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THE SYSTEMS OF MINOR MORAINES (DE GEER TYPE,...) ASSOCIATED TO THE LAURENTIDE ICE SHEET - QUÉBEC - CANADA. GENESIS. APPLICATIONS TO MINERAL PROSPECTION (LES SYSTÈMES DE MORAINES MINEURES (TYPE DE GEER,...) ASSOCIÉS À LA CALOTTE LAURENTIDIENNE - QUÉBEC - CANADA. GENÈSE. APPLICATIONS À LA PROSPECTION MINÉRALE.)

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RÉSUMÉ

Cette thèse présente les résultats des travaux de terrain réalisés pendant les étés de 1988 à 1990, dans les régions de Chapais et de Radisson, Québec. La thèse est divisée en trois chapitres. Les deux premiers concernent l'étude des moraines de De Geer qui font partie des Champs Opémisca et Fort-George. Le troisième chapitre est élaboré autour d'une problématique plus appliquée aux ressources minérales, soit l'étude de la dispersion glaciaire clastique dans le till de surface de la région de Chapais.

Traditionnellement, l'étude des moraines de De Geer a surtout été orientée vers l'analyse de données géomorphologiques et sur des fabriques de till. Ici, l'approche favorisée est surtout basée sur l'analyse des faciès sédimentaires à laquelle s'ajoute quelques éléments plus traditionnels. Douze coupes creusées à la rétroexcavatrice sont étudiées. Trois faciès sédimentaires sont identifiés.

(1) Sédiments triés: ces sédiments triés forment des lits obliques inclinés vers l'aval glaciaire, perpendiculairement à l'axe de la forme. Du diamicton ou du till drapent parfois le versant proximal de la coupe ou forment des lentilles ayant été injectées dans les sédiments triés. Ces moraines forment des séries regroupant jusqu'à 15 segments successifs et parallèles.
(2) Till peu compact et non fissile: ce faciès est observé dans la majorité des moraines. Le till de la moraine recouvre parfois des sédiments fins stratifiés et il peut contenir de fines laminations sablo-silteuses. Par contre, plusieurs moraines ne présentent pas de structures sédimentaires. Les fabriques de till mesurées n'ont pas d'orientation préférentielle et la composition lithologique des débris contenus dans le till des moraines est généralement semblable à la composition du till de fond situé directement en amont.
(3) Till compact et fissile: ce till peut recouvrir des sédiments stratifiés, mais il repose en général directement sur le till de fond. Les galets mesurés dans une fabrique de till sont inclinés vers l'amont glaciaire. La composition lithologique des débris du till de la moraine est comparable à celle du till de fond adjacent.

Les structures sédimentaires primaires des sédiments de ces trois faciès sont déformées. Il s'agit de plis déversés à couchés, de failles inverses, de figures de charge et de structures d'entraînement. Ces déformations ont des plans inclinés vers l'amont glaciaire et traduisent une déformation en direction de l'aval glaciaire.

Le modèle proposé suggère une mise en place dans des crevasses situées à la base d'un glacier actif. Dans les secteurs où les eaux de fonte étaient chenalisées, des sédiments triés se sont accumulés sous forme de lits obliques. Latéralement à ces zones, là où l'activité des eaux de fonte était moindre, du till s'est accumulé. L'activité de la glace a provoqué la remobilisation de lambeaux de la nappe de till de fond et leur déplacement vers des crevasses localisées en aval. Dans les secteurs où l'eau de fonte avait un impact mineur, le till a été déposé dans les crevasses par accrétion. L'activité de la glace a parfois provoqué l'injection de till dans les sédiments triés du premier faciès. Les trois faciès sédimentaires font partie d'un continuum qui est expliqué par la disponibilité des eaux de fonte qui était maximale dans certains couloirs, et qui diminuait latéralement. La relation spatiale entre ces faciès suggère que plusieurs moraines successives auraient été construites simultanément, ce qui tend à infirmer l'hypothèse de leur valeur comme marqueurs chronologiques.

