt-out till, is deposited by the slow release of glacial detritus from ice that is neither sliding nor deforming internally (Dreimanus, 1988). Common properties of melt-out tills include the following: 1) banding of debris, bedrock blocks and rafts; 2) alignment of elongate clasts parallel to glacier flow; and 3) the retention on englacial fabrics (McGown and Derbyshire, 1977; Boulton and Paul, 1976; Dreimanis, 1988). These properties are consistent with the characteristics of the upper portions of till profiles observed in test pits and test borings on landfill sites in the Appalachian Plateau.

The hydrogeologic reports for most sites do not identify ablation tills explicitly, although water-sorted lenses are mentioned frequently. The ablation till/lodgement till boundary is commonly obscured by the cross-cutting oxidation front and may be best defined by contrasting N-values and seismic velocities, and the depth of water-sorted lenses in local vertical sections. Ablation tills generally have lower N-values than lodgement tills. An estimated average N-value for ablation tills is 13 blows per foot whereas the average N-values for regional lodgement tills are 52 and 68 for the weathered and unaltered profiles, respectively. Typical seismic velocities for ablation tills range between 3300 and 4800 feet per second (Kick, 1992). The range of values is narrower and at the low end of the spectrum (3500-7000 fps) for regional lodgement tills. Lastly, test boring logs for

Table 5. Grain size trends of lodgement tills of the Appalachian Plateau.

Site/Deposits	% Gravel	% Sand	% Silt	% Clay	% Fines*	n
Hylands Ash Monofill[1]	22.1	20.3	38.7	18.9	57.6	7
BFI-Eagle south[2]	27.3	28.0	NA	NA	44.7	14
BFI-Eagle north[2]	19.2	25.1	NA	NA	55.7	6
Ellery Landfill[3]	22.0	22.4	46.5	9.1	55.6	14
Southern Tier Sanitary Landfill[4]	35.0	15.0	NA	NA	50.0	21
Average	25.0	22.0	43.0	10.0	53.0	62

[1]Earth Investigations LTD (1990b)
[2]TAMS Consultants (1994)
[3]Malcolm-Pirnie (1991)
[4]AFI Environmental (1992a)
*Silt & Clay

Table 6. N-values for Lodgement Tills of the Appalachian Plateau

Site	Average	Range	Number
Southern Tier Sanitary Landfill[1]	112	15-198	71
Gray	68	6-162	106
Brown			
Hylands Ash Monofill[2]			
Gray	51	16-182	41
Brown	45	13-120	75
Olean Landfill[3]			
Brown	43	20-100+	33
BFI-Eagle[4]			
Gray	51	43-60	6
Brown	67	8-189	42
Ellery Landfill[5]			
Gray	59	25-166	45
Brown	35	5-140	52

1 AFI Environmental (1992a)
2 Earth Investigations LTD (1990b)
3 Earth Investigations LTD (1990a)
4 TAMS Consultants (1994)
5 Dunn Geoscience (1988)

Table 7
Lodgement till hydraulic conductivities (cm/sec) of the Appalachian Plateau

Site	Geometric Mean	Min	Max	N
Hylands Ash Monofill[1]				
Gray	$3.6x10^{-9}$	$3.2x10^{-9}$	$2.0x10^{-8}$	4
Brown	$3.6x10^{-7}$	$3.4x10^{-9}$	$6.9x10^{-9}$	4
Ellery Landfill[2]				
Gray	$2.5x10^{-5}$	$3.8x10^{-6}$	$8.5x10^{-5}$	8
Brown	$9.9x10^{-5}$	$2.9x10^{-5}$	$2.9x10^{-4}$	
Eagle-Modern[3]				
Gray	$3.2x10^{-8}$*	–	–	1
Brown	$5.1x10^{-7}$*	–	–	1
Olean Landfill[4]				
Brown	$8.4x10^{-6}$	$4.5x10^{-7}$	$1.6x10^{-5}$	2
Southern Tier Sanitary Landfill[5]				
Gray	$1.6x10^{-6}$	$1.8x10^{-7}$	$2.2x10^{-5}$	3
Brown	$5.9x10^{-6}$	$1.8x10^{-7}$	$1.6x10^{-4}$	8

1 AFI Environmental (1992a)
2 Earth Investigations LTD (1990b)
3 Earth Investigations LTD (1990a)
4 TAMS Consultants (1994)
5 Dunn Geoscience (1988)

* Recompacted permeability values.

many of the landfill sites indicate water-sorted lenses in tills to depths typically on the order of 30 feet below ground surface in the lower elevation portions of the valleys. When these lenses contain pockets of water, slug testing of wells yields an average hydraulic conductivity value of approximately $5x10^{-5}$ cm/s which is slightly higher than geometric mean values calculated for both weathered and unaltered lodgement tills.

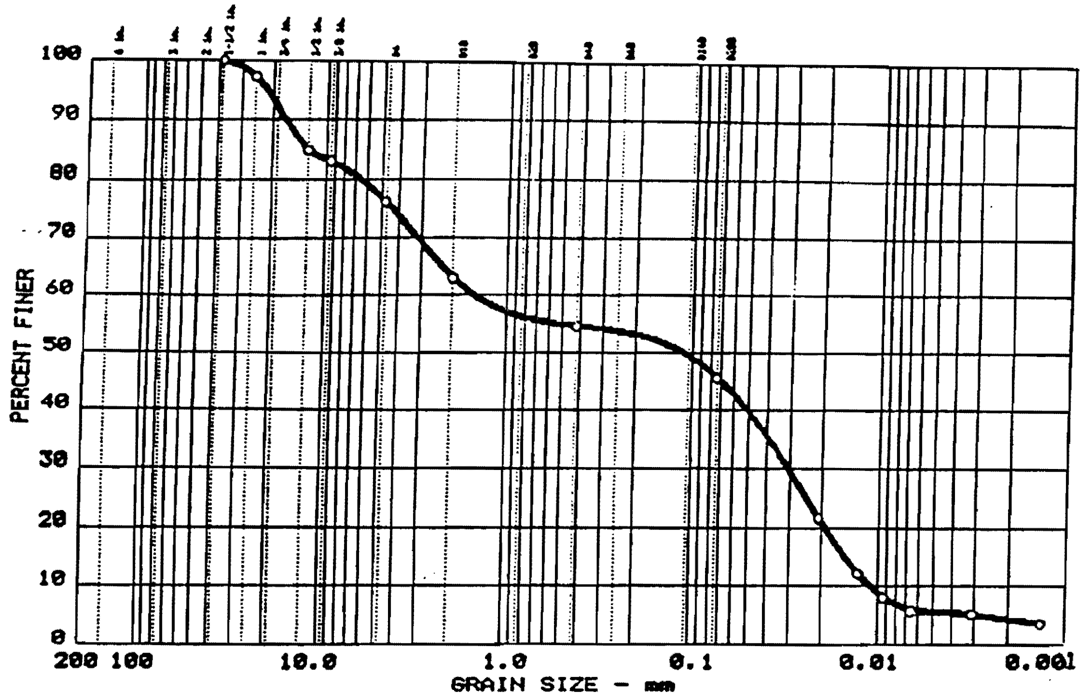
Flow Till

In the low elevation area of the Southern Tier Sanitary Landfill site in Farmersville, Cattaraugus County, a localized pod of normally graded, poorly sorted, silty sand and gravel was encountered. Clasts in this unit are noted by AFI Environmental (1992a, b) to be angular to subrounded. This unit has been interpreted as a flow till on the basis of internal characteristics and the lateral and vertical association with lodgement tills (Cole and Others, 1993). Flow tills are formed when glacial debris is remobilized downslope by gravity and may be deposited supraglacially, subglacially, subaerially or subaqueously (McGown and Derbyshire, 1977; Boulton, 1968; Lawson, 1982; Dreimanis, 1988). Flow till deposits are typically discontinous lenses of variably sorted detritus. The debris that comprises the flow till may have been reworked from other tills or may have been derived from the release of detritus from glacial ice. Overall, the poor sorting, massive nature, and the weak grading of flow till deposits at Farmersville suggest deposition from viscous sediment gravity flows (mudflows or debris flows).

The flow till unit consists of an upper silty gravel facies and a lower sand and boulder unit (Figs. 10a, b). The hydraulic conductivity values reported for the upper silty gravel range between $1.0x10^{-3}$ and $1.0x10^{-5}$ cm/s with a geometric mean of $2.0x10^{-4}$ cm/s. The lower sand and boulder facies is more permeable. Slug tests on monitoring well yield values averaging approximately $3.0x10^{-3}$ cm/s. A full-scale pumping test, however, yielded a hydraulic conductivity value of approximately $2.0x10^{-2}$ cm/s for the localized, permeable, lower horizon (AFI Environmental, 1992b).

Mottled Silt

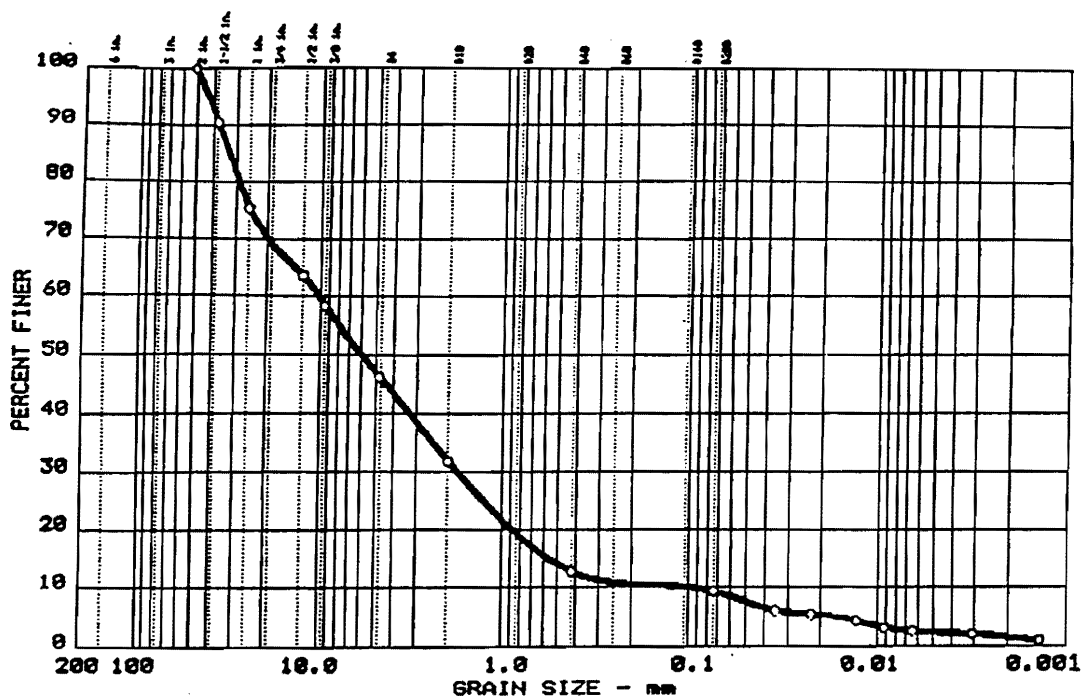
A surficial mottled silt bed has been documented at several sites in the Appalachian Plateau. The facies is typically gray and brown mottled silt with small percentages of sand and gravel (Fig. 11). The beds range in thickness between 1 and 6 feet. The unit apparently disconformably overlaps underlying lodgement and ablation till facies suggesting that the mottled silt accumulated during and/or following the waning phases of glacial recession. Furthermore, typical N-values based upon standard penetration tests average approximately 15 blows per foot, a value much lower than representative of the underlying, over-consolidated, lodgement till facies but similar to the mean value calculated for ablation tills. The mottled silt has a seismic velocity ranging between 1700 and 3500 feet per second. This range of values is also lower than the range for regional lodgement and ablation till facies. The genesis of the mottled silt remains uncertain. Working hypotheses are that the facies may be any of the following: 1) a bioturbated,



% +3"	% GRAVEL	% SAND	% SILT	% CLAY
0.0	23.9	30.4	40.0	5.7

LL	PI	D_{85}	D_{60}	D_{50}	D_{30}	D_{15}	D_{10}	C_c	C_u
nv	none	12.88	1.51	0.11	0.031	0.0151	0.0109	0.06	138.

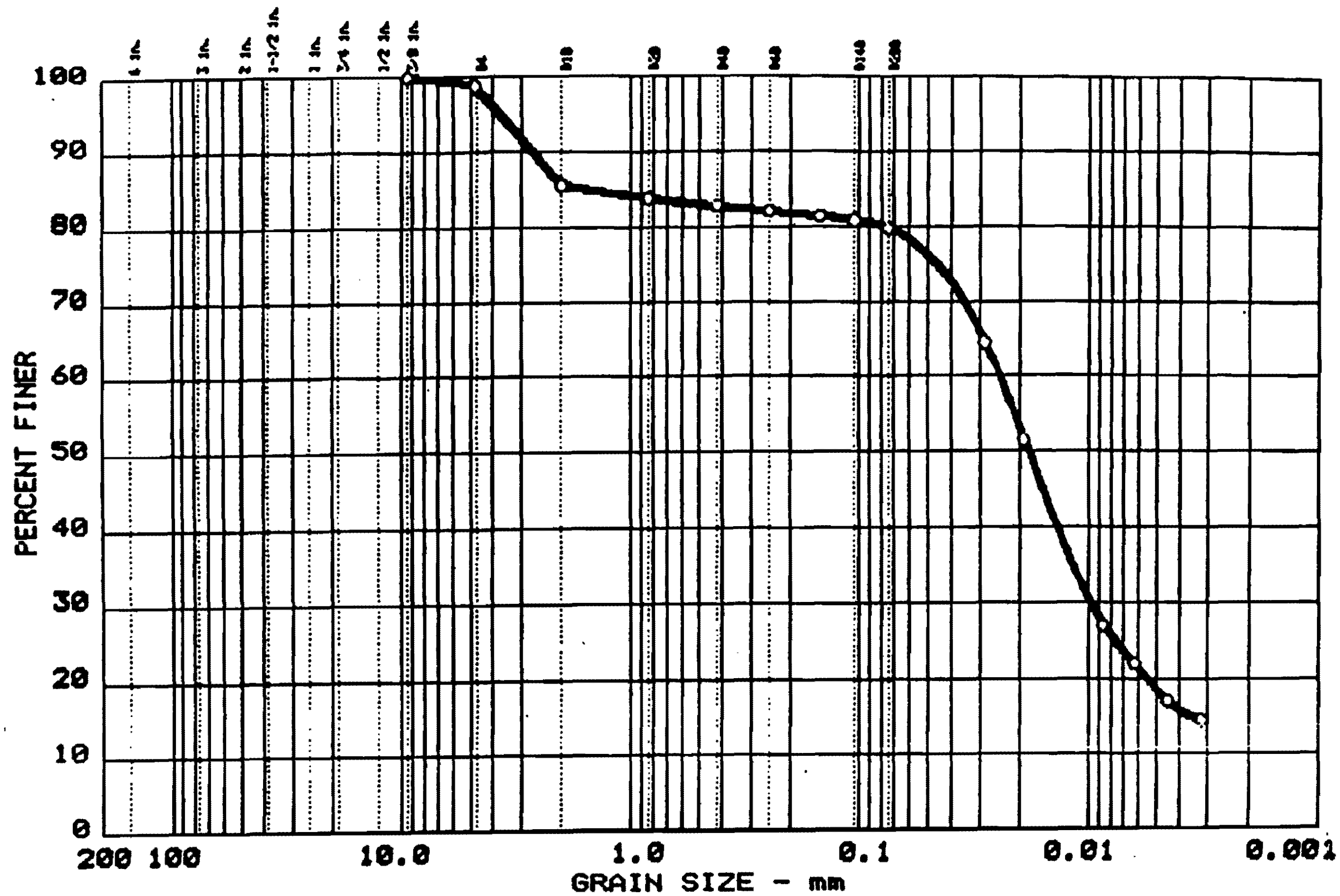
Figure 10A. Grain-size distribution for upper flow till horizon.



