"A Basin Analysis of the Wabigoon Area of Lake Agassiz, a Quaternary Clay Basin in Northwerstern Ontario"

David R. Sharpe, Susan E. Pullan et Timothy A. Warman

A BASIN ANALYSIS OF THE WABIGOON AREA OF LAKE AGASSIZ, A QUATERNARY CLAY BASIN IN NORTHWESTERN ONTARIO*

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ABSTRACT Information from a wide range of sources is integrated in a basin analysis of the Wabigoon Basin, a Quaternary clay basin located on the Canadian Shield in northwestern Ontario. The basin sediments were deposited between 10.9 ka and 9.5 ka, along the margin of the Rainy Lobe of the Laurentide Ice Sheet, which formed the northern boundary of proglacial Lake Agassiz. The basin architecture is dominated by four major elements: end moraines, eskers, kames and a clay plain, all of which overlie irregular bedrock topography. End moraines, eskers and kames are composed mainly of a fining upward sequence of gravels and sands. The geometry of these sedimentary units, and their sedimentary structures indicates they were deposited mainly by high and low-density turbidity currents, on ice-marginal subaqueous outwash fans. Eskers contain a core of coarse gravel and sand deposited within subglacial meltwater conduits, overlain by subaqueous fan sediments deposited at the conduit mouth. Esker ridges were formed during conduit filling events and flanking deposits were formed when a conduit remained in use during ice-marginal retreat. Where conduits were short-lived, isolated subaqueous fans (kames) were formed. A depositional model is proposed which relates moraine formation to catastrophic releases of subglacial meltwater and sediment simultaneously along the entire margin of the Rainy Lobe. The clay plain forms a broad blanket of fine-grained, rhythmically-bedded sediment which obscures bedrock topography, and often buries esker and kame deposits. Seismic profiles and overburden drilling reveal deep (50-70 m) bedrock lows beneath the clay plain. These lows, oriented sub-parallel to the ice margin, acted as sediment traps, and were infilled by the deposits of underflows generated at the ice margin.

RÉSUMÉ *Analyse du bassin de Wabigoon du Lac Agassiz, un bassin argileux quaternaire au nord-ouest de l'Ontario*. Les renseignements tirés d'un grand nombre de sources sont intégrés en vue de l'analyse du bassin de Wabigoon, situé sur le Bouclier canadien. Les sédiments qui le composent ont été déposés entre 10,9 et 9,5 ka, le long de la marge du lobe Rainy de l'Inlandsis laurentidien, qui formait la limite nord du Lac Agassiz. Les quatre formes principales qu'on y trouve sont les moraines frontales, les eskers, les kames et une plaine argileuse; ces formes recouvrent le relief irrégulier du substratum. Les moraines frontales, les eskers et les kames sont surtout composés d'une séquence de graviers et de sables s'affinant vers le haut. La géométrie de ces unités sédimentaires et leur structure montrent qu'elles ont en grande partie été déposées sur des épandages fluvio-glaciaires sous-aquatiques de marge glaciaire par des courants de turbidité de haute et de basse densité. Les eskers renferment un noyau de gravier et de sable grossier déposé à l'intérieur des chenaux de fonte sous-glaciaires, recouverts par les sédiments de cône sous-aquatique déposés à l'embouchure des chenaux. Les crêtes d'eskers ont été édifiées en même temps que s'effectuait le remplissage des chenaux et les dépôts latéraux ont été formés alors qu'un chenal demeurait actif pendant le retrait glaciaire. Là où l'activité a été de courte durée, des cônes sous-aquatiques isolés (kames) se sont formés. On propose ici un modèle de mise en place des sédiments qui lie la formation des moraines à des écoulements sous-glaciaires catastrophiques et simultanés d'eau de fonte et de sédiments tout le long de la marge du lobe Rainy. La plaine argileuse forme une couverture étendue de sédiments à grains fins, à stratification rythmique, qui cache le relief du substratum et enfouit souvent les eskers et les kames. Les profils sismiques et les forages dans les dépôts meubles révèlent des dépressions profondes (50-70 m) dans le substratum sous la plaine argileuse.

ZUSAMMENFASSUNG *Eine Becken-Analyse des Wabigoon-Beckens des Agassiz-Sees, ein Quaternär-Lehm-Becken in Nordwest-Ontario*. Informationen aus einer Vielfalt von Quellen sind für die Analyse des Wabigoon-Beckens vereinigt, ein Quaternär-Lehm-Becken, das sich auf dem kanadischen Schild befindet. Die Beckensedimente wurden zwischen 10.9 ka und 9.5 ka abgelagert, entlang dem Rand der Rainy-Lobe der laurentidischen Eisdecke, welche die nördliche Grenzlinie des proglazialen Agassiz-Sees bildete. Die Becken-Architektur wird von vier Hauptelementen beherrscht: Endmoräne, Eskers, Kames und eine Lehmebene. Die drei ersteren bestehen vor allem aus einer nach oben hin feiner werdenden Sequenz von Kies und Sand. Die Geometrie dieser Sediment-Einheiten und ihre Sediment-Strukturen zeigen, daß sie hauptsächlich durch Dichtigkeitsströmungen mit hoher und niedriger Dichte abgelagert wurden auf Unterwasser-Eisrand-Schwemmfächern. Die Eskers enthalten einen Kern von grobem Kies und Sand, der innerhalb subglazialer Schmelzwasserkanäle abgelagert wurde, überlagert von Unterwasser-Fächersedimenten, die an der Mündung der Kanäle abgelagert wurden. Die Esker-Rücken wurden während der Füllung der Kanäle gebildet und seitliche Ablagerungen wurden gebildet, wenn ein Kanal während des Rückzugs des Eisrands aktiv blieb. Wo Kanäle kurzlebig waren, bildeten sich isolierte Unterwasser-Fächer (Kames). Ein Ablagerungsmodell wird vorgeschlagen, das die Bildung der Moräne mit katastrophenartigem gleichzeitigem Freiwerden von subglazialem Schmelzwasser und Sedimenten entlang des ganzen Rands der Rainy-Lobe verbindet. Die Lehmebene bildet eine breite Decke von feinkörnigem, rhythmisch gelagertem Sediment, welches die Topographie des anstehenden Gesteins verdeckt und häufig Esker- und Kame-Ablagerungen überlagert. Die seismischen Profile und Bohrungen in den lockeren Ablagerungen lassen tiefe Niederungen (50-70 m) unter der Lehmebene im anstehenden Gestein erkennen.

INTRODUCTION

The goal of a basin analysis is to reach an understanding of the basin's stratigraphy, structure, palaeogeography and depositional history. A key aspect of this method is to develop a sedimentary model and to make successful predictions about those portions of the basin that are concealed or unexplored (Potter and Pettijohn, 1977). Basin analysis techniques are standard procedures for many resource evaluation studies, whether petroleum exploration, placer mining, regional groundwater potential or engineering planning (Miall, 1984; De Mulder and Hagerman, 1989), and they have a role to play in land use planning. Quaternary basins, however, have seldom been studied in this way (Eyles *et al.*, 1985), despite the fact that they are of great economic and environmental importance. The basins which form the clay belts of the Canadian Shield cover mineral-rich Precambrian greenstone terrains, and provide the medium for drift prospecting studies. They provide precious soil cover for forestry and agriculture, as well as level terrain for transportation and population centres. They also form groundwater aquifers, as well as providing sources of aggregate and sites for waste disposal (Minning *et al.*, in press), and as such, they are often the focus of conflicting environmental issues.

This paper examines the Wabigoon Basin, a typical clay-belt basin centred on lake Wabigoon, near the town of Dryden in northwestern Ontario (Fig. 1). The Wabigoon Basin was a

sub-basin within proglacial Lake Agassiz, and was deglaciated between 10.9 and 10.4 ka. Sedimentation in the basin began during the Lockhart Phase of Lake Agassiz (Teller and Thorleifson, 1983), and continued through the Moorhead and Emerson Phases. Evidence from the study area suggests that Moorhead water levels were much higher than previously believed (Warman, 1991) and follows from the recognition of widespread subaqueous deposition (Sharpe and Cowan, 1990). Sedimentation in the basin ended during the Nipigon Phase of Lake Agassiz (~ 9.5 ka), when the area became subaerially exposed.

In order to understand the three-dimensional character and structure of the basin, and unravel its complex depositional history, information from a wide variety of sources was obtained and integrated. The data base includes: 1) six reflection seismic lines north of Dryden; 2) 30 line-km of sub-bottom sonar profiles from Lake Wabigoon; 3) four boreholes drilled north of Dryden, and; 4) more than 25 measured sections in the area, mainly in the major moraines and eskers and along the lake bluffs of Lake Wabigoon (Fig. 2). These field data were supplemented by water well records (Ontario Ministry of Environment) and records from diamond drilling operations in the area (Ontario Geological Survey, 1987).