Dans la région de Chapais, une séquence de quatre écoulements glaciaires a été identifiée (1- sud-est; 2- sud; 3- sud-ouest; 4- ouest-sud-ouest). Une étude a donc été réalisée pour vérifier leur influence sur les patrons de dispersion de débris du granitoïde du pluton d'Opémisca dans la partie superficielle de la nappe de till régionale (till de fond, 127 sites; till de moraines de De Geer, 66 sites), sur un territoire couvrant une superficie de 3 700 km^2 (grille d'échantillonnage de 1 échantillon/19 km^2). Les débris de trois fractions granulométriques ont été analysés (0.8 à 5cm; 5 à 15 cm; 15 à 25 cm). Le contenu en débris du pluton d'Opémisca a servi au traçage d'une carte présentant des isolignes, et à établir une courbe de dispersion glaciaire. Une traînée de dispersion majeure d'une longueur d'au moins 90 km est orientée parallèlement à l'écoulement glaciaire de direction sud-ouest. La courbe de dispersion glaciaire réalisée sur cette traînée de dispersion montre un enrichissement rapide à l'amont du pluton et une décroissance exponentielle vers l'aval. Mais une traînée de dispersion résiduelle parallèle à l'écoulement ancien, dirigé vers le sud-est, est identifiée pour la première fois. Cette traînée de dispersion résiduelle a une longueur d'au moins 15 km et sa terminaison est déviée en direction du sud-sud-ouest. Les patrons de ces traînées de dispersion semblent confirmer la datation relative des écoulements glaciaires identifiés dans cette région.

ABSTRACT

This thesis presents the results of field research carried out during the summers of 1988 to 1990 in the Chapais and Radisson areas, Québec. The thesis is divided into three chapters. The first two chapters concern the genesis of De Geer moraines from Opémisca and Fort George Belts. The third chapter discusses a problem in mineral resources, this being the analysis of the dispersal patterns of the surface till of the Chapais area.

The study of De Geer moraines has traditionally been based on the analysis of geomorphological data and till fabrics. Here, the conceptual approach is focussed in large part on detailed facies analysis. More traditional data is also discussed. Twelve cross-sections excavated with a backhoe are studied and three facies are identified.

(1) Sorted sediments: the sorted sediments form foreset laminations that dip downglacier, perpendicularly to the moraine axis. Diamicton or till occasionally forms a surficial blanket on the proximal side of the exposures, or is injected into the sorted sediments. These moraines form series composed of up to 15 successive and parallel segments.
(2) Non fissile and loose till: This facies may be observed in most of the moraines. This till occasionally covers fine sorted sediments and it may contain laminae of fine sediments. Many exposures show no particular sedimentary structures. The measured till fabrics show no preferential direction. The till forming the moraines and the adjacent basal till have a similar lithological composition.
(3) Compact and fissile till: this till may overlie sorted sediments, but it generally lies directly on the basal till. A till fabric shows that the incorporated clasts dip upglacier. The lithological composition of the till forming the moraines is similar to the one of the adjacent basal till.

The primary sedimentary structures of these three facies are deformed. The deformation structures observed are thrust faults, overturned to recumbent folds, load and drag structures. The shear planes and the axial planes dip upglacier and they suggest minor compressions in a downglacier direction.

The proposed model suggests an emplacement in crevasses located at the bottom of an active glacier. In the areas where meltwaters were channelized, sorted sediments accumulated into foreset laminations. This meltwater activity decreased laterally and there, mainly till accumulated. Glacial activity locally remobilized part of the basal till and pushed it toward crevasses located downglacier. In the areas where meltwaters had almost no effect, the moraines were formed by lodgement. The activity of the ice occasionally resulted in the injection of till into the sorted sediments of the first facies. The three facies identified are part of a continuum explained by meltwater activity that was important in some channels and that was decreasing laterally. The spatial relationship between the three facies suggest that many successive moraine segments were emplaced simultaneously. This constitutes a major argument against the annuality of De Geer moraines.