% +3"	% GRAVEL	% SAND	% SILT	% CLAY
0.0	53.0	36.8	6.9	2.5

LL	PI	D_{85}	D_{60}	D_{50}	D_{30}	D_{15}	D_{10}	C_c	C_u
26	10	33.88	10.34	5.88	1.776	0.5617	0.0922	3.31	112.2

Figure 10B. Grain-size distribution for lower flow till horizon.



% +3"	% GRAVEL	% SAND	% SILT	% CLAY
0.0	1.2	19.0	61.3	18.5

Figure 11. Representative grain-size distribution for the mottled silt horizon.

humid climate loess (Donald Owens, personal communication); 2) a till-derived colluvium (Parker Calkin, personal communication); 3) a late stage, melt-out "slurry till" (Donald Cadwell, personal communication); or 4) an incipient, hydric soil profile.

Regardless of origin, the mottled silt possesses a low permeability. Although the unit is typically too thin to discretely screen wells or piezometers across, vertical hydraulic conductivity values have been obtained for the deposit at the Southern Tier Sanitary Landfill site based upon triaxial permeability tests on Shelby Tube samples. These tests yielded a mean vertical hydraulic conductivity of approximately 1.0×10^{-6} cm/s (Blasland, Bouck & Lee, 1994). The horizontal hydraulic conductivity may be one to two orders of magnitude higher if bioturbation has not completely homogenized the deposit.

Groundwater Flow Trends

The general groundwater flow conditions on landfill sites in the Appalachian Plateau are characteristic of high elevation, bedrock-supported terrains with limited recharge areas (Fig 12). Recharge occurs on high elevation ridges where weathered glacial tills are typically less than 10 feet thick. Flow vectors are oriented vertically downward in the recharge areas until groundwater intercepts one of several potentially transmissive zones. Preferred flow paths become more numerous on valley side-slopes as the glacial till profile thickens and the influence of till aquicludes and aquitards becomes increasingly pronounced.

The uppermost preferred flow path occurs at the base of the mottled silt layer. This hydrostratigraphic unit typically contains a throughflow or interflow system which diverts a significant volume of vadose water (sensu Fetter, 1994, p. 5) from deeper, transmissive units below the water table. Throughflow systems typically discharge as diffuse spring lines at the base of the valley side slopes. The vadose water then flows overland toward surface water bodies. The interflow systems discharge directly to surface water bodies without the overland flow component.

A shallow, unconfined flow system typically develops in the weathered till profile. Due to the low permeability of surficial units, the seasonal high groundwater table typically occurs within 5 feet of the ground surface beneath the lower portions of the local drainage basins. Consequently, most landfills are designed with a groundwater suppression system to maintain separation between the water table and the baseliner until hydrostatic pressures equalize beneath the facility.

On some sites, the shallow-occurring "groundwater" may be restricted to dessication crack networks and water-sorted lenses in the valley-center ablation till profiles. Observations from test pits indicate that the bulk of the free water available within the top 10 to 20 feet below ground surface on some sites emanates from the throughflow/interflow horizons. Except for pockets of water in small lenses of granular material, the till matrix commonly appears to be unsaturated. None-the-less, shallow monitoring wells often produce small volumes

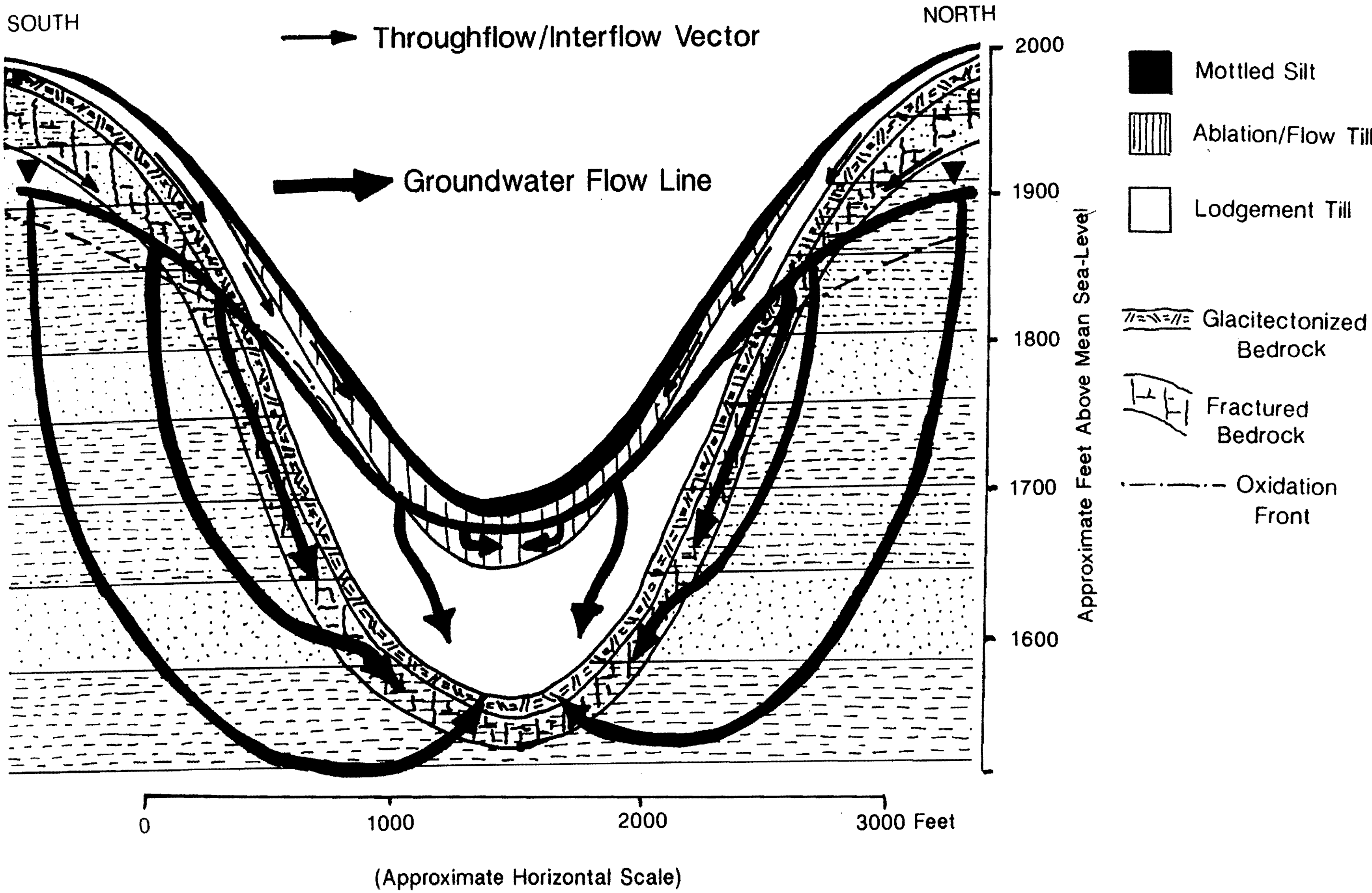


Figure 12. Generalized Groundwater Flow Patterns in a Till-Filled Valley of the Appalachian Plateau

of water. The source of this water must be either vertical leakage through dessication cracks or leakage from the interflow/throughflow zone along the well casings. Thus, definition of the shallow water table becomes equivocal on some sites, because it is difficult to reconcile the test pit observations with interpretation of a continuous phreatic surface in the weathered till profile.

A groundwater invert sometimes defines the base of a shallow "perched water table" zone in the weathered profile. Because the deeper, unaltered lodgement till is lower in permeability than the shallower, weathered ablation and lodgement till profile, the gray color marks the top of the first aquiclude. These gray tills may be at least seasonally unsaturated on some sites and may be perennially unsaturated at the Hylands site (Earth Investigations Ltd, 1990b). Regardless of whether saturated conditions extend from the weathered zone downward through the unaltered profile or not, the gray till/glacitectonized bedrock aquiclude separates the upper groundwater flow zone from the bedrock flow zone. Commonly, the aquiclude imposes artesian pressure on the flow zone in the underlying fractured bedrock aquifer just above and within valley center areas. Water table conditions, defined by a lack of pressure head in monitoring wells, commonly can be documented both above and below the aquiclude in the intermediate elevation areas of the local drainage basins. In the uppermost reaches, the aquiclude does not exist, because the oxidation front generally extends through the thin till profile and into bedrock. The water table resides in bedrock at the crests of the hills.

Background Water Quality

Representative background water quality has been compiled from several sites and is presented in Table 8. Values for field parameters (specific conductance and pH) as well as major metals, major anions and Total Organic Carbon (TOC) are provided. Most of these waters may be classified as calcium bicarbonate geochemical facies and reflect the solubility of calcareous body fossils in local bedrock units. Fossiliferous strata have been incorporated into the local tills and are directly observable in drill cores of both dislodged bedrock rafts in the glacitectonized zone and in in-situ bedrock.

The concentrations of total dissolved solids (TDS) are remarkably low for sites in the Appalachian Plateau. The low TDS values reflect the position of the plateau in the headland areas of several regional-scale groundwater basins. As will be illustrated in the following sections of this paper, these low TDS groundwaters differ significantly with water monitored near base-level of the regional flow system beneath the Erie-Ontario Plain. Near the sublacustrine groundwater outflow zones, water quality is significantly affected by naturally occurring, high concentrations of dissolved solids.

ERIE-ONTARIO PLAIN

Review of Table 2 reveals that two hydrogeologic settings within the Erie Ontario Plain have been utilized for host solid waste management facilities. These

Table 8
Representative Water Quality
Appalachian Plateau

Parameter*,(6)	Hylands Ash Monofill(1)				Southern Tier Sanitary Landfill(2)					
	Oxidized Ablation Till	Unaltered Lodgement Till	Bedrock Overburden Contact	Deep Bedrock	Flow Till	Oxidized Lodgement Till	Unaltered Lodgement Till	Shale Bedrock	Sandstone Bedrock	Carpenter Brook
pH (pH units)	6.79	7.20	7.71	7.58	7.88	7.71	8.16	7.75	7.83	7.60
Specific Conductance (umhos/cm)	540	530	468	370	348	279	485	242	250	231
Total Dissolved Solids	294	312	277	228	268	177	313	155	191	161
Hardness	252	258	216	207	173	153	157	146	183	144
Alkalinity	213	NA	230	195	103	150	157	145	151	126
Chloride	5.20	0.57	1.40	92.2	59.0**	2.18	6.64	1.50	2.42	23.3
Sulfate	43.1	42.4	33.0	28.0	54.0	26.2	110	14.9	28.7	12.9
Nitrate	0.27	0.18	ND	0.35	1.08	0.66	0.79	0.09	0.30	0.08
Ammonia	0.15	0.06	0.13	0.08	<0.05	0.07	0.08	0.07	0.06	0.05
Manganese	0.32	1.15	0.23	ND	0.25	0.33	0.38	0.14	0.34	0.04
Iron	3.00	3.00	0.54	0.40	3.04	1.91	27.9	1.27	27.6	0.23
Magnesium	16.4	20.4	17.0	0.20	6.91	8.40	5.65	8.70	6.20	3.98
Calcium	51.3	48.0	55.0	59.0	36.0	64.2	51.2	35.3	43.2	32.1
Sodium	11.0	11.6	16.3	5.10	33.0	13.4	52.3	6.50	10.6	10.3
Potassium	2.20	3.40	3.40	5.00	2.04	3.58	2.60	1.82	2.17	1.08
TOC	2.55	1.50	1.45	1.40	1.64	1.67	1.62	1.87	1.58	3.43

* all values in mg/l unless otherwise specified
** possible road salt influence
*** acid shale exposed at ground surface
(6) Values reported are mostly arithmetic means for each geologic interval.

(1) Source: Earth Investigations Ltd. (1990b)
(2) Source: AFI Environmental (1992a)
(3) Source: Earth Investigations Ltd. (1990a)
(4) Source: Malcolm-Pirnie (1994)
(5) Source: Malcolm-Pirnie (1991)

Table 8
Representative Water Quality
Appalachian Plateau

Parameter*,(6)	Olean Landfill(3)		Modern-Eagle(4)		Ellery Landfill(5)	
	Shallow Bedrock	Surface Water	Bedrock Overburden Contact	Shallow Bedrock	Bedrock Overburden Contact	Oxidized Ablation Till
pH (pH units)	4.68***	6.96	7.56	7.40	7.30	6.60
Specific Conductance (umhos/cm)	125	191	470	488	283	1280
Total Dissolved Solids	94.8	126	260	255	177	687
Hardness	10.0	39.0	173	166	101	700
Alkalinity	12.0	71.9	222	204	384	718
Chloride	2.53	5.60	2.00	3.50	8.86	8.01
Sulfate	9.61	12.7	21.5	29.0	17.4	25.7
Nitrate	0.01	0.31	0.68	5.00	ND	ND
Ammonia	0.12	0.92	NA	NA	0.39	0.10
Manganese	0.32	0.38	0.28	0.44	0.13	0.89
Iron	6.53	1.00	1.36	0.80	0.51	1.34
Magnesium	5.69	5.64	12.4	11.2	NA	NA
Calcium	1.58	13.7	49.0	48.0	34.3	140
Sodium	1.09	2.85	21.0	17.0	21.5	14.0
Potassium	3.47	2.10	NA	NA	NA	NA
TOC	4.24	7.72	15.5	17.0	4.33	7.40

* all values in mg/l unless otherwise specified
** possible road salt influence
*** acid shale exposed at ground surface
(6) Values reported are mostly arithmetic means for each geologic interval.