Although the Wabigoon Basin (Fig. 1) covers a relatively small portion of glaciated shield terrain (Zoltai, 1961), the methods used here may be applied to other clay-belts in shield areas of Canada.
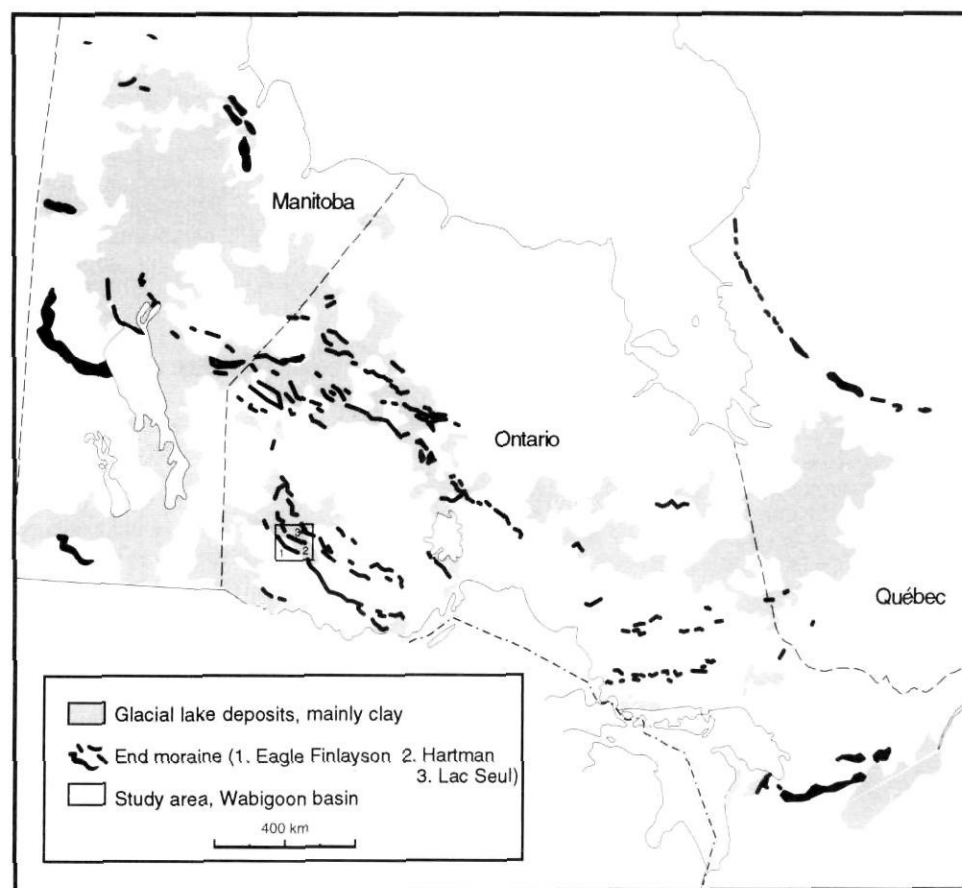

FIGURE 1. Location of clay basins and major moraines in Ontario and parts of Manitoba and Québec (after Dredge and Cowan, 1989).

Localisation des bassins argileux et des principales moraines en Ontario et dans certains secteurs du Manitoba et du Québec.

METHODS

SEISMIC PROFILES

The "optimum offset" shallow seismic reflection technique is the simplest method for land-based reflection profiling of surficial sediments and the underlying bedrock topography. Each individual trace seen on the final seismic section is obtained by recording the output of a single geophone, which is placed at a given distance (the offset) from the source (Hunter *et al.*, 1984; Pullan and Hunter, 1990). Under favourable site conditions (usually areas with fine-grained, water-saturated sediments), the "optimum offset" method provides a high definition tool for mapping bedrock topography and delineating structure within the overlying sediments (Figs. 3, 4 and 5). The clay belts in Pre-Cambrian areas of Canada have proven to be excellent sites for high-resolution seismic reflection surveys.

After an initial phase of recording test spreads across the study area, six "optimum offset" profiles were recorded in areas of suspected deep bedrock lows (Fig. 2). These profiles averaged about 1 km in length, with 3 m spacing between the traces, and a 15 m offset between the source and the receiver.

The profiles show an irregular contact defining the bedrock-sediment interface, and rugged relief on the bedrock surface, which has been infilled by 50-70 m of unconsolidated sediments (Figs. 3, 4 and 5). Reflectors within the sediments correspond very well to lithologic changes seen in drill cores recovered from these bedrock lows (Fig. 4). A detailed description of the field program, data processing techniques and results can be found in Hunter and Pullan (1989).

It should be noted that interference between shallow reflections and the "direct" arrival (in this case, the refraction from the water table), means that shallow structures cannot
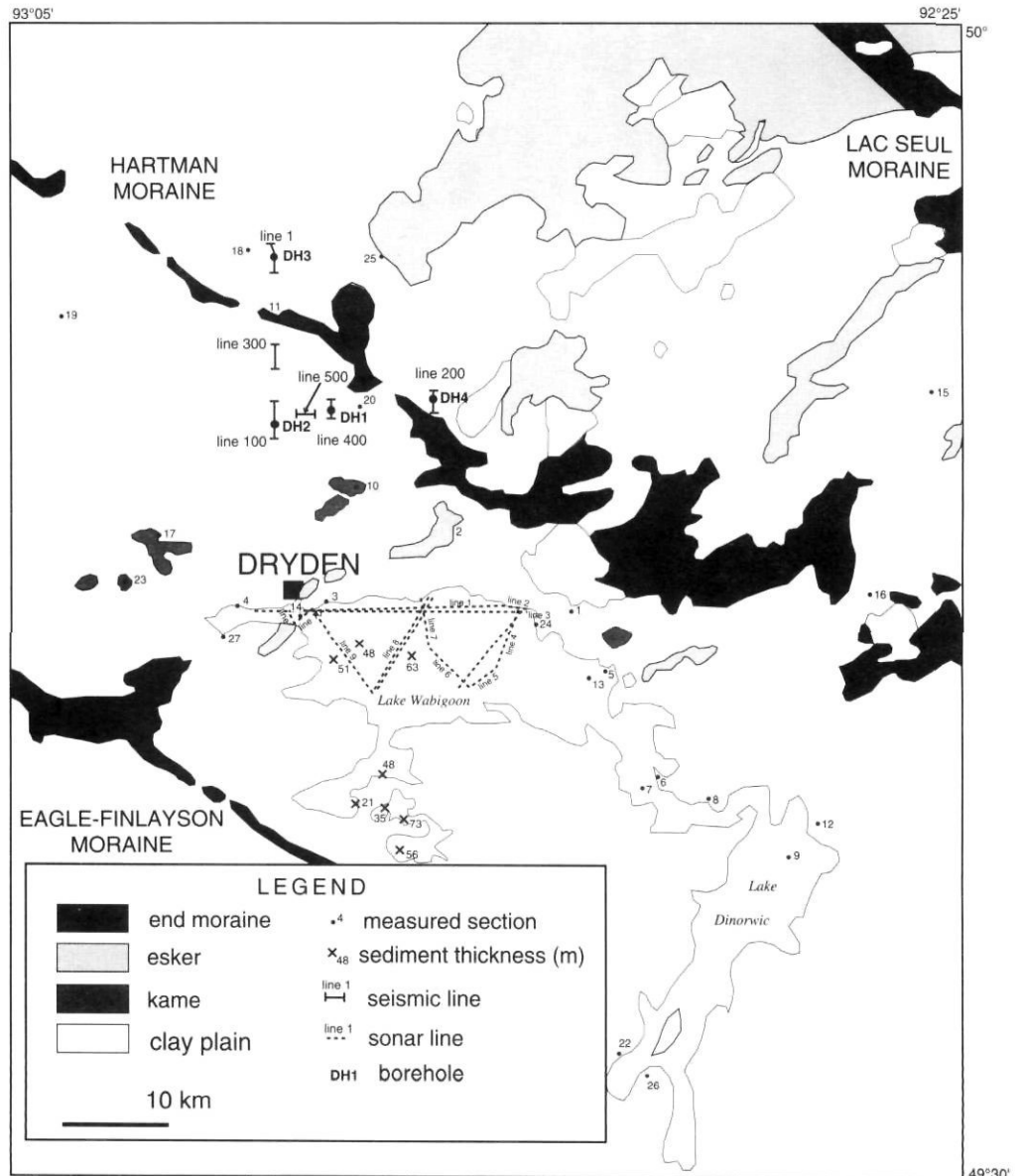
FIGURE 2. Simplified surficial geology showing major landforms and deposits in the Lake Wabigoon area (after Cowan and Sharpe, 1991) and location of seismic and sonar profiles, boreholes and measured sections.

Géologie simplifiée des formations superficielles montrant les principaux reliefs et dépôts de la région de Lake Wabigoon (selon Cowan et Sharpe, 1991) et emplacements des profils sismiques et acoustiques, des trous de sondage et des sites de mesure.
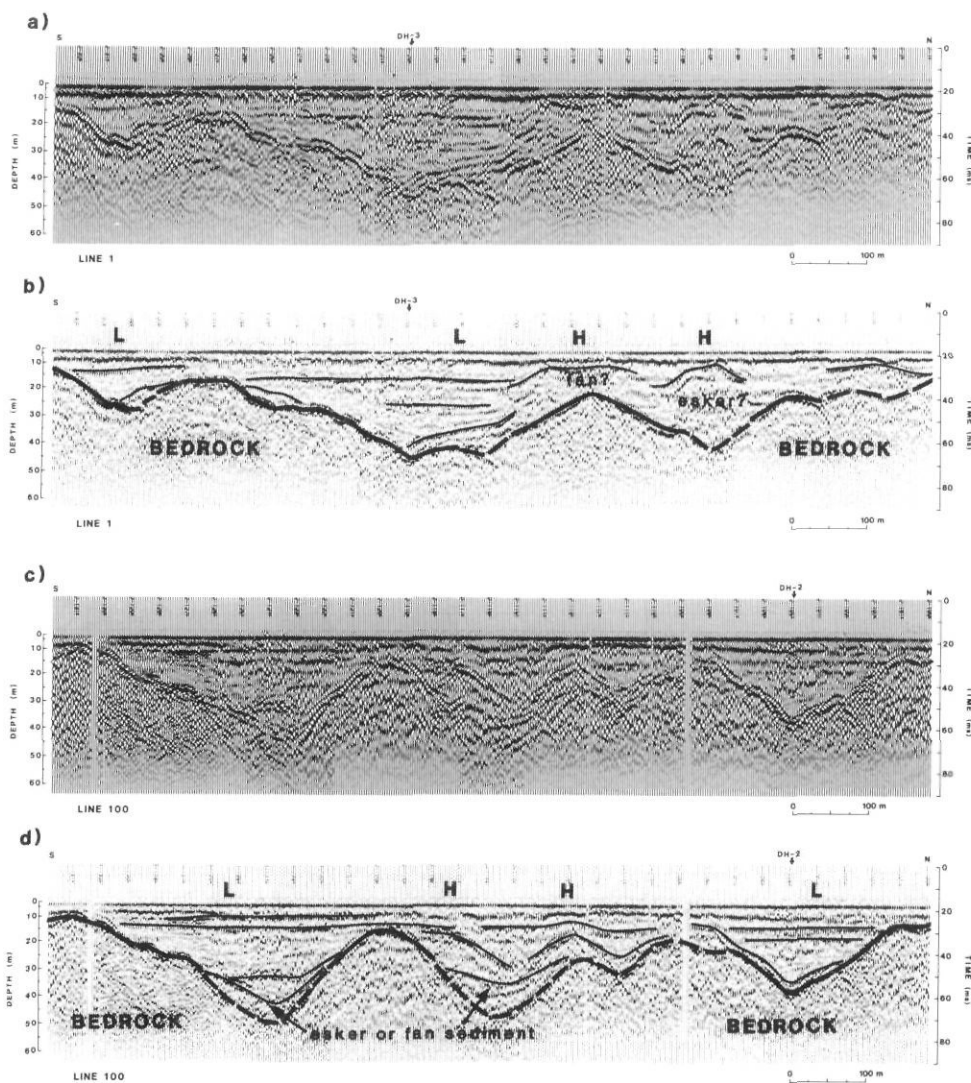
FIGURE 3. Shallow reflection seismic profiles (lines 1 and 100) from north of Dryden showing bedrock relief and sediment fills. Vertical exaggeration is ≈3.5. See Figure 2 for location of profiles. a) Line 1 profile with location of borehole 3. b) Interpretation of line 1 profile; L = horizontal layering; H = hummocky reflectors. c) Line 100 profile with location of borehole 2. d) Interpretation of line 100 profile. Lines oriented north-south.