In the Chapais area, a sequence of four ice flows has been identified (1- southeast; 2- south; 3- southwest; 4- west-southwest). The disersal patterns of the granitoid debris from the Opémisca Pluton in the surficial till sheet are studied (basal till, 127 sites; till from De Geer moraines, 66 sites) on a surface area of 3 700 km^2 (sampling grid of 1 sample/19 km^2). The debris from three size fractions is analyzed (0.8 to 5cm; 5 to 15cm; 15 to 25 cm). The proportions of Opémisca Pluton debris are reported on a contour line map and on a dispersal curve. A major dispersal train with a length of at least 90 km is oriented parallel to the last southwestward ice flow. The dispersal curve shows a rapid increase on the upglacier contact of this pluton and an exponential decrease downglacier from this pluton. But a residual dispersal train, parallel to the old southeastward ice flow, is identified for the first time. This residual dispersal train has a length of at least 15 km and its tail is diverted toward the south-southwest. The patterns of these dispersal trains seem to confirm the relative chronology of the main regional ice movements.

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INTRODUCTION

Les champs de moraines de De Geer couvrent de grandes superficies de Finlande, de Suède, de Norvège, des Etats-Unis et du Canada. Ces moraines ont été décrites pour la première fois par De Geer (1889) dans la région de Stockholm, en Suède. Elles ont reçu différentes appellations telles que moraines annuelles (annual moraines; De Geer, 1889; Norman, 1938; Shaw, 1944; Hoppe, 1948), moraines en planche à laver (wash-board moraines; Mawdsley, 1936; Hoppe, 1957), moraines transversales de vallées (cross-valley moraines; Andrews, 1963a, 1963b; Andrews et Smithson, 1966) et moraines sous-lacustres (sublacustrine moraines; Barnett, 1967; Barnett et Holdsworth, 1974). Finalement, Hoppe (1959) a proposé de les nommer moraines de De Geer (De Geer moraines).

Elson (1968) a rangé ces formes d'accumulation glaciaire à côté de plusieurs autres types de moraines mineures (minor moraines). Il les a décrites comme étant des "segments parallèles, rectilignes ou légèrement incurvés, souvent sinueux dans le détail et quelques uns ayant des appendices mineurs". Ces moraines sont localisées dans "des bassins glaciolacustres et des régions ayant été ennoyées par les eaux marines" (traduit de Elson, 1968, p.1216). Zilliacus (1987b, p.229) a plutôt défini les moraines de De Geer de Finlande en fonction du mode de mise en place qu'il a proposé.

"De Geer moraines in Finland can be defined as glacial inframarginal surface landforms deposited through squeezing of subglacial material from opposite directions in basal crevasses and not subject to post-depositional form or material changes by the ice. The distances between the De Geer moraines was determined by the formation of crevasses and a redistribution of the subglacial material in connection with rapid ice flow followed by a quiescient phase."

Ici, une définition descriptive est préférée (modifiée de Beaudry et Prichonnet, 1991, p.377-378). Les moraines de De Geer forment des séries de segments morainiques irrégulièrement ou régulièrement espacés et parallèles entres eux. Les segments sont étroits et allongés, rectilignes ou sinueux, et certains comportent des appendices. Leur profil peut être symétrique ou asymétrique. Ils sont généralement constitués de till, mais certains sont composés de sédiments triés dans des proportions variables.

Cette thèse est divisée en trois chapitres constitués de manuscrits d'articles. Deux portent sur l'étude des moraines de De Geer des régions de Chapais et de Radisson, Québec. L'étude des moraines de De Geer a été entreprise, suite aux travaux de Beaudry (1988), à cause de lacunes dans l'analyse sédimentologique. Deux des huit coupes décrites par Beaudry ont été étudiées plus en détail à cause de la valeur des informations qu'elles présentaient. Dix nouvelles coupes ont également été étudiées en détail.

Le premier chapitre est centré sur un type de moraine particulier, à savoir des moraines de De Geer constituées de sédiments triés, tandis que dans le second, des moraines de De Geer formées de plusieurs types de sédiments sont étudiées. Le troisième chapitre concerne une problématique particulière, appliquée aux ressources minérales. En effet, dans ce chapitre, les sédiments morainiques et le till de fond sont utilisés pour l'étude des patrons de dispersion glaciaire clastique dans la région de Chapais. Notons que dans la présente introduction, la région à l'étude n'est pas décrite pour éviter des répétitions avec les trois manuscrits.