(1) Source: Earth Investigations Ltd. (1990b)
(2) Source: AFI Environmental (1992a)
(3) Source: Earth Investigations Ltd. (1990a)
(4) Source: Malcolm-Pirnie (1994)
(5) Source: Malcolm-Pirnie (1991)

two terrains are the "Glacial Till Over Bedded Sedimentary Rock" and "Glacial Lake Deposits" hydrogeologic settings of Aller and others (1987). The terrains dominated by glacial tills fall into three categories based upon depositional settings: 1) ground moraine (Fig. 13); 2) drumlin (Fig. 14); and 3) water-lain till/subaqueous flow till (Fig. 15).

Although the Lake Ontario Plain incorporates outcrop belts of diverse strata ranging in age from Ordovician to Lower Devonian, the upper 100 feet or so of bedrock may be divided into hydrostratigraphic units comparable to the intervals defined for the Appalachian Plateau. These hydrostratigraphic units include: 1) an uppermost, decomposed rock aquitard; 2) a medial, fractured rock aquifer; and 3) a deeper, competent rock aquitard.

Weathering (oxidation) of both surficial deposits and bedrock is also common to depths of 10 to 30 feet. As is often the case with the sites in the Appalachian Plateau, the weathered profile typically obscures lateral and vertical glacigenic facies boundaries in the shallow subsurface zone.

General characteristics of landfill sites on the Erie-Ontario Plain are more fully discussed in the following sections.

Regional Bedrock Hydrostratigraphy

Hydrogeologic studies for a variety of environmental projects including landfill siting have contributed significantly to the understanding of regional bedrock stratigraphic trends on the Lake Ontario Plain. Major hydrogeologic investigations such as the recent study of the bedrock hydrology "in press; also in this volume" by the USGS Water Resources Division have produced valuable drill core sections that have facilitated regional correlations of Ordovician and Silurian strata (see Brett and others, 1990a,b; impress). Drill cores from landfills near Middleport (Niagara County), Albion (Orleans County) and Webster (Monroe County) as well as from sewer projects in Rochester and the defunct super collider project in Walworth (Wayne County) have been instrumental in extending correlations between Niagara County and Wayne County, a distance in excess of 100 miles (150 km). Based, in part, upon these drill cores, cross-sections of Upper Ordovician through Upper Silurian strata may be developed (Fig. 16a-c).

The hydrostratigraphy of the bedrock units is profoundly influenced by past and present surficial processes. Chemical weathering and post-glacial isostatic rebound have resulted in the tripartite division of the shallow bedrock profile into three hydrostratigraphic units: 1) an upper aquitard consisting of disaggregated (decomposed) rock; and medial, fractured rock aquifer; and 3) a lower, competent rock aquitard.

Decomposed Rock Zone

The decomposed rock aquitard is typically overlain directly by a lodgement till facies. The hydrostratigraphic unit is best defined atop shale formations.

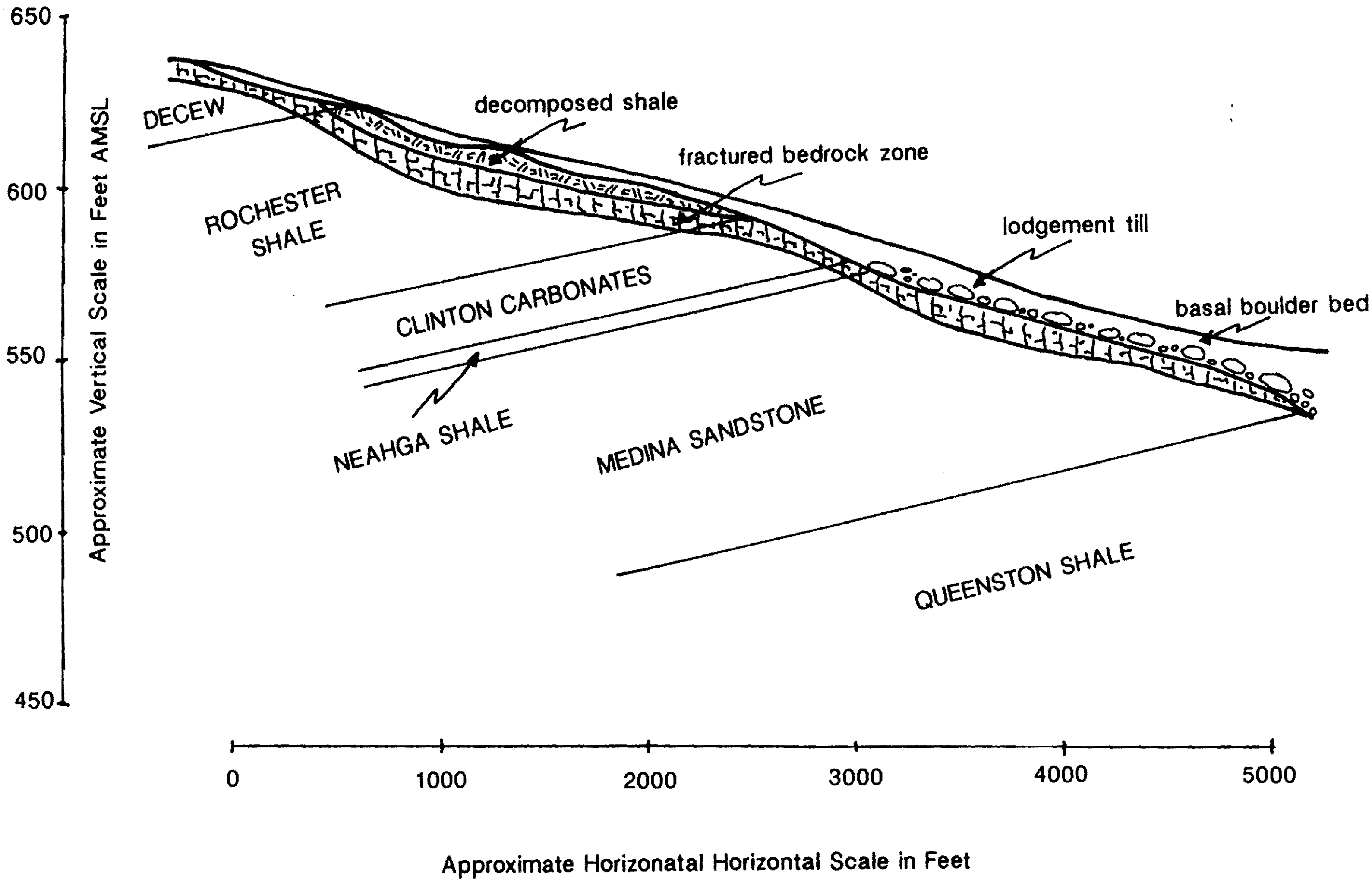


Figure 13. Geologic cross-section of ground moraine and underlying bedrock strata on the Lake Ontario Plain.

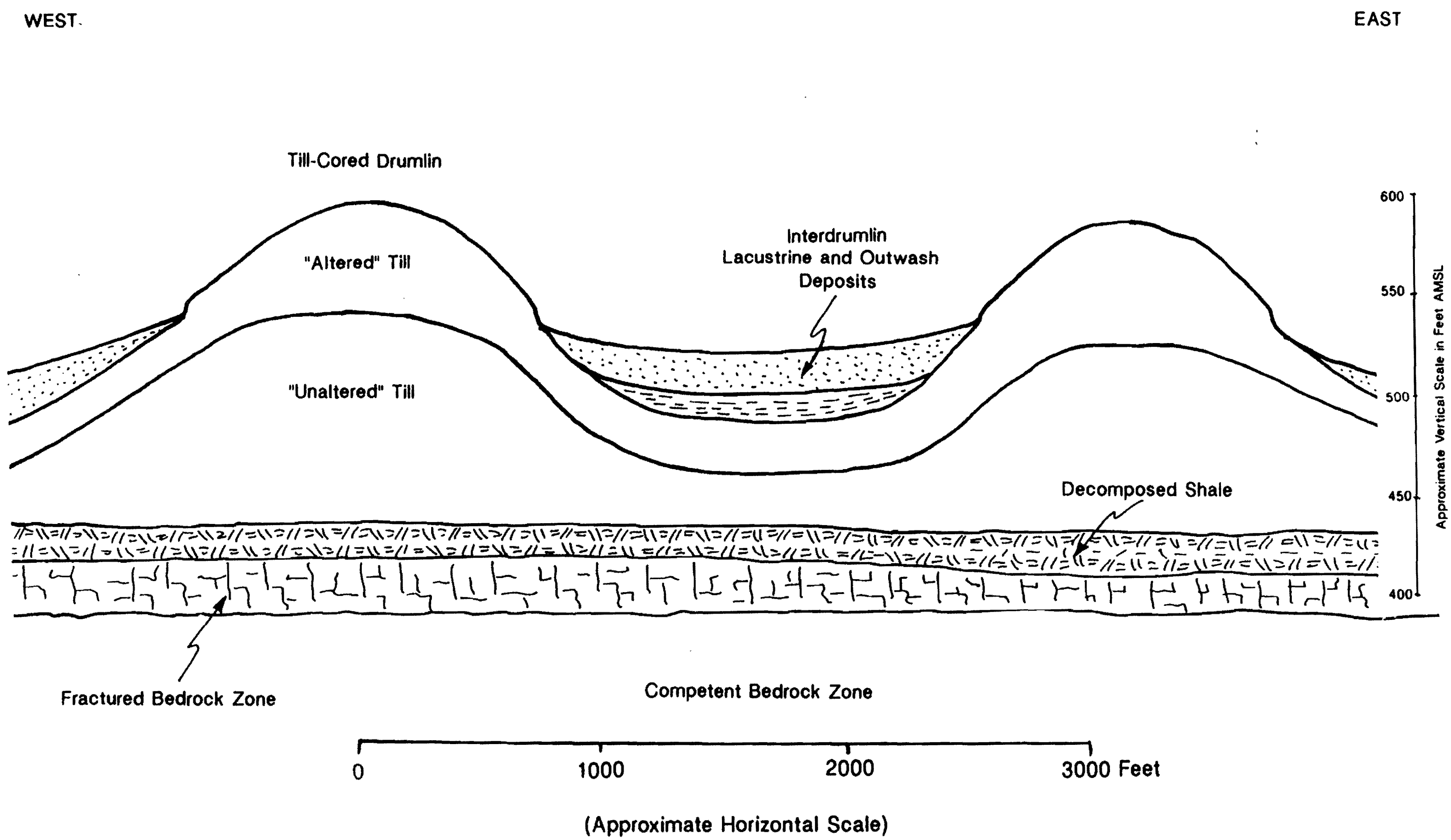
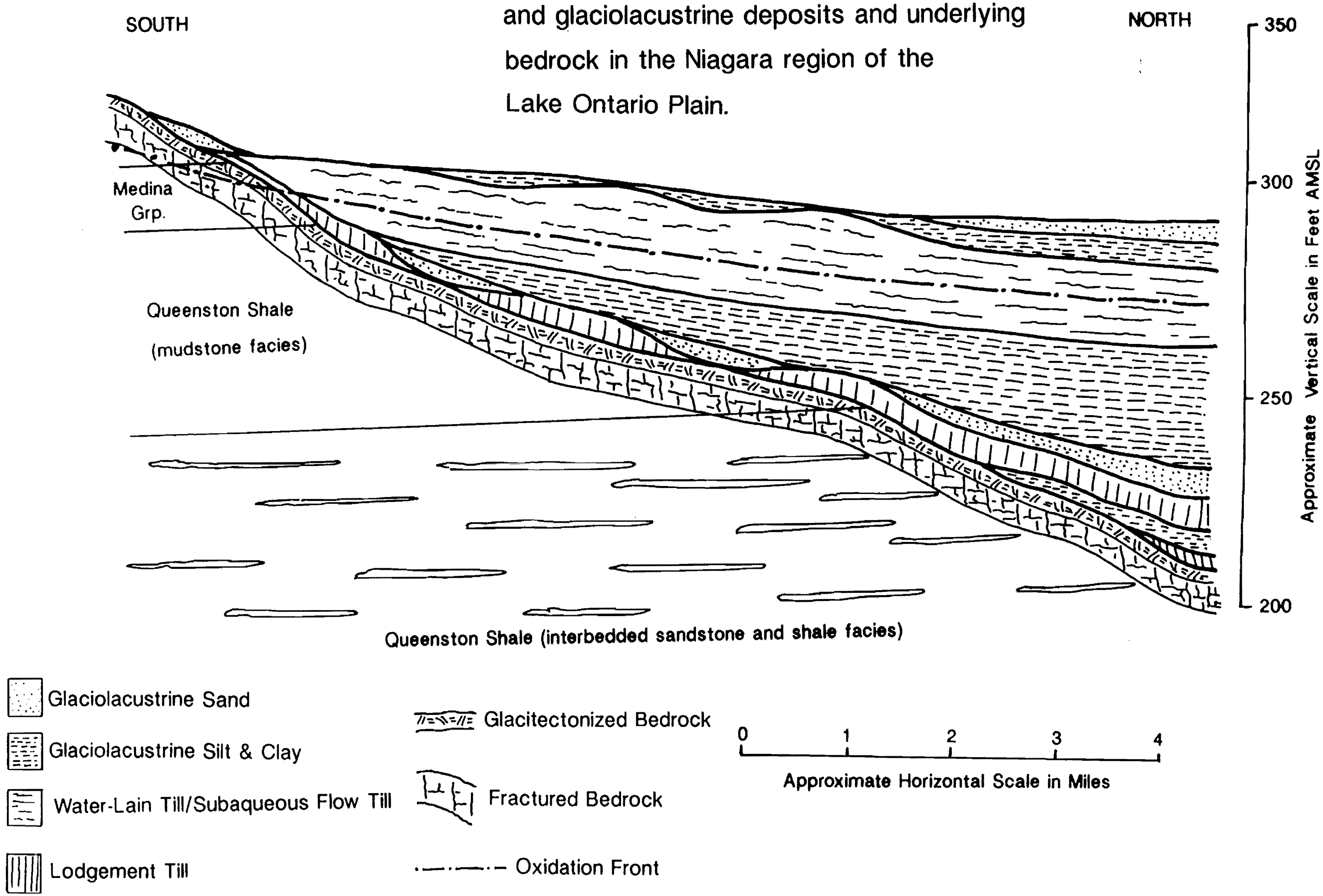


Figure 14. Geologic cross-section of drumlin and bedrock hydrostratigraphic units on the Lake Ontario Plain.