Profils de sismique réflexion peu profonde (lignes 1 et 100) au nord de Dryden montrant le relief du substratum et les matériaux de remplissage. L'exagération des hauteurs est de ≈3,5 fois. Voir l'emplacement des profils à la figure 2. a) Profil de la ligne 1 et emplacement du trou de sondage n° 3. b) Interprétation du profil de la ligne 1; L = stratification horizontale; H = réflecteur bosselé. c) Profil de la ligne 100. d) Interprétation du profil de la ligne 100.
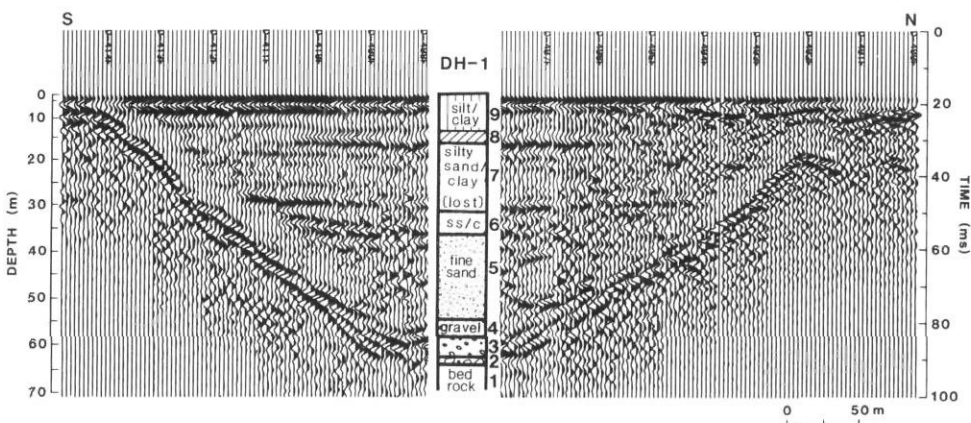

FIGURE 4. Shallow refection seismic profile oriented north-south (part of line 400), north of Dryden. Borehole DH-1 shows flat-lying clay above sand and gravel filling bedrock depression. Major lithologic boundaries show excellent agreement with seismic reflectors: 1) bedrock; 2) diamicton; 3) sand; 4) gravelly sand; 5) current-bedded fine sand; 6) sand/clay rhythmites; 7) lost core (silty sand/clay rhythmites); 8) sand/clay rhythmites; 9) silt/clay rhythmites including red clay marker beds. For location of line see Figure 2. Vertical exaggeration ≈3.

Profil de sismique réflexion peu profonde, orienté nord-sud (partie de la ligne 400), au nord de Dryden. Le sondage du trou DH-1 révèle la présence d'une couche d'argile au-dessus de la dépression remplie de sable et de gravier. Les principales limites lithologiques concordent très bien avec les réflecteurs sismiques; 1) substratum; 2) diamicton; 3) sable; 4) sable graveleux; 5) sable fin stratifié; 6) rythmites sablo-argileuses; 7) carotte perdue (rythmites sablo-limono argileuses); 8) rythmites sablo-argileuses; 9) rythmites; limono-argileuses comprenant des lits repères d'argile rouge. Voir l'emplacement des profils à la figure 2. Exagération en hauteur ≈3 fois.

FIGURE 5. a) Seismic profile oriented east-west (line 500), north of Dryden. b) Interpretation displays undulating, non-continuous reflections, possibly channel structures within a sediment-filled bedrock depression. Vertical exaggeration ≈3.5.

a) Profil sismique orienté est-ouest (ligne 500), au nord de Dryden. b) L'interprétation montre des réflecteurs ondulés interrompus, qui pourraient représenter des structures de chenaux à l'intérieur d'une dépression du substratum comblée de sédiments. Exagération en hauteur ≈ 3,5 fois.
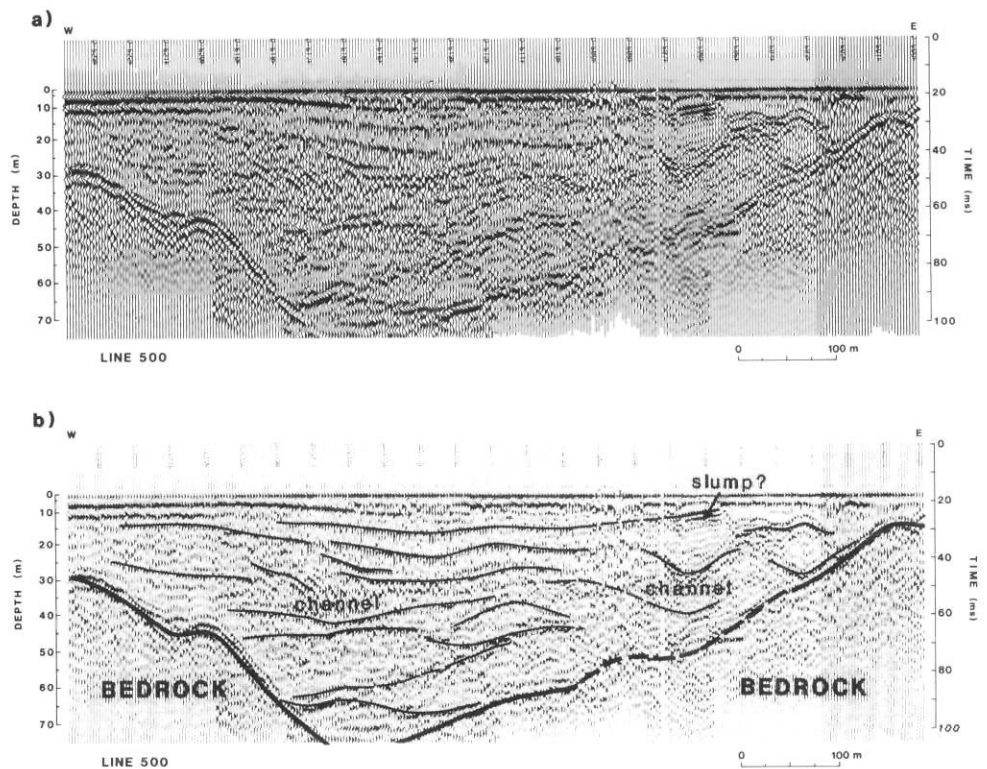
be resolved by this technique. In the study area, this unresolvable zone varied between 0 and 10 m below the ground surface. In addition, the contrast between the large amplitude of the bedrock reflection and the small amplitudes of the sediment reflections, combined with the effects of the digital processing (automatic gain control), occasionally results in small "blank zones" immediately above the bedrock surface (Fig. 4).

SONAR PROFILES

Eleven sonar profiles covering 30 line-km were recorded across the northern end of Wabigoon Lake (Fig. 2), providing a partial picture of the bedrock topography, and its cover of proglacial and post-glacial sediments (Fig. 6). Penetration of the acoustic signal is limited to about 20 m below the lake bottom, due to attenuation of the signal by underlying sandy strata. Diamond drilling records indicate infilled bedrock topography of 30-50 m exists beneath the lake floor, so the sonar records show only the upper portion of these sediments. Nevertheless, sediment layering is well defined on these records (Fig. 6), and although no drill cores are available, the sediments are well exposed in nearby lake bluffs.