Dans le premier chapitre, des moraines localisées dans la région de Chapais et ayant les mêmes caractéristiques morphologiques que celles décrites par De Geer (1889), Elson (1968) et Zilliacus (1987a, 1987b, 1989) sont étudiées. Ces segments morainiques diffèrent cependant par leur composition interne puisqu'ils ne sont pas majoritairement constitués de till, mais plutôt de sédiments triés. Ils ne sont pas largement distribués et ils pourraient facilement passer inaperçus dans l'ensemble des moraines composées de till. Des moraines présentant des faciès semblables ont été décrites en Finlande (Virkkala, 1963), aux Etats-Unis (Jong, 1980; Smith, 1982) et au Canada (Beaudry, 1988). Aucune étude détaillée n'a été faite sur ce faciès, bien que son analyse puisse apporter de précieux renseignements sur la dynamique glaciaire lorsque les moraines qu'il constitue ont été mises en place. Notons que Virkkala (1963, p.32) a nommé ces formes eskers transversaux (<u>transverse eskers</u>, ibid.). L'objectif est de détailler les faciès sédimentaires que présentent ces moraines et de déterminer s'il s'agit de moraines de De Geer. Un modèle est proposé pour leur mode de mise en place. Ce modèle est basé sur une analyse détaillée des faciès sédimentaires et des structures internes de six moraines appartenant à deux séries distantes de 12 km. Des coupes ont été creusées à la rétroexcavatrice. Les paléocourants ont été mesurés sur des lits obliques et les structures de déformation telles des failles inverses et des plis déversés à couchés ont été analysées. La composition lithologique des sédiments de deux moraines successives a aussi été étudiée. Enfin, leur géomorphologie a été décrite et comparée aux moraines de De Geer adjacentes.

Dans le deuxième chapitre, douze coupes creusées dans des moraines de De Geer des régions de Chapais et de Radisson sont étudiées. Ces moraines font partie de deux champs majeurs, soit les Champs Opémisca et Fort-George (Shaw, 1944). Trois différents faciès sont étudiés: (1) des sédiments triés; (2) un till peu compact et non fissile; (3) un till compact et fissile. Le till constitue la majeure partie de ces sédiments morainiques, mais des sédiments triés y sont également présents, en petites quantités. En conséquence, lorsque ce fut possible, les paléocourants ont été mesurés et les variations verticales de faciès ont été détaillées. Dans la plupart de ces moraines, les structures sédimentaires primaires des sédiments triés et les laminations contenues dans le till sont déformées par des failles inverses et des plis déversés à couchés. Les plans de ces structures de déformation ont été mesurés. Huit fabriques de till ont été mesurées (axes a et c) et la composition lithologique des sédiments morainiques a été comparée à celle du till de fond identifié à proximité, pour six sites de la région de Chapais. Une relation spatiale entre les trois faciès est établie. L'analyse des faciès constitue la base de ce chapitre, mais la relation spatiale entre les moraines de De Geer et les eskers, ainsi que les variations dans la densité des drumlins à l'intérieur et à l'extérieur des champs de moraines est examinée. Les résultats obtenus permettent de proposer un modèle général de mise en place, applicable aux moraines de De Geer des régions de Chapais et de Radisson.