Figure 15. Geologic cross-section of interstratified till and glaciolacustrine deposits and underlying bedrock in the Niagara region of the Lake Ontario Plain.



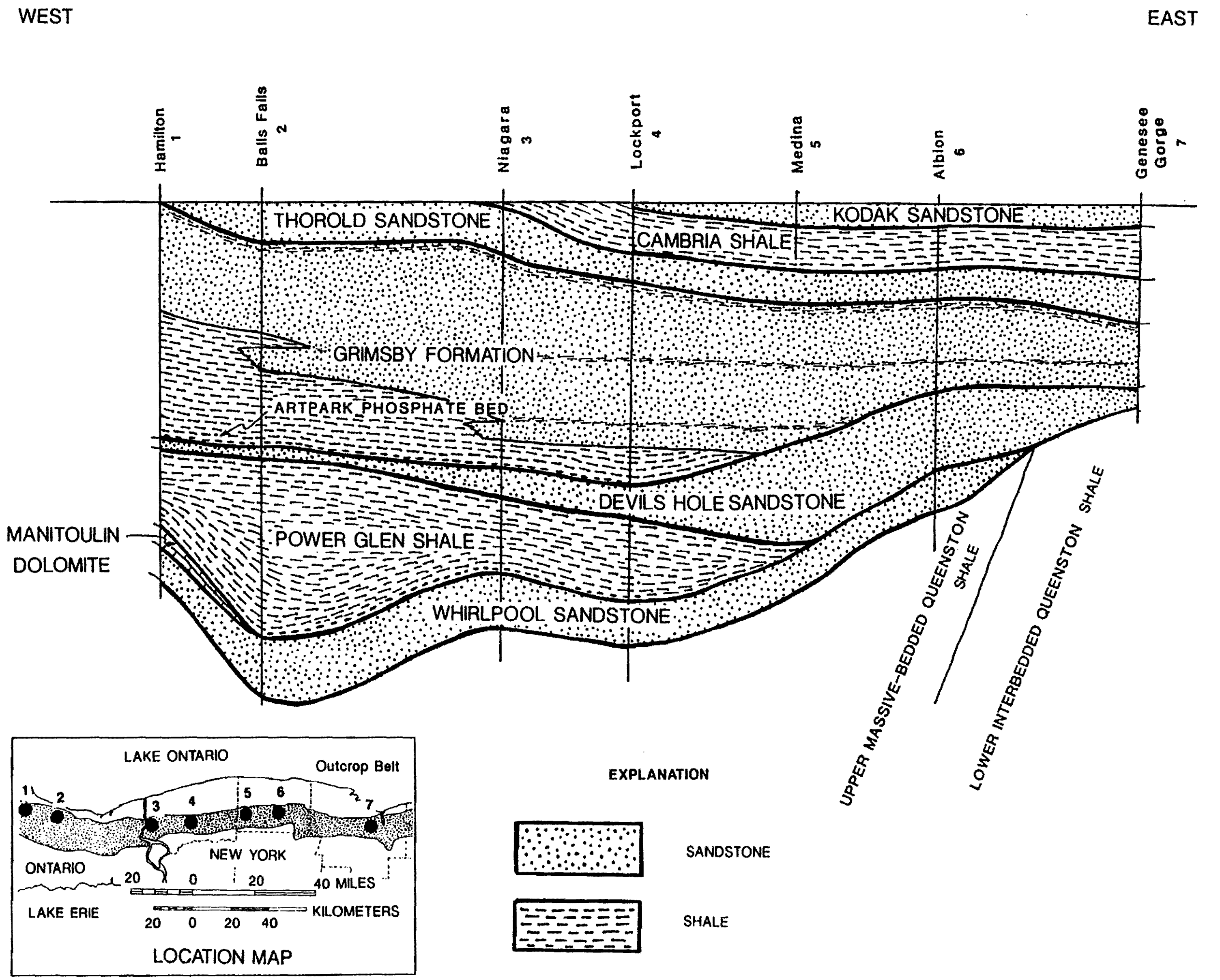


Figure 16A. Geologic cross-section of Medina Group strata on the Lake Ontario Plain.

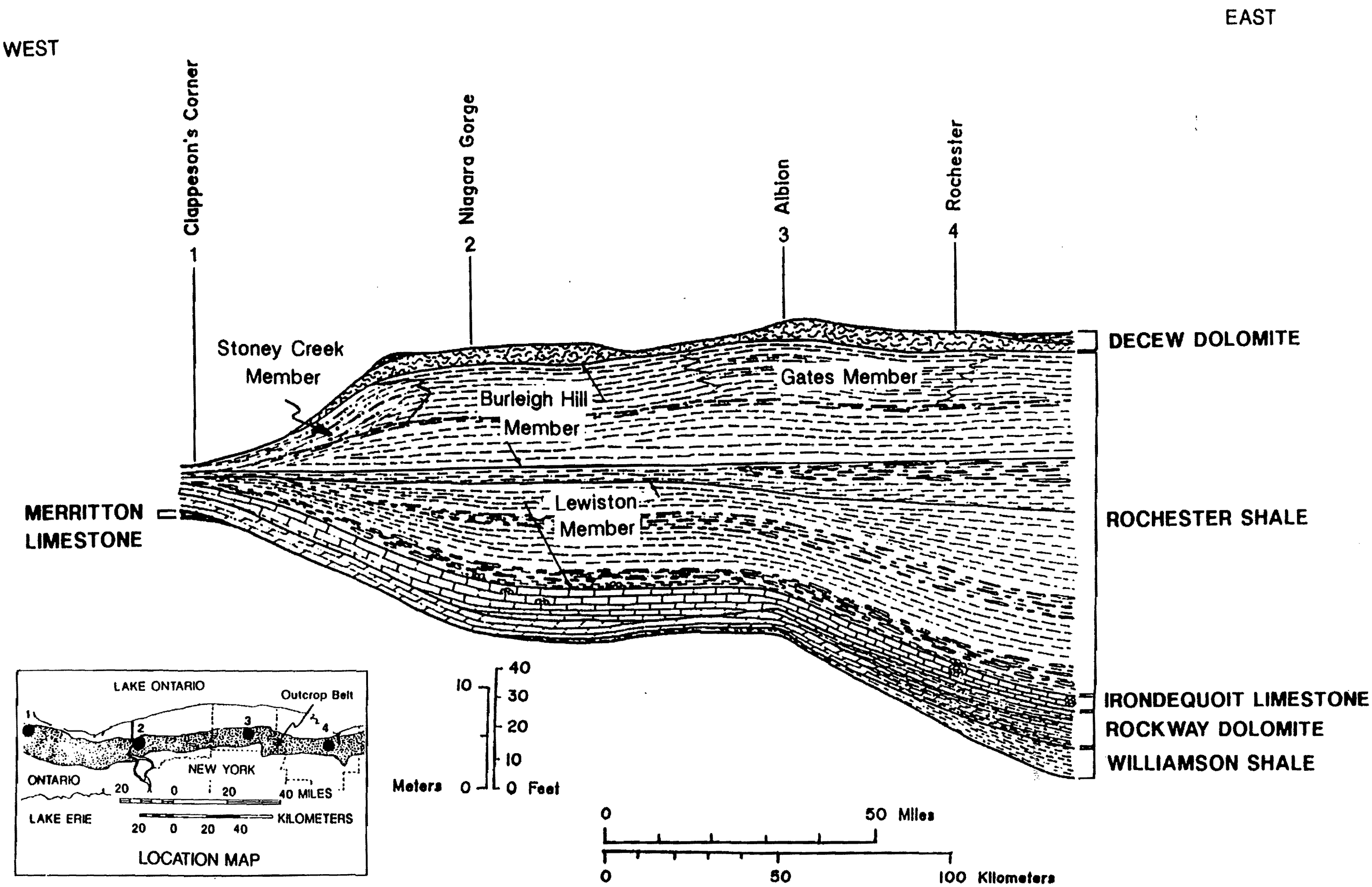


Figure 16B. Geologic cross-section of upper Clinton Group strata on the Lake Ontario Plain.

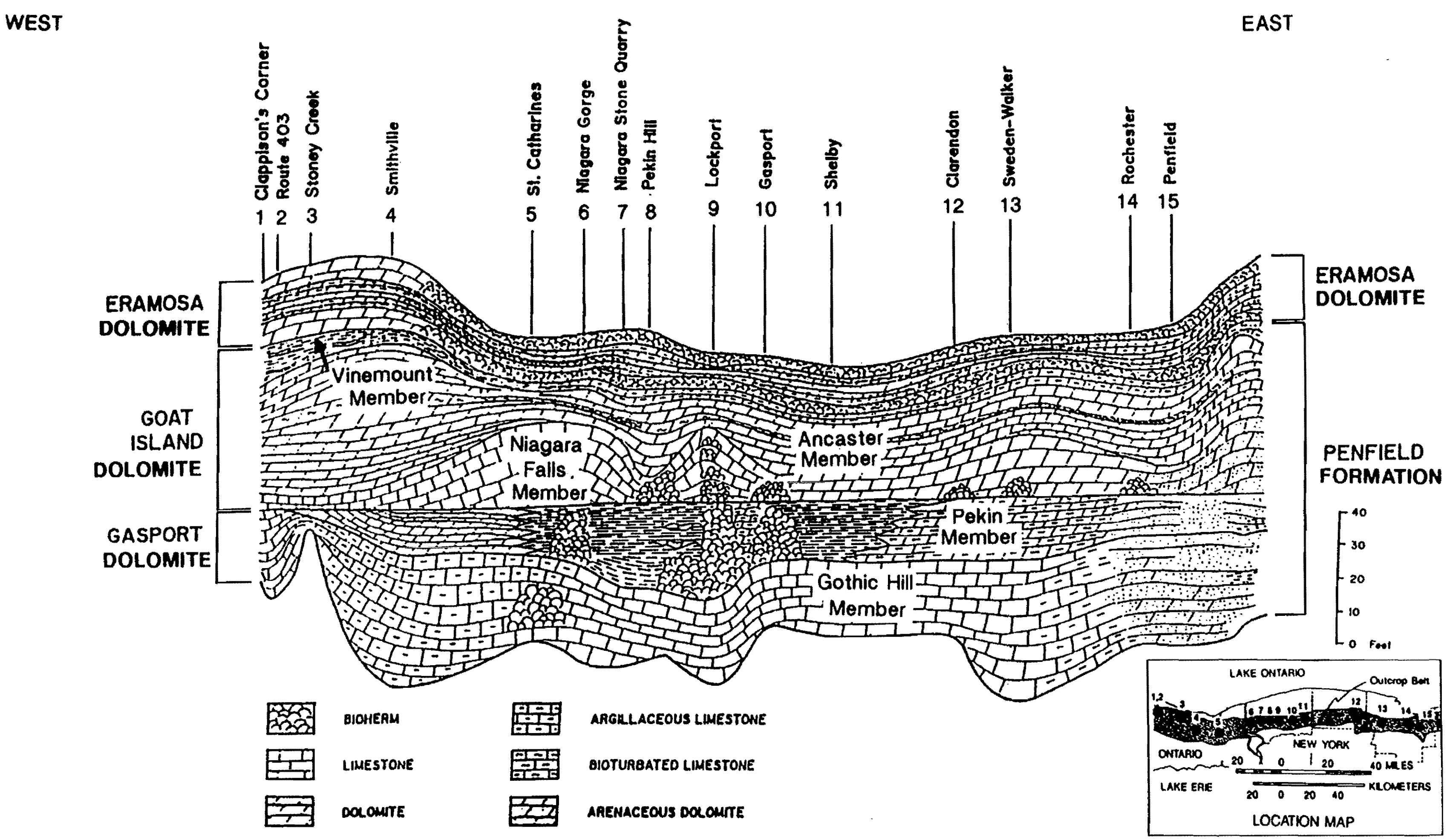


Figure 16C. Geologic cross-section of lower Lockport Group strata on the Lake Ontario Plain.

Documented, low permeability clay and silt horizons consisting of decomposed shale occur atop the Queenston Shale at the Modern Landfill (Lewiston, Niagara County), the Rochester Shale in borrow pits immediately south of the Orleans Sanitary Landfill (Albion, Orleans County), and the Vernon Shale at the Mill Seat Landfill (Riga, Monroe County), the High Acres Landfill (Perinton, Monroe County), and the Galen-Lyons Sanitary Landfill (Galen, Wayne County). Although the regulatory definition of bedrock mandates that the decomposed shale be treated as bedrock, the unit may be sampled using standard penetrations tests through hollow stem augers, i.e. conventional soil sampling techniques.

For most sites the decomposed shale has been combined with the basal lodgement till profile to form a single layer in conceptual and numerical hydrologic models. Consequently, discrete hydraulic conductivity values are not widely available. However, a fairly comprehensive data base consisting of slug test results from 15 piezometers screened in the upper 9 feet of Queenston Shale at the Modern Landfill is reported by Wehran Envirotech (1991). These data are included in Table 9. Hydraulic conductivity values for decomposed Queenston Shale at the Modern Landfill range between $8.3x10^{-6}$ and $1.9x10^{-3}$ cm/s. The geometric mean of these values for decomposed Queenston Shale is $2.6x10^{-4}$ cm/s.

Limited data are also available from both the High Acres Landfill and the closed Galen-Lyons Sanitary Landfill for the decomposed Vernon Shale horizon (see Table 9). Two wells screened in the interval at High Acres yield a geometric mean hydraulic conductivity of $2.7x10^{-5}$ cm/s (Eckenfelder, 1992). Four wells screened in the interval at the Galen-Lyons Landfill yielded hyraulic conductivity values between $3.9x10^{-5}$ and $9.9x10^{-3}$ cm/s (Larsen, 1990). The geometric mean K value from the Galen-Lyons site for decomposed Vernon Shale is $2.6x10^{-4}$ cm/s.

Although hydraulic conductivity data have not yet been compiled on the decomposed Rochester Shale aquitard, its use at the closed Orleans Sanitary Landfill for the low permeability layer in the cover system suggests that the material may be recompacted to achieve a $1.0x10^{-7}$ cm/s or lower permeability. In-situ hydraulic conductivity values are likely to be within an order of magnitude of the recompacted permeabilities.