ROTASONIC DRILL CORES

Four rotasonic boreholes (three to bedrock) were drilled in bedrock lows identified by the reflection seismic profiles (Fig. 2), providing a direct look at these sediments (Figs. 4 and 7), as well as a tool for calibrating and interpreting the seismic profiles. Depths of these boreholes ranged from 35-63 m, and correlate well with the depths to bedrock estimated from the seismic profiles.
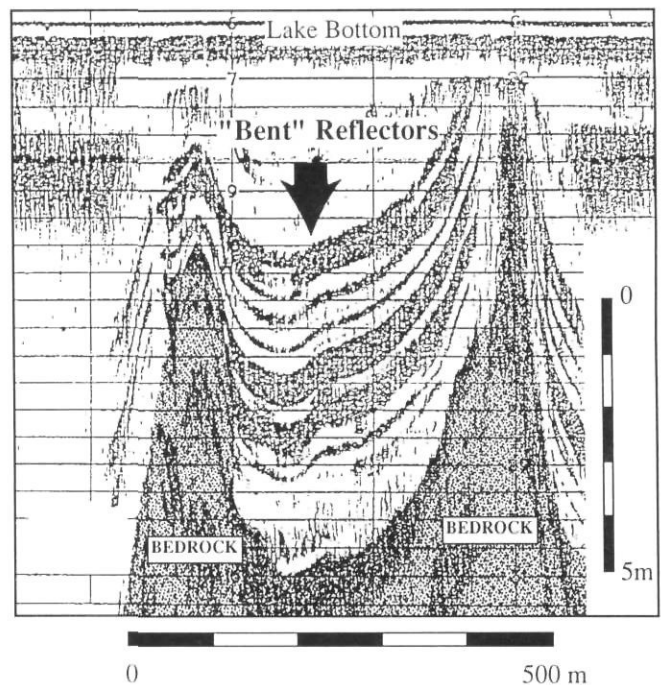
FIGURE 6. Acoustic profile from part of line 8, Lake Wabigoon. Note draping of sediment over bedrock highs and thickening of sediment in depressions. Note break in sediment slope (arrow) which may indicate slumping. Vertical exaggeration ≈50.

Profil acoustique d'une partie de la ligne 8, dans le Lake Wabigoon. Noter la couverture sédimentaire au-dessus des parties élevées du substratum et l'épaississement de l'accumulation dans les dépressions. Noter le fléchissement dans la pente (flèche) qui pourrait refléter un glissement. Exagération en hauteur ≈50 fois.

BASIN ARCHITECTURE

The basin architecture is defined by the nature, distribution and three-dimensional geometry of the sediments. The architecture determines the regional and local hydrogeology, the location of aggregate resources, and the dispersion of indica-

tor minerals from buried ore bodies. Data from all available sources, including sediment descriptions from outcrop and boreholes, maps of large-scale surficial geology (Cowan and Sharpe, 1991), and geophysical records, are employed in determining the basin architecture. This process is carried out in a step-wise fashion, beginning with the smallest units, the
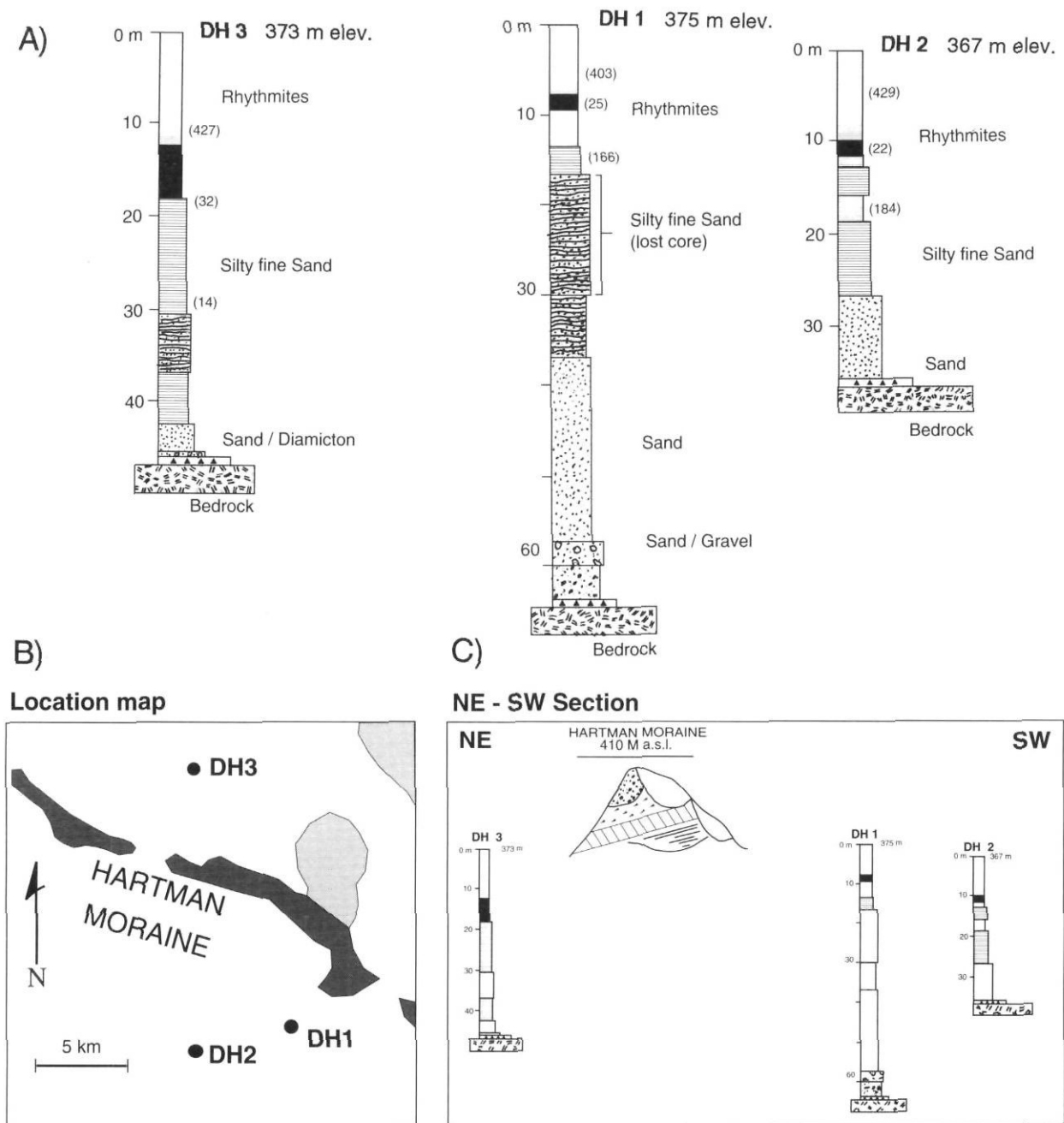

FIGURE 7. A) Borehole logs (DH 3, DH 1, DH 2) showing details of sediments in the Wabigoon basin relative to the Hartman Moraine. Numbers (in brackets) indicate couplets (varves) above and below red marker strata (solid black unit). B) Plan view showing boreholes with respect to moraine; shading is esker complex. C) Cross section shows boreholes with respect to Hartman Moraine; generalized structure shown within moraine including drape of rhythmites on south flank.

A) Diagrammes des sondages (DH 3, DH 1, DH 2) révélant la nature détaillée des sédiments dans le bassin de Wabigoon par rapport à la Moraine de Hartman. Les nombres (entre parenthèses) identifient les couplets (varves) au-dessus et en-dessous de la couche repère d'argile rouge (en noir). B) Plan montrant l'emplacement des trous de forage par rapport à celui de la Moraine de Hartman (la partie tramée identifie l'ensemble d'eskers). C) Diagrammes des sondages par rapport à la Moraine de Hartman: structure interne de la moraine, y compris la couverture de rythmites sur le flan sud.

facies, proceeding through the local- or outcrop-scale geometry, and ending with the large- or basin-scale distribution and geometry. This section will briefly outline the sedimentary facies (the building blocks), and will then discuss how these facies make up the four major "architectural elements" in the Wabigoon Basin; moraines, eskers, isolated fans (kames), and the clay plains (Fig. 2).

FACIES

Sediments in the Wabigoon Basin have been grouped into eight facies by Warman (1991) but are simplified into four facies for this report. The major facies are: 1) rhythmites, 2) sand, 3) gravel, and 4) diamicton. These facies can be mapped in outcrop, boreholes (Fig. 7) and possibly on geophysical profiles.

Rhythmites

Rhythmically-stratified sediments are common in the Wabigoon Basin, and three couplet types are identified: 1) silt-clay, 2) sand-clay, and 3) sand-silt. Silt-clay rhythmites (Fig. 8) consist of a light-coloured, laminated to bioturbated silt member, 0.1-1.0 cm thick, with sharp upper and lower contacts. This is paired with a darker, massive clay member, usually somewhat thinner than the silt member. Sand-clay rhythmites (Fig. 8) consist of a medium to very-fine sand member, 1-10 cm thick, displaying sedimentary structures such as ripples, climbing ripples, sub-horizontal laminations, and normal and reverse grading. The clay member of the couplet is 0.1-1.0 cm thick, and often drapes the rippled surface of the underlying sand member. The contacts of both members are sharp. Sand-silt rhythmites are similar to sand-clay

rhythmites, except that the clay member is replaced by a laminated to massive silt member, 0.5-3.0 cm in thickness.

Rhythmite deposits normally record a gradational fining and thinning upward sequence, beginning with sand-silt rhythmites, and grading upward through sand-clay rhythmites into silt-clay rhythmites.

The silt-clay and sand-clay rhythmites show a very consistent geometry in all of the outcrops examined, draping and mantling the underlying lithologies (e.g. Fig. 8a), and mimicking any pre-existing topography. Syndepositional slumping related to topographic highs can also be recognized in some exposures. Sand-silt rhythmites are more commonly found in association with current bedded sands, conformably infilling broad, shallow channels (Fig. 9).

The thickness of the all of the rhythmites in outcrop ranges from 1-5 m but the rhythmites are up to 10-20 m thick in basin fills (Fig. 7).

Within the rhythmite deposits occurs an abnormal series of rhythmites which show thick, red clay members and relatively thinner silt or sand members. These abnormal red-clay rhythmites form an important marker horizon (Fig. 7) in the eastern basins of Lake Agassiz, which has helped to refine the chronology in the Lake Agassiz basin (Warman, 1991).