L'approche conceptuelle des deux premiers chapitres diffère de l'approche utilisée dans les études précédentes. Ces dernières ont surtout été basées sur des données géomorphologiques comme la morphologie des segments morainiques et leur distribution spatiale, ainsi que sur des fabriques de till. Cette orientation de la recherche a probablement été causée par les méthodes traditionnelles et la rareté des coupes disponibles. En utilisant une telle approche, plusieurs auteurs ont conclu que les moraines de De Geer pouvaient servir de marqueurs chronologiques relatifs. Même si cette hypothèse est rejetée par quelques auteurs (Hoppe, 1948, 1957, 1959; Strömberg, 1965; Zilliacus, 1981, 1987a, 1987b, 1989), elle a longtemps dominé l'ensemble du débat puisque ces moraines paraissent, à première vue, régulièrement espacées, ce qui suggère donc un dépôt cyclique au front du glacier ou près de celuici. Il est donc raisonnable de croire que plusieurs auteurs ont cherché à expliquer leur mode de mise en place en fonction de phénomènes glaciaires cycliques, négligeant ainsi l'analyse des faciès. Le plus souvent, les descriptions publiées ne sont pas très explicites. Toutefois plusieurs fabriques de till ont été reportées et Larsen et al. (1991) ont encore conclu à une mise en place annuelle par réavancée du front glaciaire . Dans cette thèse, il est considéré que l'analyse des faciès sédimentaires, soit l'étude des structures sédimentaires primaires et des structures de déformation, permet de mieux comprendre les processus de mise en place des sédiments constituant les moraines de De Geer. Cette approche a donc été privilégiée dans les deux premiers chapitres.

Le troisième chapitre concerne une problématique appliquée aux ressources minérales. Le till constituant la plupart des moraines de De Geer et le till de fond adjacent, définis ici comme étant le till de surface, sont utilisés dans une étude de dispersion glaciaire clastique d'un territoire couvrant une superficie de 3 700 km^2 près de Chapais. Dans cette région, quatre mouvements glaciaires régionaux successifs semblent avoir érodé le substratum rocheux au Wisconsinien supérieur (Prichonnet et Beaudry, 1990). L'écoulement glaciaire le plus ancien était dirigé vers le sud-est (Martineau et al., 1984; Prichonnet et al., 1984; Bouchard et Martineau, 1984, 1985; Prichonnet et Beaudry, 1990; Veillette et Pomares, 1991). Cet écoulement a été suivi d'un mouvement de direction sud et d'un écoulement plus récent en direction du sud-ouest (Prichonnet et Beaudry, 1990). Localement, un écoulement glaciaire en direction de l'ouest-sud-ouest a succédé à ces mouvements (Prichonnet et al., 1984). Même si des stries appartenant à l'écoulement glaciaire sud-est ont été identifiées à la surface de plusieurs affleurements rocheux, son influence sur la composition lithologique de la nappe de till régionale n'a pas encore été définie, et ce, malgré quelques évidences suggérées par des patrons de dispersion locaux (de Corta, 1988). L'objectif de ce chapitre est de définir les patrons de dispersion du granitoïde du pluton d'Opémisca, localisé au nord de Chapais, dans le till de surface. Le till a été échantillonné à une profondeur variant entre 75 cm et 1,5 m sous la surface, dans 193 sites. Trois fractions granulométriques ont été analysées (0.8 à 5 cm, 193 sites; 5 à 15 cm et 15 à 25 cm, 21 sites) et séparées en cinq classes lithologiques (1- granitoïde du pluton d'Opémisca; 2- autres granites et gneiss; 3- roches volcanoclastiques; 4- lithologies distales incluant les roches sédimentaires protérozoïques du Groupe de Mistassini et de la Formation de Chibougamau; 5- débris non identifiés). Ces échantillons ont servi à tracer une carte illustrant les isolignes du contenu moyen du granitoïde du pluton d'Opémisca dans le till de surface, et des courbes de dispersion glaciaire clastique de différentes lithologies. Ces résultats pourront être appliqués à la région de Chapais, dans des programmes d'exploration minérale.

Ces trois chapitres devraient contribuer à l'avancement des connaissances scientifiques. Les deux premiers chapitres proposent un modèle pour la genèse des moraines de De Geer, défini à partir d'une nouvelle approche conceptuelle. L'emphase a été accordée à l'analyse des faciès sédimentaires. Dans le troisième chapitre, la présence d'un train de dispersion résiduel mis en place par l'écoulement glaciaire le plus ancien est suggérée. La nécessité d'effectuer d'autres études locales, permettant de mieux définir l'influence des écoulements glaciaires successifs sur la composition verticale de la nappe de till, pourrait renforcer notre hypothèse.