<u>Fractured Bedrock Zone</u>

On sites where the fractured and underlying competent bedrock zones are defined discretely, RQD data commonly reflect the differences in rock competency (Table 10). These data indicate that the RQD of a formation whose upper surface lies within the bedrock fracture zone is commonly considerably lower than the RQD value representative of the formation in the competent bedrock zone. The low RQD values of the aquifer zone reflect the numerous, bedding-parallel fractures that probably developed during unloading of glacially compressed bedrock. Consequently the hydraulic conductivity of the fractured bedrock zone is generally higher than corresponding values for the overlying glacitectonized zone and the underlying competent bedrock zone (see Table 9).

Table 9. Hydraulic conductivity (cm/sec) of formations in the fractured and competent bedrock zones for the Lake Ontario Plain.

Site Formations	*Weathered Zone &* Fractured Zone Mean	Max	Min	N	Competent Zone Mean	Max	Min	N
Modern Landfill[1] Queenston Shale	*2.6×10^{-4}* 1.1×10^{-2}	*1.9×10^{-3}* 1.5×10^{-2}	*8.3×10^{-6}* 7.3×10^{-5}	*15* 2	8.1×10^{-6}	4.8×10^{-5}	9.2×10^{-7}	5
Niagara Landfill-Tonowanda[2] Camillus Shale	--	3.0×10^{-4}	4.5×10^{-5}	--	--	--	--	--
Niagara Landfill-Cecos[3] Lockport Group	9.0×10^{-4}	--	--	--	--	2.0×10^{-5}	4.0×10^{-6}	--
Mill Seat Landfill[4] Vernon Shale	6.1×10^{-4}	2.4×10^{-3}	8.4×10^{-5}	12	4.1×10^{-5}	1.0×10^{-3}	4.9×10^{-8}	24
Niagara Landfill-Lockport[5] Rochester Shale	--	--	--	--	--	10^{-6}	10^{-8}	--
High Acres[6] Vernon Shale	*2.7×10^{-5}* 1.5×10^{-2}	-- 1.5×10^{-1}	-- 3.2×10^{-7}	-- 16	2.5×10^{-5}	5.2×10^{-4}	1.1×10^{-6}	20
Seneca Meadows[7] Camilus Shale and Bertie Group	1.7×10^{-3}	4.0×10^{-3}	1.8×10^{-5}	--	--	--	--	--
Galen Lyons[8] Vernon Shale	*7.5×10^{-5}* --	*1.0×10^{-4}* 10^{-2}(est)	*4.0×10^{-5}* 10^{-4}(est)	-- --	--	--	--	--
Orleans Sanitary Landfill[9] Devils Hole/Whirlpool Sandstone Grimsby Sandstone Thorold Sandstone Cambria Shale	 1.1×10^{-5} 5.7×10^{-6} 7.6×10^{-5} 1.1×10^{-4}	 3.3×10^{-5} 1.4×10^{-5} 1.0×10^{-4} 2.0×10^{-4}	 1.9×10^{-6} 1.7×10^{-6} 6.7×10^{-5} 5.3×10^{-5}	 3 4 3 3	 8.3×10^{-6} 1.8×10^{-5} 1.8×10^{-7} 1.5×10^{-5}	 5.8×10^{-5} 8.6×10^{-5} -- --	 5.8×10^{-7} 5.8×10^{-6} -- --	 10 4 1 1

[1]Wehran-New York, Inc. (1991)
[2]RECRA Environmental (1988)
[3]RECRA Environmental (1985)
[4]H & A of New York (1987)
[5]GZA (1984)
[6]Eckenfelder (1992)
[7]Dunn Geosciences (1990)
[8]Larson (1990)
[9]AFI Environmental and Beak Consultants, Ltd. (1988)

Table 10. RQD values of formations in the fractured and competent bedrock zones for the Lake Ontario Plain.

Site	Average RQD Fractured Zone	Average RQD Competent Zone
Modern Landfill[1]		
Queenston Shale	27	72
Orleans Sanitary Landfill[2]		
Whirlpool/Devils Hole Sandstone	42	78
Grimsby Sandstone	64	65
Thorold Sandstone	43	77
Cambria Shale	9	60
Kodak Sandstone	34	No data available
Maplewood & Reynales fms.	10	No data available

[1]Wehran-New York, Inc. (1991)
[2]AFI Environmental and Beak Consultants, Ltd. (1988)

Table 11
General Surficial Stratigraphies
of Sites on the Erie-Ontario Plain

Modern Landfill upper glaciolacustrine cap upper till lower glaciolacustrine sequence basal till	Niagara Landfill-Tonawanda upper till lower glaciolacustrine sequence basal till
Mill Seat Landfill upper glaciolacustrine sequence upper till lower glaciolacustrine sequence basal till	High Acres outwash glacial till/outwash brown "weathered" till gray basal till
Galen-Lyons Landfill outwash "weathered" till basal till	Seneca Meadows upper glaciolacustrine sequence upper till lower glaciolacustrine sequence basal till

Competent Bedrock Zone

In the competent bedrock zone, drill core samples are well-preserved. The hydraulic conductivity of the competent bedrock zone is slightly lower than that of the overlying bedrock hydrostratigraphic units (Table 11). Most sites possess a competent bedrock profile exhibiting a geometric mean K value in the low to mid 10^{-5} cm/s range although stratigraphic control on permeabilities at some sites may result in slightly higher mean values.

Regional Surficial Hydrostratigraphy

Surficial geologic maps covering parts of the study area are provided by Kindle and Taylor (1914), Muller (1977), Young (1980), Yager and others (1984), Cadwell (1988) and Goodman and Stanwix (1994). In addition, a regional Pleistocene stratigraphy for the Erie-Ontario Plain has been synthesized by Calkin and Muller (1992).

Review of hydrogeologic reports for several of the 10 landfill sites situated on the Erie-Ontario Plain reveal general similarities in their stratigraphic successions (Table 11). Furthermore, at least some of these site-specific stratigraphies may be understood within the context of the regional synthesis recently published by Calkin and Muller (1992).

The general stratigraphy of the Lake Ontario Plain consists of two or more couplets of glacial till and recessional lacustrine/outwash facies (Fig. 17) that mostly record Port Huron stade and younger Quaternary history (Calkin and Muller, 1992). This general stratigraphy appears to be recorded in the surficial stratigraphy of several landfill sites on the Lake Ontario Plain (Table 11).

Lower Glaciolacustrine Beds

The oldest documentated surficial deposits on the Lake Ontario Plain appear to be glaciolacustrine silts and clays that are exposed along the shoreline near Somerset, Niagara County. As the bedrock topography increases to the south, this lowest unit probably pinches out against the bedrock subcrop and is beveled at its upper surface by an overlying lodgement till, designated the Furnaceville Till by Calkin and Muller (1992). At landfill sites south of the Onondaga Escarpment, lodgement tills that share the same general geotechnical and hydraulic properties with the Furnaceville Till occur immediately above bedrock except where deeply incised fluvial valleys created topographic lows in the bedrock surface. One such valley has been documented on the Ontario County Landfill site in the Town of Flint (Wehran Engineering, 1986). In the bedrock valley, a glaciolacustrine silt and clay unit attaining a maximum documented thickness of 58 feet overlies shales assigned to the Ludlowville and/or Moscow Formation of the Hamilton Group. Similarities in the succession of overlying till and glaciolacustrine units on sites both north and south of the Onondaga Escarpment suggests that the basal silt and clay deposit at the Ontario County Landfill occupies the same stratigraphic position as the basal silt and clay deposit documented along the Lake Ontario shore by Calkin and Muller

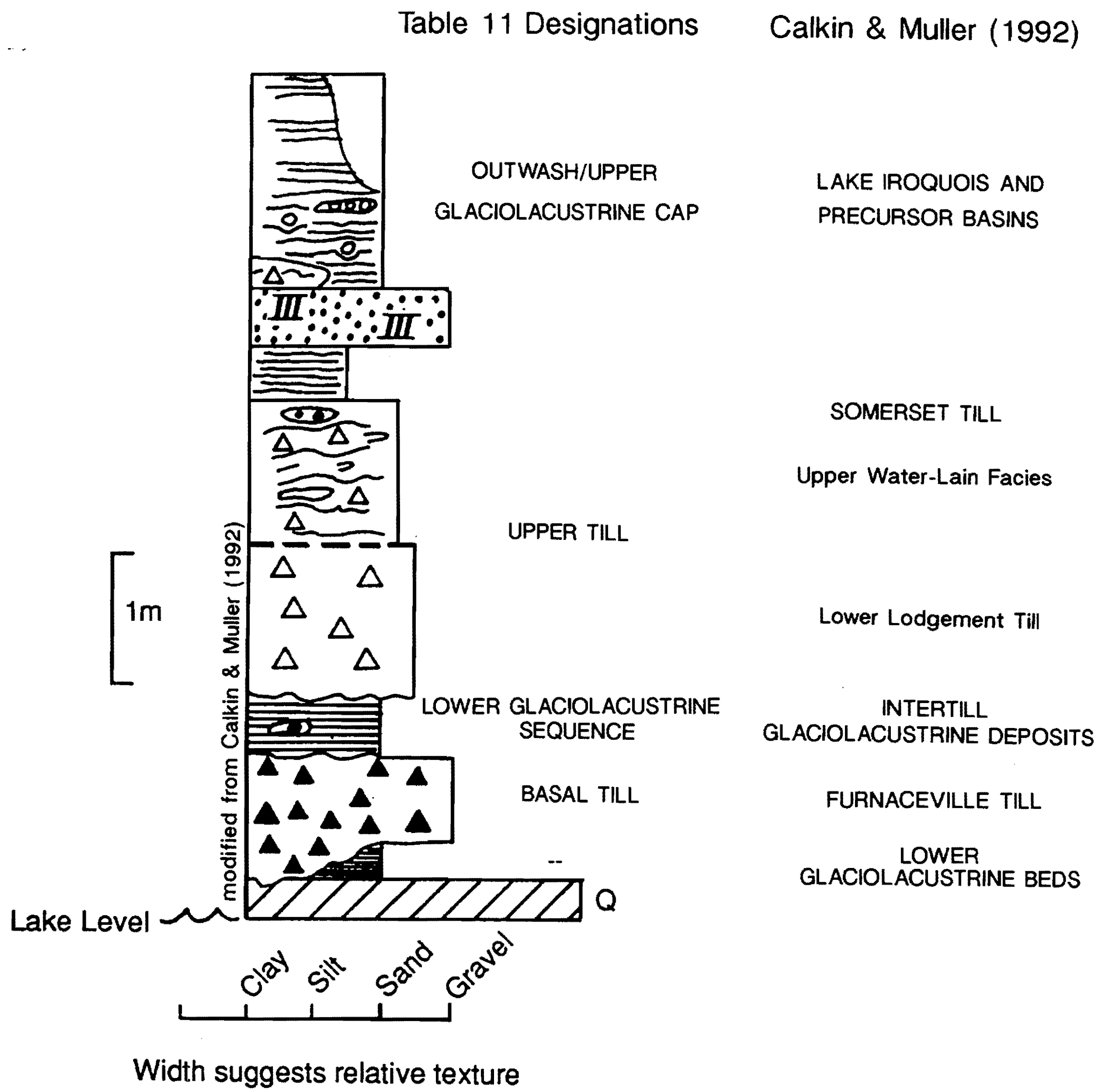


Figure 17. Composite stratigraphic section of regional surficial geologic units encountered on landfill sites on the Lake Ontario Plain.

(1992).

Furnaceville Till

The Furnaceville Till is described by Calkin and Muller (1992) as a stony, massive, red diamicton. Clasts are particularly concentrated near the base of the unit. Large clasts may comprise 50 to 80 percent of the unit by mass. Analysis of 37 till matrix samples by Brennan and Calkin (1984) yielded an average sand:silt:clay ratio of 45:32:23.

Calkin and Muller (1992) have been able to establish correlation of the Furnaceville Till between Niagara and Wayne Counties, a distance in excess of 150 km. Review of till stratigraphies on landfill sites within the same region supports correlation of the Furnaceville Till across ground moraines and drumlin cores.

As would be expected for a lodgement till, the unit is over-consolidated and densely compacted. N-values derived from standard penetration tests (ASTM-D-1586) are summarized in Table 12. Average N-values collected from 6 sites on the Erie-Ontario Plain range between 42 and 124. Caution must be used in evaluating these N-values, however. High blow counts may be attributable to splitspoon contact with cobbles and boulders and are not always an indication of the compaction of the till matrix.

The Furnaceville Till forms an aquitard-grade hydrostratigraphic unit. Average hydraulic conductivity values for this lodgement till at 6 landfill sites are presented in Table 13. The geometric mean K-values for these sites range between $1.0x10^{-7}$ and $4.1x10^{-5}$ cm/s.

Intertill Glaciolacustrine Deposits

Overlying the Furnaceville Till along the shoreline of Lake Ontario is a glaciolacustrine sand to clay sequence ranging up to approximately 8 feet thick. The glaciolacustrine sequence is erosionally overlain by a second diamicton designated the Somerset Till by Calkin and Muller (1992). Identical successions have been documented at the Modern Landfill, Niagara Landfill-Tonawanda, Mill Seat Landfill and Seneca Meadows Landfill.

At most sites, the intertill glaciolacustrine sequence may be divisible into lowstand sand and silt and highstand silt and clay intervals. The lowstand sands apparently record initial transgression and reworking of the Furnaceville Till substrate during glacial recession. At the Modern Landfill, the lacustrine lowstand deposit is primarily a sandy silt exhibiting a gravel:sand:silt ratio of 18:27:55 (Table 14). In constrast, the glaciolacustrine highstand deposit is a fairly lean, varved, silty clay.