These rhythmically-stratified deposits may explain much of the layering seen on the sonar profiles, although individual beds are not resolved (Fig. 6).

Sand Facies

This facies encompasses both sorted sands and pebbly sands. The sorted sands range from fine to coarse grained,
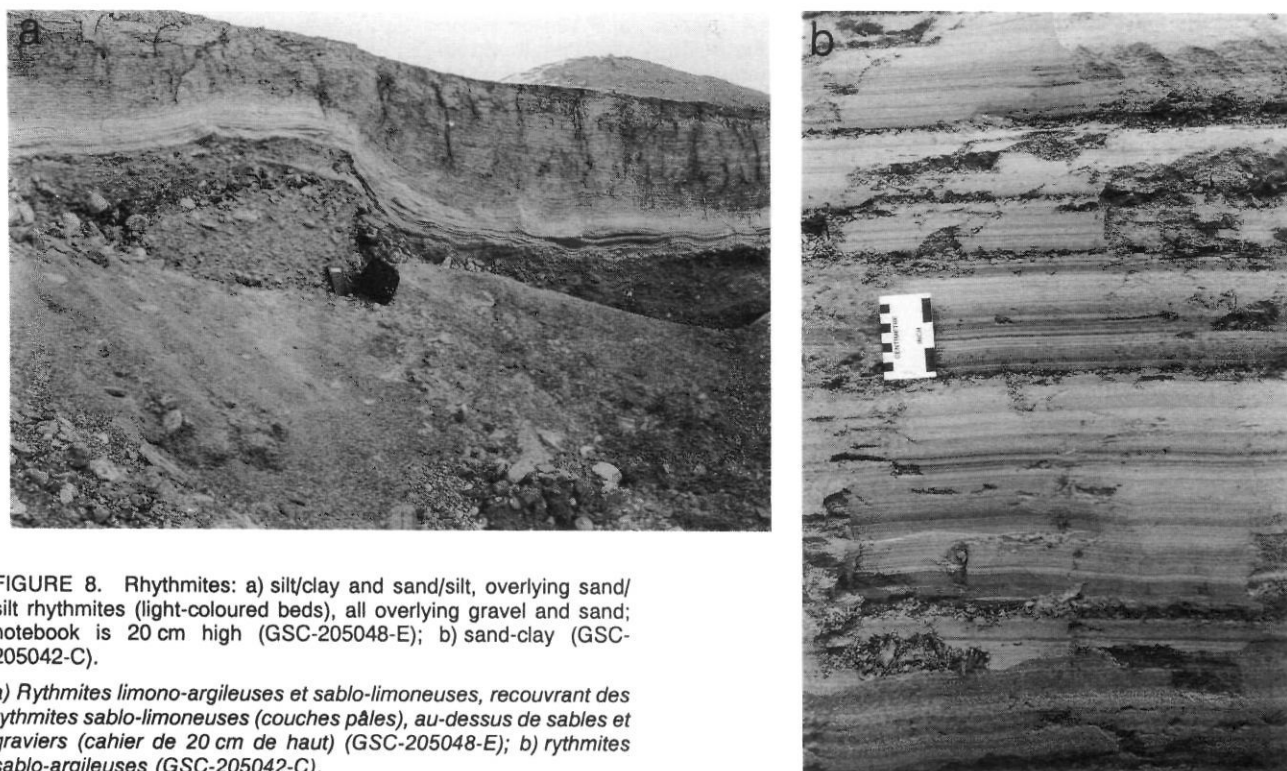
FIGURE 8. Rhythmites: a) silt/clay and sand/silt, overlying sand/silt rhythmites (light-coloured beds), all overlying gravel and sand; notebook is 20 cm high (GSC-205048-E); b) sand-clay (GSC-205042-C).

a) Rythmites limono-argileuses et sablo-limoneuses, recouvrant des rythmites sablo-limoneuses (couches pâles), au-dessus de sables et graviers (cahier de 20 cm de haut) (GSC-205048-E); b) rythmites sablo-argileuses (GSC-205042-C).
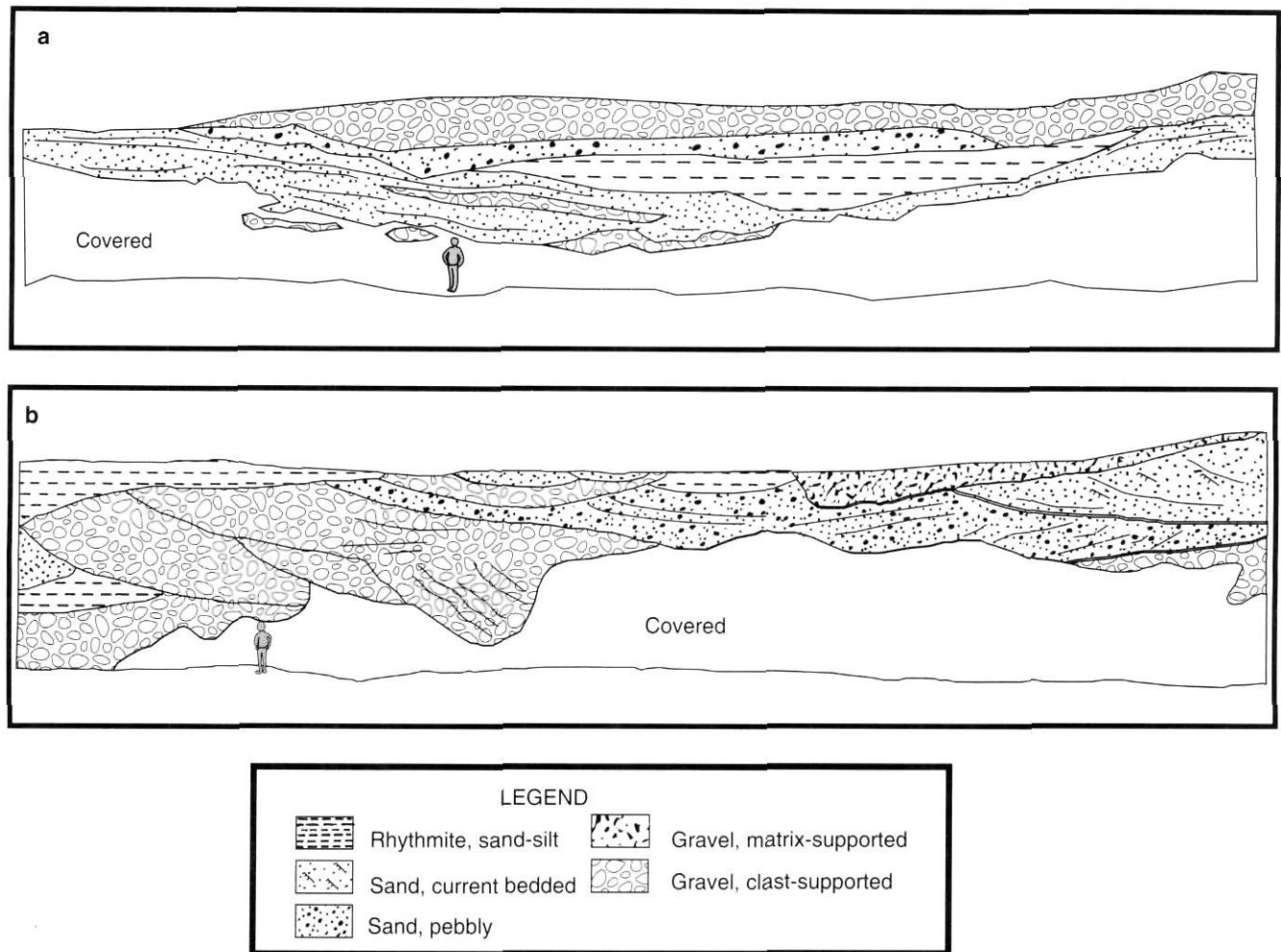
FIGURE 9. a) Sandy rhythmites infilling a broad, shallow channel cut into Eagle-Finlayson Moraine (Warman, 1991, Fig. 2-26). b) Nested channels infilled with clast-supported gravel and current bedded sand on the crest of the Eagle Finlayson Moraine (Warman, 1991, Fig. 2-34).

a) Rythmites sablonneuses comblant un large chenal peu profond taillé dans la Moraine d'Eagle-Finlayson (Warman, 1991, fig. 2-26). b) Chenaux emboîtés comblés de gravier à support détritique et de sable stratifié sur le sommet de la Moraine d'Eagle-Finlayson (Warman, 1991, fig. 2-34).

and show a variety of sedimentary structures, including sub-horizontal bedding, centimetre to metre scale, two- and three-dimensional crossbedding (including abundant climbing ripples), and both normal and reverse grading.

Pebbly sands are medium to coarse grained, and contain less than 10 % pebbles and rare cobbles. Clasts are normally not in contact. Sub-horizontal bedding and normal grading dominate, although centimetre scale, two-dimensional cross-bedding is observed.

Gravel Facies

Clast-supported gravels are composed mainly (>50 %) of clasts ranging in size from granules to boulders, with most exposures showing clasts in the pebble to cobble range. The distinguishing aspect of this facies is that the majority of clasts are in contact, forming a supporting framework. Clasts are generally moderately sorted, subangular to well rounded and usually display a relatively high sphericity. Maximum clast size observed in the study area was about 50-60 cm. When

a matrix is present it is usually poorly sorted and ranges from fine to very coarse sand and granules. Gravels are usually massive to horizontally bedded, although they form large (2-5 m high) crossbeds in some areas (*e.g.* Fig. 5a Sharpe and Cowan, 1990).