On two sites in the Niagara region, the intertill glaciolacustrine clay is apparently normally consolidated and soft. The average N-values for the lower clay at the Niagara Landfill-Tonawanda and Modern Landfill sites are 8 and 6 blows per

Table 12
Surficial deposit N-values of the Lake Ontario Plain

Site	Average	Range	n
Seneca Meadows[1]			
Upper lsc*	14	wor*-46	60
Upper till	33	3-195	95
Lower lsc	27	wor-94	26
Basal sand/basal till	49	4-94	11
Niagara Landfill-Tonawanda[2]			
Upper till	35	11-87	31
Lower lsc	8	wor-20	53
Basal sand/basal till	67	7-120	13
Modern Landfill[3]			
Upper till	19	7-36	72
Lower lsc	6	2-21	73
Basal sand/basal till	78	10-185	77
MillSeat Landfill[4]			
Drumlin tills	85	6-205	146
High Acres Landfill[5]			
Upper till/outwash	60	--	60
Basal till	124		25

1 Dunn Geoscience (1990)
2 Recra Environmental (1988)
3 Wehran-New York, Inc. (1991)
4 H&A of New York (1987)
5 Eckenfelder (1992)

*lsc = lacustrine silt and clay
xwor = weight of rod

Table 13. Hydraulic conductivity of surficial deposits (cm/sec) of the Lake Ontario Plain

Site/Deposits	Geometric Mean	Max	Min	n
Seneca Meadows[1]				
upper lacustrine	5.6×10^{-5}	7.1×10^{-5}	1.1×10^{-6}	4
upper till	8.1×10^{-7}	2.9×10^{-4}	1.8×10^{-8}	17
lower lacustrine	1.5×10^{-5}	1.9×10^{-4}	1.1×10^{-7}	4
Niagara Landfill-Tonawanda[2]				
upper till	1.6×10^{-8}			1
lower lacustrine	1.6×10^{-8}			1
basal till	7.0×10^{-5}	9.4×10^{-5}	4.5×10^{-5}	2
Modern Landfill[3]				
upper till	5.8×10^{-6}	4.2×10^{-4}	2.6×10^{-7}	13
lower lacustrine	5.9×10^{-8}	5.9×10^{-8}	5.9×10^{-8}	3
basal sand	4.9×10^{-5}	3.4×10^{-3}	1.5×10^{-7}	25
basal till	1.0×10^{-7}	2.4×10^{-7}	1.3×10^{-9}	7
Mill Seat Landfill[4]				
coarse grained levels	2.8×10^{-5}	1.9×10^{-4}	4.2×10^{-6}	5
weathered till	1.4×10^{-6}	2.5×10^{-5}	3.2×10^{-9}	8
unweathered till	3.3×10^{-6}	2.1×10^{-5}	8.1×10^{-8}	11
High Acres[5]				
outwash	1.2×10^{-3}	4.7×10^{-3}	5.1×10^{-5}	7
weathered till	1.7×10^{-5}	7.9×10^{-5}	8.7×10^{-7}	11
Galen Lyons[6]				
alluvium	1.9×10^{-4}			1
upper till	8.6×10^{-6}	2.8×10^{-4}	2.1×10^{-8}	7
lower till	3.8×10^{-6}	1.4×10^{-4}	7.3×10^{-8}	5

[1]Dunn Geoscience (1990)
[2]RECRA Environmental (1988)
[3]Wehran-New York, Inc. (1991)
[4]H&A of New York (1987)
[5]Eckenfelder (1992)
[6]Larson (1990)

Table 14. Grain size trends of surficial deposits of the Lake Ontario Plain.

Site/Deposits	% Gravel	% Sand	% Silt	% Clay	n
Modern[(1)]					
brown till	0.2	9.2	29.4	61.2	3
grey till	2.2	8.4	35.4	54.0	8
lacustrine lowstand	18.4	26.5	55.1	0.0	1
Seneca Meadows[(2)]					
upper till	7	45	25	23	1
glaciolacustrine silt & clay	0	0	35	65	1

[1]Wehran-New York, Inc. (1991)
[2]Dunn Geoscience (1990)

foot, respectively. These values suggest that the unit has not been subjected to significant compaction by the overlying Somerset Till. Consequently, either the Somerset Till does not contain a true lodgement till facies beyond northern Niagara County or anomalously high hydrostatic pressures were able to offset the weight of the advancing ice sheet.

For the most part, hydraulic conductivity values reported for the intertill glaciolacustrine deposts reflect the relative percentages of sand and clay in local sections (see Table 13). Values representative of the basal sand and silt are generally in the 10^{-5} cm/s range. Values representative of the overlying silt and clay highstand unit are in the 10^{-8} cm/s range.

Somerset Till

The predominant diamicton of the Lake Ontario Plain in western New York is a gray to purplish-gray unit that overlies the intertill glaciolacustrine sequence, the Furnaceville Till or bedrock (Calkin and Muller, 1992). This unit has been designated the Somerset Till.

Calkin and Muller (1992) recognize two facies in sections along the shore of Lake Ontario: 1) a basal, compact, massive-bedded, homogeneous, silty till; and 2) an overlying, subaqueously deposited succession of diamictic beds and stratified, water-sorted facies. The basal contact of the Somerset Till is apparently sharp in the type area based upon consistent identification in test borings. Conversely, the upper contact appears gradational with the capping glaciolacustrine sequence, and a distinction is not always made in test boring logs.

Although the texture of the Somerset Till may be widely variable, Calkin and Muller (1992) indicate that the unit is generally finer-textured than the older Furnaceville Till. These workers report that the gravel component averages only 4 percent by mass. Grain-size data from the Modern Landfill and Seneca Meadows Landfill are consistent with the reported low gravel content (see Table 14).

Generally, the Somerset Till is less compact than the older Furnaceville Till. One reason may be that at least the upper half of the Somerset Till was deposited subaqueously. Varved interbeds are common at the Modern Landfill site (Wehran, 1991). The lower degree of compaction is reflected in lower average N-values for the upper till than the lower diamicton (see Table 12). Average N-values for the Somerset Till at four landfill sites range between 19 and 60 blows per foot compared to a range between 42 and 124 blows per foot for the Furnaceville Till.

Due to the high percentages of silt and clay in the Somerset Till, the diamicton forms a low permeability, aquitard-grade, hydrostratigraphic unit. Average hydraulic conductivity values from 5 landfill sites range between 1.6×10^{-8} and 8.6×10^{-6} cm/s (see Table 13).

Upper Glaciolacustrine Deposits

A progradational clay to sand sequence overlies the Somerset Till or ice contact facies along the shore of Lake Ontario (Calkin and Muller, 1992). Lacustrine sequences cap the upper till at many landfill sites both north and south of the Niagara Escarpment (see Table 11). North of Route 104, these deposits are attributed to Lake Iroquois. South of the escarpment, the glaciolacustrine sequence may be attributed to one of several Iroquois-precursor basins.

Because of the gradational contact with the water-lain till facies of the underlying Somerset Till, the glaciolacustrine sequence is not always treated discretely on landfill sites. At Seneca Meadows, however, a distinction between the two units can be made (Dunn Geoscience, 1990). N-values for the glaciolacustrine unit range between 0 (weight of drill rods) and 46 with an average N-value of 14 (see Table 12).

At some landfill sites in eastern Monroe and Wayne Counties, the upper glaciolacustrine silt and clay sequence appears to be replaced by coarse-grained, lacustrine shoreface to outwash facies (see Table 11). These coarse-grained materials are widespread in the Irondogenesee Valley (Yager and others, 1984). On the High Acres and Galen-Lyons Landfill sites, coarse-grained deposits occupy interdrumlin areas. Coarse-grained deposits also rim a portion of the drumlin on which the Mill Seat Landfill is constructed. The coarse-grained materials exhibit site-specific, geometric mean hydraulic conductivities ranging between $2.8x10^{-5}$ and $1.2x10^{-3}$ cm/s (see Table 13).

Groundwater Flow Trends

Groundwater flow conditions on landfill sites of the Lake Ontario Plain reflect gentle topography and the alternating succession of aquitards and transmissive horizons. Recharge of the shallow groundwater zone occurs atop flat-lying ground moraines and glaciolacustrine plains (Figures 18a, b). On drumlin sites, runoff and shallow interflow proceed radially from topographic highs to groundwater recharge areas between the drumlins (Figure 18c). Flow vectors are oriented vertically downward to potentially transmissive zones in the overburden or fractured bedrock zone. On ground moraines and glaciolacustrine plains, the first transmissive zone may occur within a glaciolacustrine sand and silt lowstand horizon atop the Furnaceville Till (Wehran-New York, 1991). On drumlin sites, the first transmissive zone may occur in interdrumlin outwash at very shallow depths. These deposits are typically removed on landfill sites in order to insure that landfill subgrades consist of low permeability materials.

On most flat-lying sites, the water table occurs within 5 feet of the ground surface. In drumlins, a shallow water table may be difficult to define because of the anisotropy of the upper till horizon. Groundwater may exist as perched lenses in an otherwise unsaturated till matrix (H&A of NY, 1989). A perched groundwater table may also exist in the weathered till profile on the drumlin (Eckenfelder, 1992).

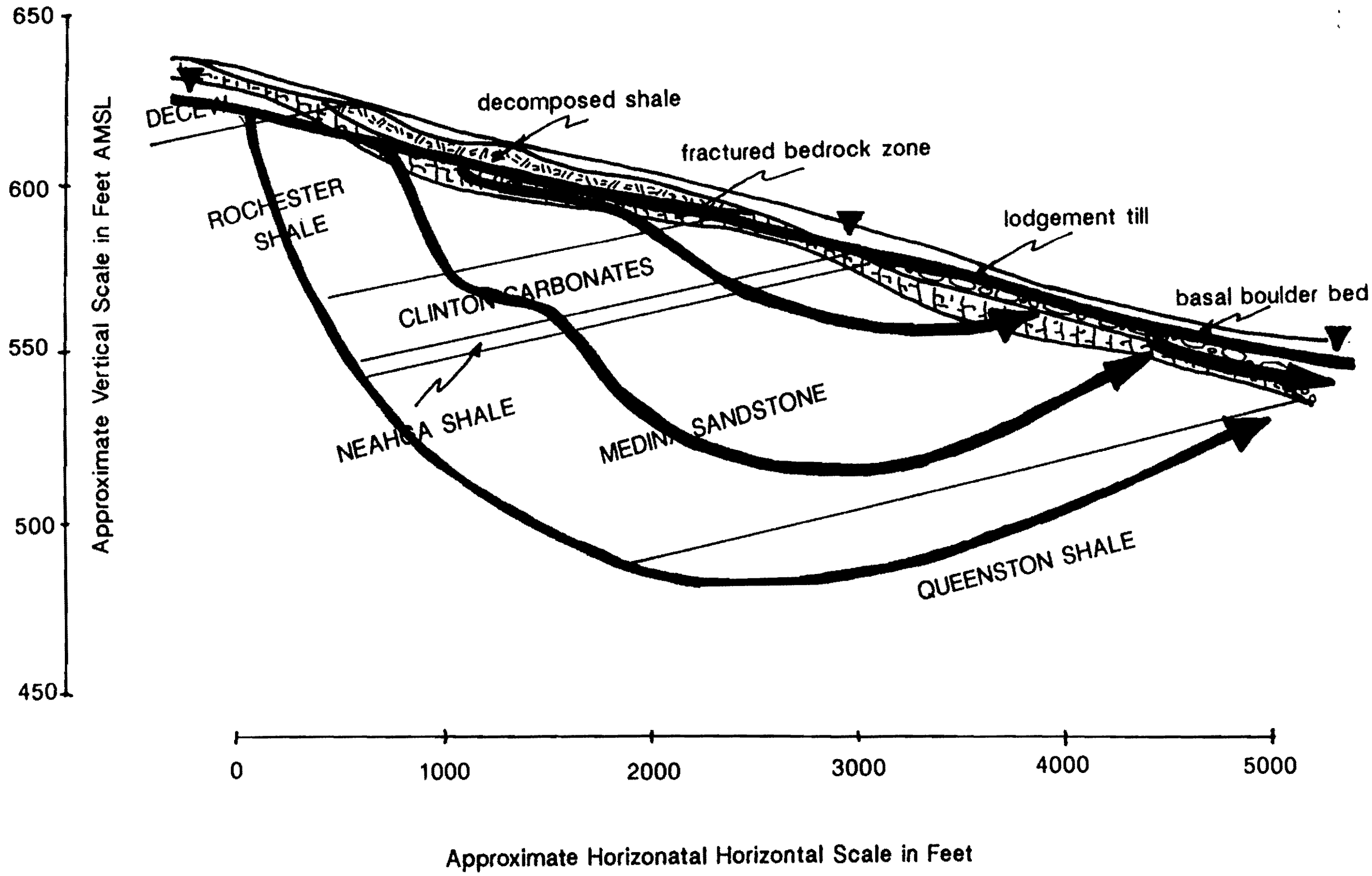


Figure 18A. Generalized groundwater flow patterns beneath the ground moraine hydrogeologic setting, Lake Ontario Plain.

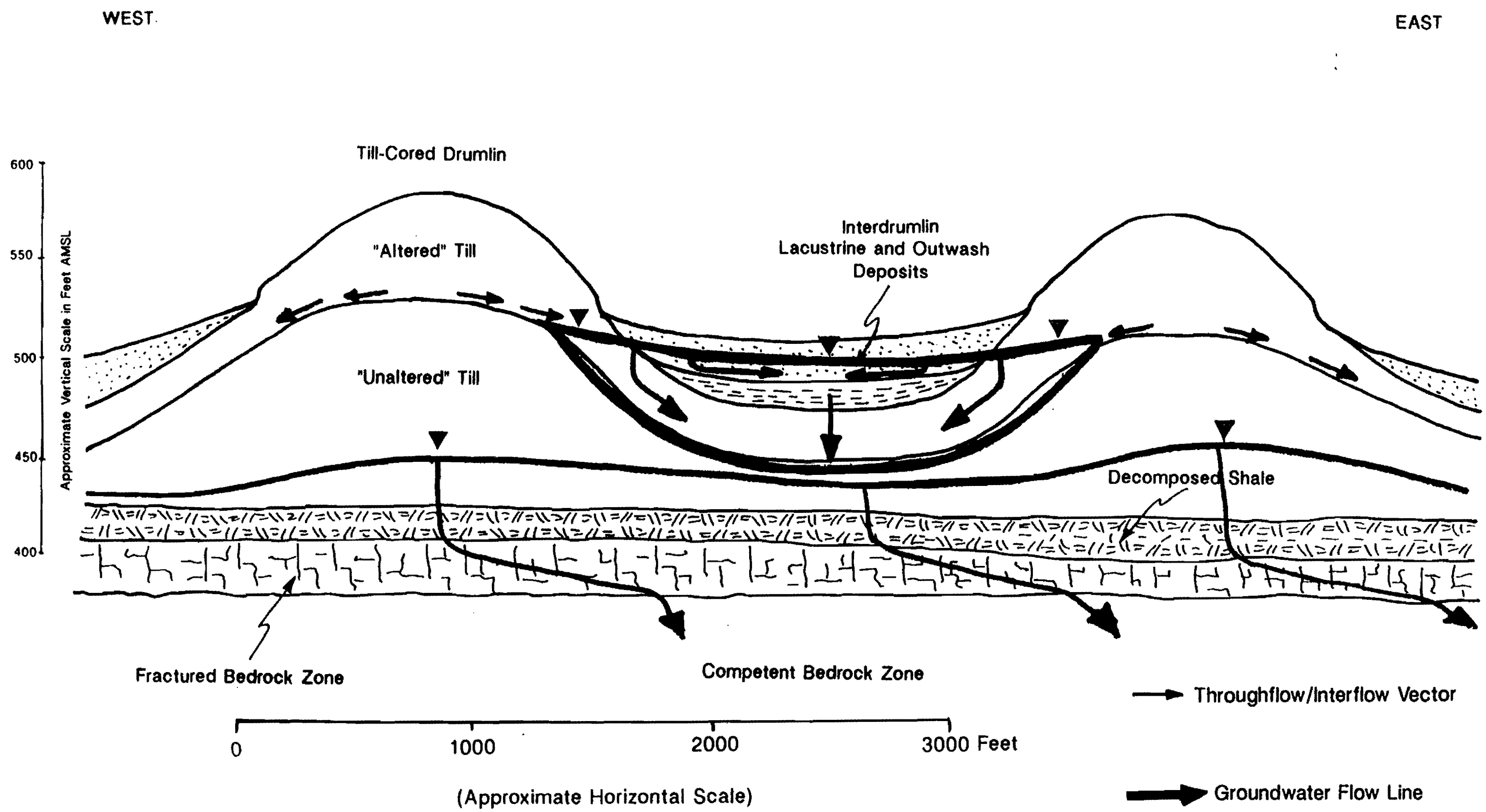
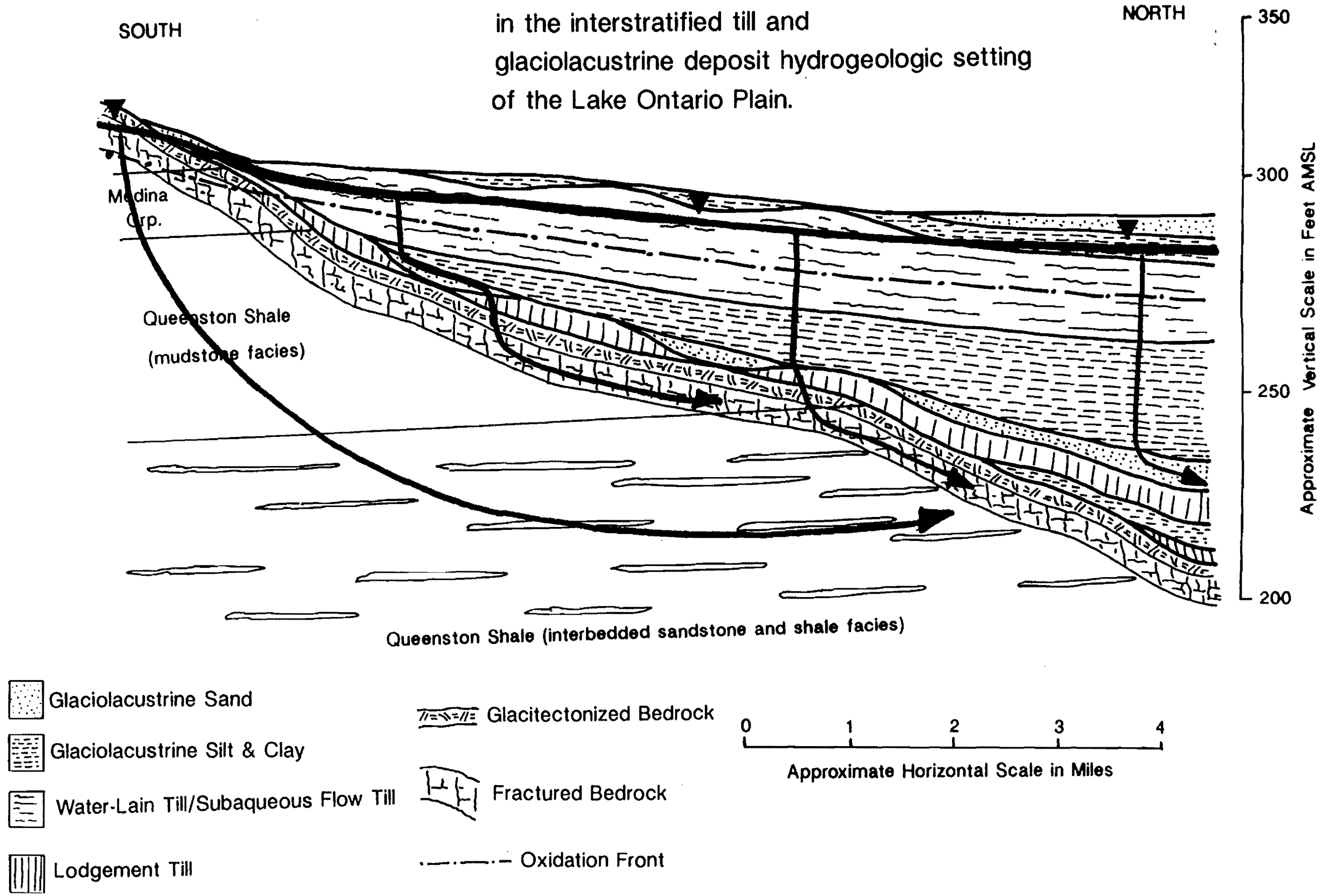


Figure 18B. Generalized groundwater flow patterns beneath the drumlin hydrogeologic setting, Lake Ontario Plain.

Figure 18C. Generalized groundwater flow patterns in the interstratified till and glaciolacustrine deposit hydrogeologic setting of the Lake Ontario Plain.



Regional Background Water Quality

A summary of representative background water quality for landfill sites on the Erie-Ontario Plain is provided in Table 15. These data reflect the position of the lake plain near regional base-level. The plain lies in close proximity to major sublacustrine groundwater discharge zones for regional-scale flow systems that may originate in the Appalachian Plateau. Thus, a remarkable contrast in concentrations of dissolved solids exists between water quality data in Tables 8 and 15.

Water quality is significantly impaired by high concentrations of naturally-ocurring calcium, sodium, sulfate and chloride. The majority of the dissolved ionic species are likely derived from the evaporites of the Silurian Salina Group. Discharging brine springs at the contact between the Silurian Medina Group and Ordovician Queenston Shale have been described as early as Amos Eaton (1824). These Medina brines may not be associated with the Salina evaporites, but may instead be connate formation waters or very old meteoric waters.

CONCLUSION

This study demonstrates that hydrogeologic reports for landfill sites contain valuable data for characterization of regional hydrostratigraphic units. Access to documents was provided by the NYSDEC after filing of a Freedom of Information Law request. Technical reports from 19 landfills were reviewed. The quantitative data available in these reports can be reconciled with and may compliment existing published regional surficial and bedrock stratigraphic syntheses.

Common elements of hydrogeologic settings that are appropriate for landfill siting may be used to construct general models for till-dominated terrains in the Appalachian Plateau and the Erie-Ontario Plain. These models may be used predictively and may be modified following further testing through future comparative studies.

ACKNOWLEDGMENTS

Thanks are in order to several people and agencies for their assistance in this study. First, sincere thanks to former students Dawn Weaver and Denise Woodman for writing term papers that assisted in the preliminary planning stages of this exercise. Secondly, access to the data necessary to complete the comparative analysis could not have been gained in a timely fashion without the support of staff at the Region 8 and Region 9 NYSDEC offices. Specific thanks are extended to Mary McIntosh, Patrick Concannon, Ed Keida and Vonnie Gerrace. In addition to presentation of data from NYSDEC files, this study also provided an opportunity to share a proprietary landfill map with the scientific community. The authors would like to express their appreciation to William Heitzenrater of AFI who released the copyrighted terrain suitability map for publication.

Table 15
Representative Background Water Quality
Erie-Ontario Plain

Parameter*,(6)	CECOS	Niagara County Landfill	Niagara Landfill Inc. Tonawanda		High Acres Landfill		Orleans Sanitary Landfill					
							Western Area			Eastern Area		
	Bedrock/ Overburden Contact	Shallow Bedrock	Shallow Bedrock	Lodgement Till	Lodgement Till	Shallow Bedrock	Lodgement Till	Shallow Bedrock	Deep Bedrock	Lodgement Till	Shallow Bedrock	Deep Bedrock
pH (pH units)	6.68	6.59	8.62	7.62	7.43	7.72	7.40	7.48	7.70	7.90	7.68	7.62
Specific Conductance (umhos/cm)	1750	1592	2973	3340	1000	2794	520	2450	14600	540	680	805
Total Dissolved Solids	N/A	1119	3438	7625	625	2500	370	1575	9300	260	390	528
Hardness	N/A	1310	N/A	N/A	496	1260	230	895	2300	350	375	383
Alkalinity	N/A	301	N/A	N/A	320	205	153	199	250	290	298	228
Chloride	340	171	372	1385	127	101	25.0	615	5600	11.6	27.3	74.4
Sulfate	2.10	541	1998	586	75.0	1402	126	77.0	135	7.30	54.0	70.6
Nitrate	N/A	0.31	N/A	N/A	1.31	0.70	0.01	1.21	0.10	0.02	0.08	0.58
TOC	62.0	19.9	35.0	284	0.80	1.6	9.5	1.25	18.0	21.0	0.67	0.67
Ammonia	N/A	N/A	N/A	N/A	N/A	N/A	0.08	0.02	1.93	0.23	0.02	0.37
Iron	N/A	10.8	0.09	5.63	7.10	2.50	0.04	0.03	N/A	10.5	0.04	0.12
Manganese	N/A	0.86	0.14	1.34	N/A	N/A	0.005	0.08	N/A	11.5	0.17	0.13
Magnesium	N/A	N/A	N/A	N/A	50.0	57.0	13.1	50.2	123	17.6	27.5	30.8
Calcium	113	N/A	N/A	N/A	113	409	59.0	244	700	110	105	94.4
Sodium	300	N/A	N/A	N/A	550	258	77.0	155	2200	15.2	13.9	17.0
Potassium	N/A	N/A	N/A	N/A	6.90	18.1	3.70	13.3	56.0	1.82	2.57	13.9

* all values in mg/l unless otherwise specified

(6) Values reported are mostly arithmetic means for each geologic interval.

Table 15
Representative Background Water Quality
Erie-Ontario Plain

Parameter*	Galen-Lyons Landfill			Mill Seat Landfill				Modern Landfill	
	Weathere d Till	Unaltered Till	Shallow Bedrock	Weathered Till	Unweathered Till	Shallow Bedrock	Deep Bedrock	Lacustrine Silt & Sand	Shallow Bedrock
pH (pH units)	6.21	7.39	8.66	7.43	8.22	6.98	6.91	7.53	7.80
Specific Conductance (umhos/cm)	597	473	460	859	661	1491	1963	2356	3458
Total Dissolved Solids	451	362	142	543	389	1283	1776	3822	5818
Hardness	434	320	187	466	315	992	1325	2043	2075
Alkalinity	364	237	110	375	271	305	319	433	292
Chloride	37.9	11.4	1.98	14.9	13.1	37.5	59.7	190	460
Sulfate	29.3	80.0	327	122	77.0	638	928	2072	3190
Nitrate	1.50	0.11	<0.05	1.35	0.80	0.12	0.03	0.19	0.06
TOC	6.41	1.53	1.83	120	1.13	2.16	4.47	2.39	2.98
Ammonia	1.93	0.05	0.09	0.03	0.11	0.06	0.14	0.28	0.75
Iron	7.05	0.61	2.69	0.09	0.08	0.16	0.57	7.60	1.87
Manganese	0.49	0.03	0.07	0.08	0.02	0.06	0.04	0.27	0.24
Magnesium	N/A	N/A	N/A	60.0	43.3	41.6	43.7	271	235
Calcium	115	66.9	36.1	83.3	46.0	326	456	193	337
Sodium	11.8	10.2	14.5	16.3	37.1	11.2	13.7	222	628
Potassium	4.35	1.39	14.5	4.00	7.87	2.44	5.40	9.95	34.9

* all values in mg/l unless otherwise specified

(6) Values reported are mostly arithmetic means for each geologic interval.

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ROAD LOG
HYDROGEOLOGY OF LANDFILL SITES
IN WESTERN NEW YORK

TOTAL MILES	MILES FROM LAST POINT	ROUTE DESCRIPTION
0.0	0.0	Depart from U of R parking lot; turn left (south) onto Wilson Blvd.
0.1	0.1	Intersection with Elmwood Avenue; turn left (east) onto Elmwood Ave.
0.3	0.2	Intersection with Lattimore Road; turn right (south) onto Lattimore.
0.4	0.1	Intersection with Crittenden Blvd; turn left (east) onto Crittenden.
1.2	0.8	Intersection with Routes 15 and 15A; Bear right onto Route 15A.
2.2	1.1	Intersection with Route 390; bear left onto 390 south.
2.4	0.2	Junction with Route 590 north; bear left onto Route 590 north.
18.4	16	Browncroft Blvd. (Rt. 286) off-ramp; turn right (east) onto Browncroft.
18.5	0.1	Turn left into access road to Brighton Town Landfill.

STOP 1. BRIGHTON TOWN LANDFILL

Facility: Brighton Solid Waste Management Facility

Location: Town of Brighton, Monroe County (Rochester East 7.5" Quadrangle)

Hydrogeologic Setting: Glaciolacustrine deposits and glacial till over bedded sedimentary rock.

Site Description: The site is located on the northeast-facing side of the Irondequoit Creek valley. The site includes 75 acres; only 24 acres are considered suitable for waste disposal purposes. Topographic relief across the active portion of the site is approximately 150 feet; the average topographic slope is approximately 5 percent. The site is bounded on the west by Thomas Creek, a small tributary of Irondequoit Creek, and on the north and east by Irondequoit Creek. Irondequoit Creek drains into a major bay (Irondequoit Bay) of Lake Ontario.

The following items, listed in the Part 360 Permit Application for this facility, reflect current site conditions:

- There is no evidence of leachate derived from this facility.
- Natural vegetation is present on previous disposal areas.
- Vegetation is established on all slopes of disposal areas.
- There is no evidence of significant erosion occurring on site.
- The disposal area is adequately covered and graded to maintain safe and efficient storm water runoff.