Matrix-supported gravel consists of subangular to sub-rounded clasts ranging in size from pebbles to 90.0 cm boulders. This facies is distinguished from the clast-supported gravels by the lack of contact between the majority of clasts. Most clasts are completely supported in a matrix of poorly-sorted medium sand to small (<2.0 cm) pebbles. These gravels are generally massive, although rare indistinct stratification, normal grading of the clasts, and/or poorly-developed imbrication may be seen.

Diamicton

Diamicton is an unsorted mix of clay, silt, sand and clasts. Clasts are up to 60 cm in size, and supported by the matrix. Matrix is massive or contains disturbed bedding. Occasional

interbeds of bedded sand occur. The lower contacts of dia-micton units may be conformable or erosional.

ARCHITECTURAL ELEMENTS

The structure of the basin can be examined in terms of its architectural elements. These elements consist of landforms which have both a distinct external morphology, and internal composition and structure. In the Dryden area, four elements are identified: i) moraines; ii) eskers; iii) kames, and iv) the clay plain (Fig. 2).

Moraines

There are three major moraines in the Dryden area, the Eagle Finlayson, the Hartman, the Lac Seul, and a forth, the Sioux Lookout occurs to the northeast (Fig. 1). The first two were examined in detail, as they contain the best exposures, although visits to the latter two indicated that their internal composition was similar.

The moraines are long, narrow, arcuate ridges, several hundred kilometres in length, 10 to 50 metres high, and less than a kilometre in width (Fig. 2). In cross-section, they show a relatively steep ice-proximal side, and a gentler ice distal side (Sharpe and Cowan, 1990). Their tops are narrow and gently rounded, although in a few areas they are broader and flat-topped. These moraines appear to define temporary, for-mer ice-marginal positions of the Rainy lobe of the Laurentide Ice Sheet.

Sediments in the moraines comprise a fairly simple, fining-upward sequence dominated by gravel and pebbly and well-sorted sands, and capped by finer rhythmite facies (Fig. 10). Clast-supported gravel was encountered at the bottom of drillholes in front of the Hartman moraine (Fig. 7), and is prob-ably found at the base of the moraine sequences. In some areas the upper surface of the moraines have been reworked by nearshore processes during the later, falling stages of Lake Agassiz, leaving a thin veneer of beach sand or gravel lying on a distinct unconformity (Minning et al. in press). Nowhere is there evidence of the moraines having been over-ridden by glacier ice.

The pebbly and well-sorted sands commonly occur as infills within broad, shallow channels oriented perpendicular to the moraine crests (Fig. 9). Bedding surfaces are normally parallel to the channel margins, and the channels may be up to 10 m deep and 50 m wide. Within these large channels infills there are often smaller-scale erosional surfaces (Fig. 9b). These channels are rarely solitary features, and are often part of a series of stacked, nested channels, exceeding 20 m in thickness. Channel-like structures of similar dimen-sions can be seen on east-west seismic lines located in front of the Hartman moraine (Fig. 5). These probably represent sandy deposits analogous to those in the moraines.

Pebbly sands are characterised by the dispersion of clasts within a medium to coarse sand matrix, abundant sub-parallel stratification, and the presence of normal and reverse grading and occasional traction current structures. The features are thought to be diagnostic of rapid deposition from density-modified grain flows or traction carpets, produced by the

deceleration of high-density underflow currents (S_2 division of Lowe, 1982; Hein, 1982; Farquharson et al., 1984).

Large- and small-scale, two-dimensional ripples and sub-horizontal bedding are most common in the well-sorted sands throughout the moraines. Both large- and small-scale ripples show evidence of climbing and lee-side preservation. Normal and reverse-graded beds are not uncommon, with normal grading predominating. Sedimentary structures in the well-sorted sands are dominated by sub-parallel bedding, and small- and large-scale two-dimensional ripples. Evidence of stoss-side preservation and climbing in both large and small ripples suggests that both traction and suspension processes were occurring simultaneously (Jopling and Walker, 1968). These types of sedimentary structures appear to be best explained by deposition from density underflow (turbidity) currents (Jopling and Walker, 1968; Lowe, 1982; Walker, 1984). The lack of massive beds, or dish structures is
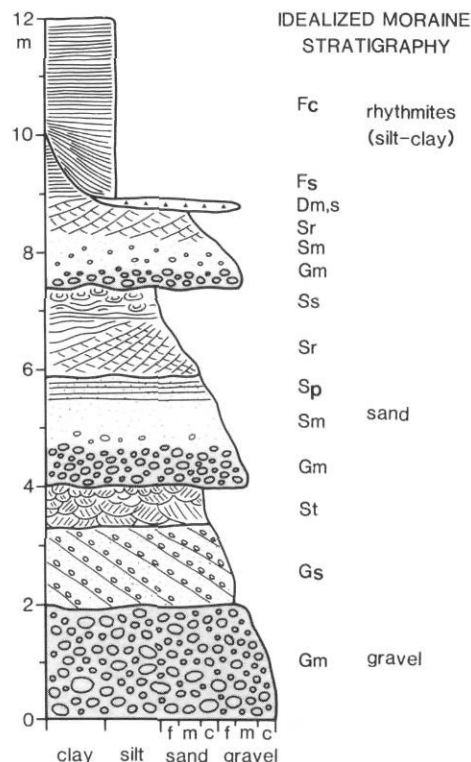

FIGURE 10. Overall schematic fining-upwards structure repre-sentative of the prominent moraines (gravelly) of the Wabigoon basin (mainly sand) defined by measured surface sections. Gm=massive gravel, matrix-supported; Gs=large scale cross stratified gravel; St=trough cross bedded sand; Sm=massive sand; Sr=ripple cross laminated sand; Ss=sand with soft sediment deformation structures; Dm=diamicton, massive or weakly stratified; Fs=sand/clay rhythmi-tes; Fc=clay/silt rhythmites.

Structure schématique d'ensemble s'affinant vers le haut, représen-tative des moraines les plus importantes (gravier) du bassin de Wabigoon (sable), déterminée à partir des coupes de surface. Gm=gravier massif, à support matriciel; Gs=gravier à stratification entrecroisée à grande échelle: St=sable à stratification entrecroisée à ondulations prononcées; Sm=sable massif; Sr=sable à stratifica-tion entrecroisée à petite échelle; Ss= sable renfermant des struc-tures de déformation tendres; Dm=diamicton, massif ou peu stratifié; Fs=rythmites sablo-argileuses; Fc=rythmites argilo-silteuses.

evidence for low-density underflow currents, while the presence of inversely graded beds, and the association of this facies with pebbly sands suggests that high-density underflow currents also played a role in their deposition. The quasi-continuous nature of underflow currents in a glacial setting may have precluded the deposition of massive beds, which are regarded as the waning stage deposits of high-density underflow currents (Lowe, 1982). Lowe (1982) has suggested that there is a continuum from high- to low-density currents, in that the deposition of the high-density suspended load leaves behind a residual low-density flow carrying material finer than about medium sand. Given the available evidence, it seems likely that both high- and low-density underflow currents were active in the depositional environment.

Matrix-supported diamictons within the moraine sequences show evidence of incomplete mixing, and disturbed remnant sedimentary structures. These are thought to be the products of downslope resedimentation of unstable, rapidly-deposited silt, sand and gravel.

The underflows responsible for the deposition of the sands were generated by the rapid deceleration of powerful, sediment-laden meltwater currents at the mouths of subglacial meltwater conduits. Because these conduits emerged at the bottom of a proglacial lake, flow expansion and deceleration were rapid, and the deposition of coarse material was restricted to a narrow zone of subaqueous outwash fans, located immediately adjacent to the ice margin (Rust, 1977; Shaw, 1985; Sharpe, 1988).

In a few areas along the Hartman moraine, these fans built above the lake level, and became ice-contact deltas (Cowan, 1987), creating a broader, flat-topped moraine profile.

Moraine sediments merge downflow into finer-grained sediments of the clay plain, and most moraines have eskers connected to their upflow sites (Fig. 2).

Eskers

Eskers form ridges of sand and gravel parallel to ice flow, which often terminate downflow in the ice-proximal side of one of the major moraines (Fig. 2). They appear to represent the former location of subglacial conduits, through which sediment-laden meltwater was delivered to the ice margin.

Eskers are composed of a core of coarse sediment deposited within the subglacial conduit. This core is often overlain by a fining upwards sequence representing subaqueous fan deposition at the conduit mouth (Banerjee and McDonald, 1975; Rust and Romanelli, 1975; Saunderson, 1975; Hebrand and Åmark, 1989). The coarse core may also be flanked by lateral sands deposited in a subglacial conduit (Gorrell and Shaw, 1991).

Conduit sediments are dominated by large, massive to indistinctly stratified gravel bodies interpreted as large-scale longitudinal or transverse bars, analogous to sandy bedforms produced in pipe-flow experiments (McDonald and Vincent, 1972). These types of bars are described by Harms et al. (1982) as being composed of massive to diffusely bedded cores, possibly with shallow to steeply-dipping foresets on the downstream ends. Well-developed, angle-of-repose foresets

are indicative of transverse bars, while low-angle foresets are more common on longitudinal or diagonal bars (p. 617). Common alternations on the foresets, of openwork and closed-work gravels, and sands with both up-foreset and down-foreset palaeoflow indicators, represent fluctuating flows (Banerjee and McDonald, 1975; Deimer, 1988), or longitudinal sorting and considerable strength of the return flow in the separation zone downflow of bedforms (Shaw and Gorrell, 1991).

Planar to crossbedded, well-sorted sand sheets found between or on top of thick-bedded gravels are interpreted as either upper or lower flow regime flat beds, and lower flow regime large scale 2-D ripples (Harms et al., 1982). These sands moved along the tops of the large gravel bars during periods of relatively lower flow velocities (Shaw, 1985; Boothroyd and Ashley, 1975). Trough crossbedded sands, deposited by the migration of 3-D large ripples (dunes and megaripples), infilled channels between the large gravel bars (Boothroyd and Ashley, 1975).