Surficial Geology: Overburden consists of probable lodgement till overlain by interbedded flow tills and stratified silt- to sand-rich glaciolacustrine facies. The overburden ranges in thickness from 22 to approximately 100 feet. The overburden is thinnest at the topographically highest (southwestern) portion of the site and thickens towards Irondequoit Creek, to the northeast. The strike of the surficial deposits generally follows the topographic contours of the valley.

The interbedded, stratified glaciolacustrine facies and water-lain till deposits include evenly laminated silt (offshore lacustrine deposits), evenly- and cross-laminated coarse silt and very fine sand (nearshore lacustrine deposits), and gravelly, clay-rich silts (tills). Based on detailed boring logs, split-spoon samples (Huntingdon-Empire Soils Investigations, Inc., 1994), and outcrop sections, the glacial and proglacial strata include, in descending order:

Unit 1:	Evenly laminated silt (10 to 25 feet thick)
Unit 2:	Very fine, silty sand (5 to 15 feet thick)
Unit 3:	Gravelly, clay-rich silt (5 feet thick)
Unit 4:	Evenly laminated silt (> 5 feet)
Unit 5:	Undifferentiated deposits (No boreholes with detailed logs or available split spoon samples penetrated Unit #4. However, tills are present over bedrock throughout the lower Irondequoit Creek valley.)

This succession mostly records accumulation in a proglacial lake basin. The glaciolacustrine succession disconformably overlies lodgement till that accumulated during the earlier glacial advance. A minor glacial advance is recorded by Unit 3, a waterlain diamicton or subaqueous flow till. The stratigraphic record of this advance is asymmetrical: offshore silts are overlain by flow till, and the flow till, in turn, is overlain by nearshore sands. Unit 3 may correlate with the Somerset Till described by Calkin and Muller (1992) from sections along the Lake Ontario shoreline.

In general, lacustrine silts and sands are extremely well sorted with D_{10} values on the order of 0.05 mm or less for the very fine sands. N-values for these deposits generally range from 15 to refusal, with the lower N values correlating to shallowest subsurface sandy deposits.

Bedrock Geology: Based on reported depth to bedrock, strata assigned to the Lower Silurian Medina and Clinton groups probably subcrop beneath glacial sediments. These strata consist of sandstone, shale, and limestone. In ascending order, the following formations are likely subcrop beneath the site: Grimsby Sandstone, Cambria Shale, Kodak Sandstone, Maplewood Shale, Reynales Limestone, and Sodus Shale.

Groundwater Flow: Groundwater flow is topographically controlled. Groundwater equipotentials are generally parallel to topographic contours; groundwater flows to the northeast.

18.7	0.2	Return west on Browncroft Blvd to Rt. 590. Turn left onto Rt. 590 south.
20.2	1.5	Junction with Route 490; take Route 490 east.
23.4	3.1	Junction with Route 31F; turn right (east) onto Route 31F.
26.2	2.8	Route 31F to the Village of Fairport;
27.4	1.2	Route 31F crosses canal on east side of village.
29.9	2.5	Intersection of Perinton Parkway and Route 31F; turn right (south) onto Perinton Parkway.
30.8	0.9	Perinton Parkway to Resident's Entrance to High Acres Landfill.

STOP 2. HIGH ACRES LANDFILL

Site Location: Town of Perinton, Monroe County, New York
Fairport and Macedon 7.5 Minute Quadrangles

Site Description: The east side of the site contains a north-south trending drumlin. The existing operational facility is constructed on the drumlin. The west side of the site is relatively flat-lying, interdrumlin terrain. The western area is presently under construction as a lateral expansion area to the landfill.

Surficial Geology: The drumlin on the west side consists of two separate till horizons: a lower, gray, bouldery lodgment till and an upper, brown weathering "altered till". The upper till contains fewer cobble and boulder size clasts than the basal, unaltered till (Dan Coon, personal communication). Given the difference in grain-size composition and density, the upper till may actually represent a separate genetic unit. One hypothesis is that the basal till correlates with the Furnaceville Till, whereas the upper till is correlative to the Somerset Till.

In the interdrumlin areas of the west side of the site, the surficial stratigraphy is more variable. The basal till that directly overlies bedrock is also divisible into a lower, unaltered zone and an upper weathered zone. The presence of this horizon may suggest a period of subaerial exposure prior to deposition of the overlying recessional sequence. Such an interpretation, however, is difficult to reconcile with the regional glacial history. An alternative hypothesis is that the "weathered till" may represent the diamictic facies of the younger Somerset Till equivalent and that the mixed water-lain and till deposits ("glacial till/outwash" deposits of Eckenfelder, 1992) may correspond to the upper water-lain till facies of the Somerset Till as defined by Calkin and Muller (1992).

Bedrock Stratigraphy: The bedrock strata that subcrop beneath glacial tills on the site are assigned to the upper part of the Silurian Vernon Shale. Eckenfelder (1992) reports that the drill core sections consist primarily of red and green shale with varying amounts of gypsum. Gamma ray logs were used to correlate borehole sections. Through correlation of gamma ray logs, Eckenfelder (1992) was able to document the regional southward dip of bedrock strata.

Groundwater Flow Conditions: Shallow groundwater flow tills and glacial outwash is topographically controlled. On the east side of the site, groundwater in the brown till horizon flows radially off the drumlin. In flat-lying areas, groundwater flow generally proceeds to the south. The low permeability of the glacial tills results in vertically oriented groundwater flow vectors. Flow lines are deflected to a more horizontal orientation in lenses of glacial outwash.

The bedrock fracture zone provides a preferred groundwater flow path. Upward gradients are common between the fractured bedrock zone and the underlying competent bedrock zone.

30.8	0.0	Exit High Acres left (west) onto Perinton Parkway.
31.7	0.9	Intersection Perinton Parkway and Route 31F; turn left (west) onto Route 31F.
37.2	6.4	Route 31F west back through Fairport until junction with Route 490; turn right onto Route 490 west.
40.3	3.1	Route 490 west to Route 590; bear right onto Route 590 south.
56.3	16.0	Route 590 south to junction with Route 390; bear righ onto Route 390 south.

85.8	32.5	Route 390 south to Exit 7 (Mount Morris, Route 408); turn left (south) on Route 408.
89.6	3.8	Village of Mount Morris; jog in Route 408.
98.4	8.8	Route 408 south to Village of Nunda; stay south on Route 408.
101.5	3.1	End Route 408 south; remain southbound on State Street. Sharp left jog in road on south side of Dalton.
104.0	2.5	State Street ends; stay southbound on Allegany County Road #16.
107.1	3.1	Sharp right jog in county road #16 at intersection with county road #24; bear right on county road #16 south.
123.1	16.0	County Road #16 south to the Village of Angelica. Intersection with Peacock Hill Road; turn left (south) onto Peacock Hill Road.
124.6	1.5	Intersection with Herdman Road (entrance to Hylands Ash Monofill); turn right onto Herdman Road.

STOP 3. PROPOSED HYLANDS ASH MONOFILL

Facility: Hylands Ash Monofill

Location: Town of Angelica, Allegany County (Angelica 7.5" Quadrangle)

Hydrogeologic Setting: Glacial Till Over Bedded Sedimentary Rock.

Site Description: The site contains a broad, southfacing, hanging valley that forms a natural amphitheater. A small intermittent stream is supplied by a bedrock spring along the east side of the site and by overland flow toward the valley center in the southern portion of the hanging valley. Surface water drainage flows into Angelica Creek which, in turn, discharges to the Genesee River.

Surficial Geology: Glacial overburden consists of lodgement till overlain by ablation till. The overburden ranges in thickness between approximately 5 and 115 feet. The till is thinnest on hill crests and thickens rapidly toward the center of the hanging valley. An oxidation front marked by the vertical change from gray, unaltered till to brown, weathered deposits cross-cuts and partially obscures the lodgement till/ablation till contact. The lodgement till is overconsolidated; assuming no net erosional lost of glacial sediments near the valley floor, the brown, oxidized lodgement till is estimated to have been compacted beneath a minimum of 500 ft. of ice and probably considerably more (Michael Mann, personal communication). The ablation till is generally less dense than the lodgement till and contains thin, discontinuous, water-sorted lenses.

High subglacial pore pressures are suggested by the fracturing of bedrock and injection of till seams to depths approaching 200 ft. below ground surface. The upper 20-30 ft. of rock is typically so intensely fractured that the contact between glacial till and bedrock may be completely gradational. In ascending order, the gradational interval consists of 1) in-situ rock mass with till seams; 2) approximately even proportions of in-situ rock mass and till with gravel-sized angular rock fragments; 3) boulder-size, rotated or detached blocks of bedrock in a gravelly clay till matrix (deformation till); and 4) channery lodgement till.

Bedrock Geology: Strata are assigned to the Upper Devonian (Fammenian) Canadaway and Conneault Groups and consist of a series of interbedded, fossiliferous sandstones, siltstones and clay shales (see Fig. 6A). In ascending order the following formations subcrop on site: Machias Shale, Cuba Sandstone and Wellsville Shale. The site is situated on the northwest limb of a northeast-trending anticline. Strata dip to northwest at approximately 1 degree.

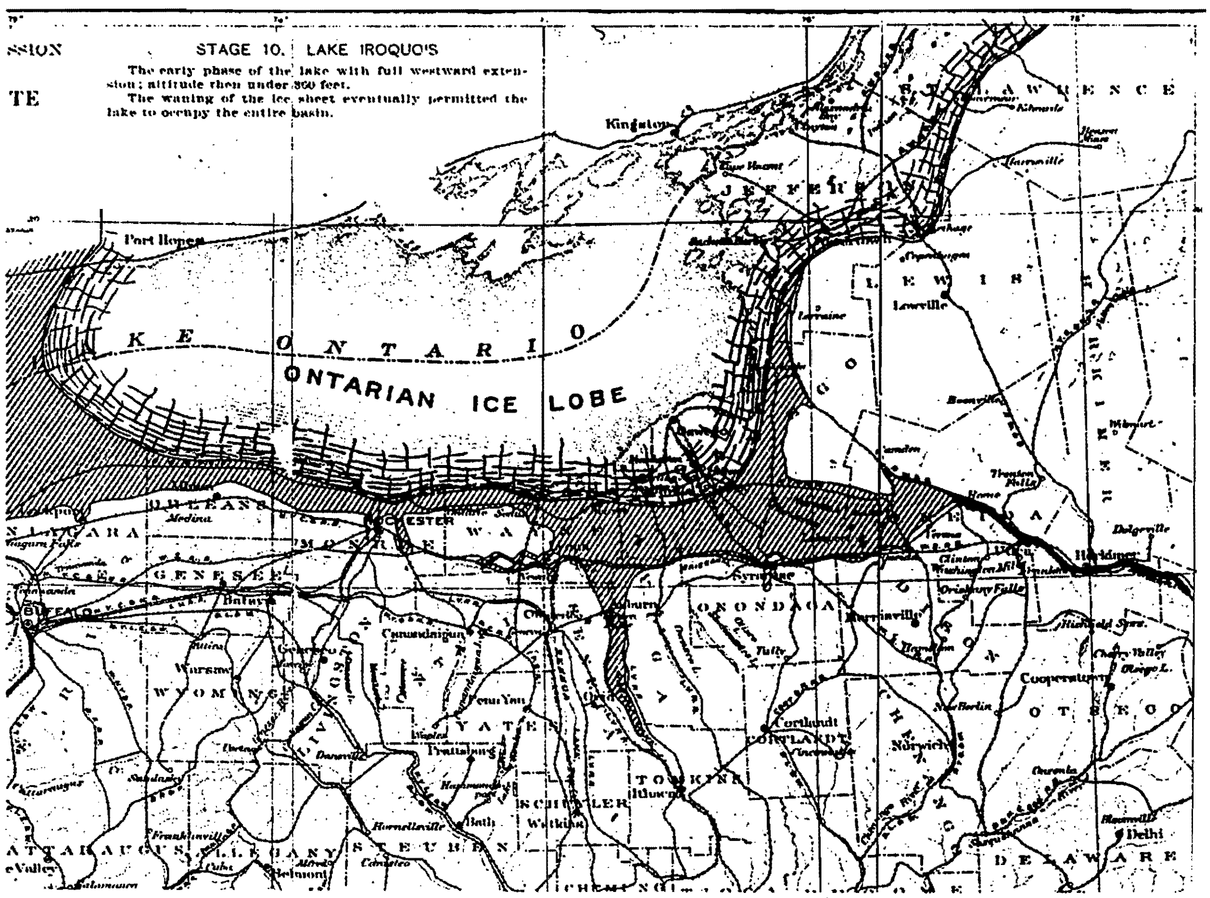
Groundwater Flow: A perched water table exists in the ablation till profile in the valley center. The perched groundwater table is recharged by interflow and overland flow directed toward the valley center from the east, west and north. Along the axis of the valley, groundwater flows southward toward the intermittent stream.

Groundwater flow in bedrock is divided into two flow systems. A high elevation flow system contains a recharge area in open pastures upgradient (east) of the site. The discharge zone occurs at the spring line that marks the base of the Cuba Sandstone subcrop belt along the east side of the site. A second, deeper bedrock flow system occurs in the Machias Shale beneath the landfill footprint. Strong downward gradients are characteristic of the upper portion deeper bedrock system. The horizontal flow vector is directed primarily to the west/southwest. Westward flow on the east side of the till-filled valley is impeded by the gray till aquiclude. Consequently, artesian pressure builds in the deeper bedrock system in the southeast corner of the site. Hydraulic gradients in bedrock beneath the west side of the site are steeply downward. Flow diverges on either side of the topographic divide in the shallow rock profile beneath the western site boundary. Deeper flow in rock trends toward the west/southwest.

124.6	0.0	Exit Herdman Road; Turn left (north) onto Peacock Hill Road.
126.1	1.5	Peacock Hill Road to Junction with Route 16. Turn right (northbound) on Route 16.
145.2	19.1	Route 16 to transition to State Street in Dalton.

147.7	2.5	State Street north to transition to Route 408 north.
163.4	15.7	Route 408 north to Mount Morris; Juntion with Route 390; Take Route 390 north.
199.4	36.0	Route 390 north to Rochester, Scottsville Road Exit; Turn left (north) onto Scottsville Road.
200.4	1.0	Scottsville Road north to Junction with Elmwood Avenue. Take Elmwood Avenue east across Genesee River.
200.9	0.5	Turn left at light onto Wilson Boulevard; Hutchinson Hall is on the right.

END OF TRIP



Map of Lake Iroquois

[From Fairchild, 1909, Glacial waters in central New York.
N.Y.S. Mus. Bulletin 127, Plate 42]