Matrix-supported gravel is found within an esker, overlying and truncating the large cross-beds of an extensive gravel bar (Sharpe and Cowan, 1990, Fig. 5b). Matrix-supported gravel implies contemporaneous deposition of a wide range of grain sizes and Saunderson (1977) argued that these characteristics could be produced by deposition from "...a sliding bed inside a subglacial tunnel during full-pipe flow" (p. 633). Since conduits in the Dryden area discharged below lake level, they must have been continuously filled with meltwater.

In another esker, matrix-supported (polymodal) gravel on large cross-beds indicates the migration of subglacial bedforms formed by mixing bedload and suspension load deposits within the zone of flow separation (Shaw and Gorrell, 1991).

Evidence of the post-depositional collapse of esker-core sediments is lacking, suggesting that most conduits were sub-, rather than en-glacial.

Isolated Fans (Kames)

Kames form isolated hills of sand and gravel, and are most commonly found protruding through the clay plain, between the major moraines, and away from the esker landforms (Fig. 2). These are thought to represent isolated subaqueous fans, formed at the mouths of subglacial meltwater conduits which were abandoned following episodic flow or before significant ice-marginal retreat had occurred.

Sedimentary sequences within these landforms are similar to those seen within the eskers and moraines. Typically, they consist of a single, fining upward sequence from clast-supported gravels, through pebbly and well-sorted sand, capped by fine-grained rhythmites. Kame structures often display remarkably gradational and continuous transitions between these facies (Fig. 8a).

The Clay Plain

In contrast to the restricted distribution of the coarser sediments, the finer, rhythmically bedded facies are quite widespread throughout the study area (Fig. 2), forming broad,

gently-rolling clay plains. Geophysical profiles (seismic and sonar) show that the bedrock topography is much more extreme than the present surface topography, due to infilling of deep (up to at least 65 m), east-west trending bedrock lows (Figs. 3, 4 and 5). Sonic cores drilled in these lows show that the lowermost units of the sedimentary infills consist mainly of medium to fine sand and minor gravel (Figs. 4 and 7). Seismic profiles show horizontal reflectors which terminate against bedrock highs (Fig. 4), suggesting these bedrock lows, oriented perpendicular to regional meltwater flow, resulted in the trapping of underflow sediments derived from ice-marginal subaqueous fans.

The sonic cores also show that these sands form part of a continuous fining upwards sequence which grades to rhythmically laminated sediments (Figs. 4 and 7). These rhythmites drape most bedrock highs, and often completely bury esker and kame deposits. Arched and hummocky reflectors seen on some seismic lines (Fig. 5) may represent such buried eskers or kames, but direct proof of this in the form of sonic core is lacking.

While the sonic cores and seismic lines were drilled relatively close to the Hartman moraine, outcrops and sonar profiles located farther downflow from this moraine demonstrate a *lateral fining trend. Here, the outcrops show thick* sequences of silt-clay rhythmites lying directly on bedrock, and the sonar profiles show a draping, rather then a planar geometry (Fig. 6), suggesting a greater influence of vertical settling processes. However, the deposits do still thicken appreciably in the bedrock lows, probably due to a combination of underflows depositing the silt portion of the rhythmites, and downslope remobilization of sediments from the bedrock highs (Fig. 6). "Bent" reflectors seen on these sonar profiles may represent such slumping (Fig. 6).

Vertical settling from over- and interflows deposited the fine component of the rhythmite couplets (usually a clay layer) during periods when underflows were inactive, due to the cessation of, or decline in the production of glacial meltwater (Church and Gilbert, 1975; Gustavson, 1975). Settling was probably aided by freezing of the lake surface (Gustavson, 1975), and by fecal pelletization of the fine clays by pelagic faunas (Warman, 1991).

Quasi-continuous underflows generated on ice-marginal subaqueous fans during periods of high meltwater production were responsible for deposition of the coarse portion of the rhythmites. Ripple marks in the coarser (sandy) portions of sand-silt rhythmites demonstrate the direct action of traction currents. Direct evidence of traction currents is lacking in the finer-grained rhythmites, probably due to pervasive bioturbation. However, the gradual vertical transition from the coarser to finer rhythmites demonstrates their lateral equivalency. These rhythmites probably represent the most distal equivalents of the sandy underflow deposits seen in the moraines, kames and eskers.

The interpretation of these rhythmites as annual deposits or varves, first suggested by Rittenhouse (1934), is confirmed by the pattern of bioturbation seen in the silt-clay rhythmites (Warman, 1991). The silt portions of the couplets are nor-

mally completely bioturbated, while the clay portions frequently show extremely fine, undisturbed laminations. Thus, the sedimentation cycle was in phase with the biological rhythm of some benthic organism(s), which was feeding in the bottom sediments while the underflows were active, but was absent during periods of vertical settling. The bioturbation seen in this facies is very similar to traces produced by chironomid larvae (Duck and McManus, 1984; Morrison, 1987; Duck and McManus, 1987), which undergo a seasonal metamorphosis from benthic infeeders to free-flying adults.

This annual layering provides an accurate, direct dating tool that has been used in interpreting the basin history (Warman, 1991; Minning et al., in press), considered to have lasted about 1000 years in the Wabigoon area.

DEPOSITIONAL MODEL

Meltwater would have been carried toward the ice margin in a series of subglacial meltwater tunnels. Sediments deposited within these tunnels formed the "core" deposits for the esker landforms. Where these tunnels entered Lake Agassiz, flow expansion occurred, resulting in deposition of a subaqueous outwash fan or a delta, depending on the elevation of the tunnel mouth relative to the lake surface (Sharpe and Warman, 1990). Most of the coarse-grained deposits in the area represent subaqueous fans. Isolated subaqueous fans (kames) formed when a meltwater tunnel was abandoned before significant ice marginal retreat had occurred (Fig. 11).

When a meltwater tunnel remained in use as the ice margin retreated, the zone of coarse sediment deposition retreated with it, and a series of back-lapping subaqueous fans was deposited over the esker "core" sediments. This resulted in the formation of an esker, consisting of an iceflow-parallel ridge (Fig. 11). These fans, likely not laterally confined by the ice, still formed significant topographic highs, since rapid flow expansion and loss of competence would have resulted in most of the coarse sediment load being deposited in the immediate vicinity of the tunnel mouth (Rust and Romanelli, 1975; Banerjee and McDonald, 1975; Deimer, 1988) or in a subglacial chamber (Gorrell and Shaw, 1991).

Quasi-continuous density underflows, carrying finer sediments, flowed off of these fans and across the lake bottom. These underflows were channelled into bedrock lows which became choked with thick infills of sandy sediment. Gradual deceleration of these underflows left a fining trend from sand to silt away from the ice margin. When the seasonal decline in meltwater production caused cessation of underflow activity, mainly in the more ice-distal regions of the basin, clays settled through the water column (particularly in winter months), draping the underflow deposits. This cycle of sedimentation operated annually and produced an excellent varve record (Fig. 7) of about 1,000 years in the Dryden area.

The formation of the end moraines in the Dryden area also seems to have occurred through subaqueous fan sedimentation (Sharpe and Cowan, 1990). But why are the moraines so continuous, over lengths of up to several hundred kilometres? The moraines could represent a series of coalescent fans
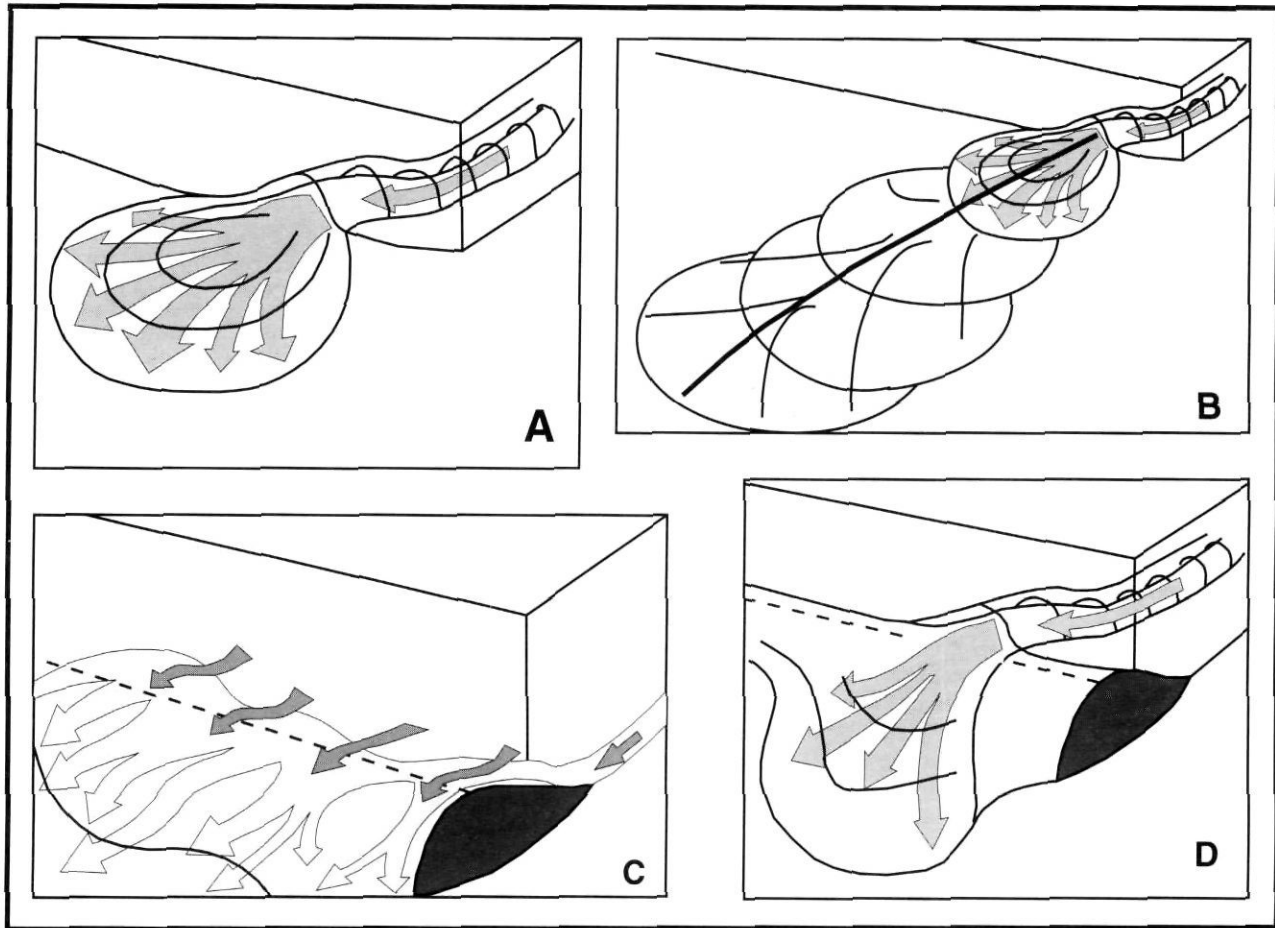
FIGURE 11. Model of landform development in Dryden area: a) normal meltwater drainage produces individual subaqueous fans or kames as meltwater is confined to subglacial conduits; b) a series of overlapping fans produces eskers, if the position of meltwater tunnel remains fairly stable with ice melt; c) meltwater floods spread beyond subglacial channels to produce a broad moraine from sheet-flow conditions; d) waning flow is re-confined to channels, and lobes develop along the moraines.

Modélisation de l'évolution du relief dans la région de Dryden: a) l'écoulement normal de l'eau de fonte, canalisé dans des tunnels sous-glaciaires, crée des cônes ou des kames sous-aquatiques; b) le chevauchement d'une série de cônes forme des eskers, à la condition que la position du tunnel de fonte demeure assez stable; c) le débordement de l'eau de fonte hors des chenaux sous-glaciaires en écoulement laminaire entraîne la formation de moraines étendues; d) l'écoulement, une fois ralenti, réintègre les chenaux et des lobes se forment à partir des moraines.

formed at the end of a network of esker tunnels during a halt in ice-marginal retreat. This would be analogous to esker lobe development (Fig. 11), except that the fans would switch laterally along the ice margin. The process would be slow however, especially if the halt in retreat were caused by climatic cooling (Saarnisto, 1984), which must be accompanied by a decrease in meltwater production. There is little evidence of glaciotectonic disturbance of the morainal sediments, which suggests a remarkably stable ice margin or no oscillation prior to rapid sedimentation. Additionally, the sedimentary sequences in, and in front of the moraines show no evidence of the complex fining and coarsening sequences which would be expected from laterally coalescing fans or from fluctuating ice margins.

Alternatively, the moraines could represent unchannelled flow beneath the ice, where sheets of meltwater swept sediment to its margins (Sharpe and Cowan, 1990) from upflow subglacial reservoirs (*e.g.* Kor *et al.*, 1991; Shoemaker,

1992a, b). Large areas of bare bedrock upflow from the moraines, the lack of till in the area, and the presence of crescentic erosion forms carved by turbulent meltwater flows appear to support the hypothesis of large subglacial floods in the study area (Sharpe and Cowan, 1990).

Such a flood would have experienced rapid flow expansion and deceleration at the ice margin, resulting in rapid deposition of the subglacial outwash (Fig. 11), which dominated fill of the Wabigoon Basin.

Subglacial flooding of this magnitude would probably lead to greatly reduced shear stresses at the base of the Rainy lobe, possibly resulting in surging of the ice margin. In fact, Zoltai (1965) noted that overridden rhythmites north of the Lac Seul moraine suggest a readvance (surge?) of approximately 30 km to the Lac Seul moraine position, prior to the actual formation of this moraine. However, neither the Lac Seul moraine, nor any other of the Dryden area moraines

show any evidence of having been overridden by readvancing ice (Cowan, 1987; Sharpe and Cowan, 1990). This would seem to indicate that, while moraine formation in the Dryden area may have been preceded by surging, the surging ended prior to the actual increase in meltwater discharge that is thought to have formed the moraines (Sharpe and Cowan, 1990).

The release of floodwaters following surge is in agreement with the observations of Kamb *et al.* (1985), who described the termination of the 1982-1983 surge of the Variegated Glacier as being "...accompanied by a particularly spectacular flood" (p. 475).

The fact that there are four, evenly spaced moraines in this area of northwestern Ontario, suggests that this cycle of subglacial meltwater buildup, ice marginal surging and catastrophic meltwater release, was repeated four times on a relatively regular basis. Each moraine-forming event was probably triggered by the buildup of subglacial meltwater beyond some critical point, possibly reflecting reservoir filling and breaching (*e.g.* Shoemaker, 1992a, b).

PRACTICAL APPLICATIONS

The picture of the Wabigoon Basin that emerges from this study is one of large, linear bodies of sand and gravel (moraines and eskers), oriented both parallel and transverse to the former ice margin. Also present are similar but isolated bodies of coarse sediment (kames). All of these structures are surrounded by, and sometimes buried in, the more extensive, finer-grained sediments of the clay plain. Lodgement till, a common sediment in other glaciated shield terrains, is virtually absent in the study area.

The arrangement of sediments has important implications for a number of economic and environmental concerns, including aggregate extraction, mineral exploration, waste disposal, and groundwater utilization and protection. This section will briefly touch on some of these implications.

AGGREGATE EXTRACTION

Studies of subaqueous fan sediments in other areas have found that the grade requirements set by the Ontario Ministry of Transportation (MOT) for asphalt and concrete aggregate can be met by only the most ice-proximal fan sediments (Gorrell, 1986). These sediments tend to be the most areally restricted, and may therefore be difficult to locate, especially where covered by finer material, or by late-stage littoral sediments.

However, the depositional model presented here can be used as a predictor for locating these sediments. Their most likely occurrence would be beneath the crests of the moraines, and in the cores of the esker and kame landforms. Aggregate extraction patterns in the study area support this prediction. Arched reflectors beneath the clay plains, seen on seismic profiles (Fig. 5) may be buried esker or kame deposits, and are good targets for aggregate exploration. These could be tested inexpensively through drilling using an auger or similar equipment.

MINERAL EXPLORATION

The lack of lodgement till in the area frustrates attempts at traditional drift prospecting methods. Meltwater flows have both eroded and reworked any preexisting tills, and erosional forms on bedrock suggest that meltwater may also have resulted in significant bedrock erosion. Since these meltwater flows were probably catastrophic in nature, transport distances may be relatively high in comparison with esker and outwash sediments in other areas.

Concentrations of heavy minerals were seen in current-bedded medium to fine sand in several esker and kame deposits in the study area. While little work has been done in this area, it is suggested that these may be representative of identifiable bedrock sources, and thus may be useful for indicator mineral prospecting.

GROUNDWATER RESOURCES

The interconnected network of coarse sediments formed by the moraines and eskers provides an excellent pathway for groundwater movement within the basin. Where these sediment are exposed at the surface, they may also form significant groundwater recharge sources.

Esker and kame deposits buried beneath the clay plain, and thick sandy infills within bedrock lows may transmit significant quantities of water (*e.g.* Freeze and Cherry, 1979), while the thick rhythmite sequences which directly overlie bedrock over much of the basin also cover groundwater targets and protect aquifers from surface contamination.

An understanding of the nature and location of these elements is essential for successfully modelling the gross features of the groundwater flow fields (Anderson, 1989), and for managing both the quantity and quality of the groundwater supply for the area. For example, storage capacity is very high within coarse morainal sediments and as water is pumped, there would be leakage from the aquifer (*e.g.* Wabigoon basin) allowing higher transmission of water. This *suggests that the ideal source of water from the Wabigoon* basin is where eskers lead into fans and at basin margins.

Reflection seismic profiling has proven especially useful in determining the subsurface geometry of the basin beneath the clay plain, indicating that it is interconnected. This technique may be particularly well suited to hydrogeological investigations of this and similar areas (*e.g.* Oak Ridges Moraine).

Information relating to groundwater flow is particularly timely, since the discovery of high levels of naturally-occurring radioactive contaminants has recently forced the abandonment of several drinking water wells in the area (Dryden Observer, 1991; Ministry of Environment, 1992).

WASTE DISPOSAL

Past practices of waste disposal in Ontario frequently involved the utilization of abandoned aggregate pits and quarries as garbage dumps. Engineering work to prevent the movement of leachate into the subsurface was rarely carried out.

In the Dryden area, several un-engineered landfill sites are located in old aggregate quarries, many of which are located

on the Hartman and Eagle-Finlayson Moraines (Ontario Ministry of the Environment, 1991). Because these moraines are topographically high features, composed of porous and permeable sand and gravel, they may act as a regional groundwater recharge source, in a manner similar to the Oak Ridges Moraine in southern Ontario.

The clay plain may protect the underlying basin aquifers from surface contamination. In the Wabigoon basin, surface clay is subject to weathering (colour change) and fractures to 6 m, which may raise vertical permeabilities 1-3 orders of magnitude (e.g. Rutland et al., 1991) but clay thickness of 10-15 m afford some natural protection.

Any leachate from the landfills and from septic systems (e.g. Robertson et al., 1991) where there is no clay cover in the Dryden area may be emplaced rapidly into the regional groundwater system, which is directly linked to Wabigoon and Eagle Lakes. Wabigoon Lake acts as the drinking water source for the Town of Dryden, while both lakes are popular recreational fishing destinations, and therefore major economic resources for the region.

ACKNOWLEDGMENTS

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