La thèse est organisée de la façon suivante:

Chapitre 1: Late Glacial De Geer moraines with glaciofluvial sediment in the Chapais area, Québec (Canada);

Chapitre 2: Sedimentology, structures and genesis of Late Glacial De Geer moraines from Central Québec, Canada;

Chapitre 3: Glacial dispersal from the Opémisca Pluton in the Chapais area, Central Québec.

CHAPITRE I

LATE GLACIAL DE GEER MORAINES WITH GLACIOFLUVIAL SEDIMENT IN THE CHAPAIS AREA, QUÉBEC (CANADA)

Abstract

Glaciofluvial De Geer moraines have rarely been described in detail in the literature. This study presents a model for the genesis of moraines of this type in the Chapais area, Québec. The model is based mainly on facies and deformation structures analysis, and geomorphological data. Well stratified glaciofluvial material is commonly found in the core of the moraines, whereas till or glacial diamicton may be present as a surficial cover on their proximal side or as injected lenses in the sorted sediments. The paleocurrents are systematically directed downglacier. The moraines were built up in subglacial crevasses in areas where meltwater was channelized. Water flowed under pressure from small upglacier cavities, carrying a load of coarse-grained material. Flow separation occurred when flowing water entered crevasses already occupied by water, reducing the capacity of the flow to carry the particles, and avalanching glaciofluvial material on the leeside of the piled sediments. The occurrence, in these sediments, of glaciotectonic deformation structures such as overturned to recumbent folds and thrust faults is evidence that the glacier was still active to some degree during and after the sedimentation phase.

Introduction

This paper describes several series of minor moraines in the Chapais area, Québec (Figs. 1.1A and B). These moraines are located west of Lake Dolomieu and south of Lake Lamarck (Fig.1.2A). The moraines exhibit the same morphological features as those described by De Geer (1889) and named after De Geer by Hoppe (1959); they have also been described by Elson (1968). De Geer moraines usually form series of irregularly spaced ridges that are parallel to one another. They are found in glacial lake or marine basins. The ridges are narrow and elongated, straight or sinuous, and some have minor appendages. Their profile may be symmetrical or asymmetrical. The material forming the ridges usually consists of till. The moraines described in this paper differ from De Geer moraines in that their sedimentary facies are formed either entirely or mainly of glaciofluvial material. Similar moraines have been described in southwest Finland by Virkkala (1963) who named these ridges "transverse eskers" because they are more or less parallel to the ice front and perpendicular to ice flow. According to Virkkala, these forms are closely linked to "annual end moraines" (p.32) and may represent the extension of moraines composed of till. The present paper focuses on some examples of glaciofluvial landforms and on their mechanism of deposition. It is concluded that these landforms are true De Geer moraines.

Geology and physiography of the area

The Chapais area is one of subdued relief with an elevation of c. 360 m. A few hills of up to 550 m in height break up this nearly flat surface. The elevation is highest toward the northeast and decreases toward the southwest (Fig.1.2A). The substratum is composed of Precambrian rocks of the Superior Province (Avramtchev & Lebel-Drolet 1981; Gobeil & Racicot 1983). These lithologies are part of the Abitibi Greenstone Belt and are mainly composed of metamorphosed sedimentary and volcanic rocks, with a subvertical dip oriented WNW-ESE. Their structural setting has not influenced the ice flow associated with the moraines described here, since the area is peneplained. Another portion of the bedrock consists of intrusive rocks, such as the Cummings Complex, the Chaleur Lake anorthositic Complex, the Opémisca Pluton and undifferentiated granitic rocks (Gobeil & Racicot 1983). The Opémisca Pluton, located from 13 to 23 km to the northeast of the moraines, the undifferentiated granitic rocks, located 50 km to the north and northeast, as well as the volcanic rocks will be used to characterize the lithological composition of till and diamictic sediments.

Even though the cover of recent deposits is thin (from a few centimeters to 33 m), bedrock rarely outcrops. West of Lake Dolomieu (Fig.1.2A), such outcrops represent only 2% of the total surface area. The remainder of the study area is occupied by lakes, glacial deposits (till, glaciolacustrine clay and sand, glaciofluvial material) and organic deposits (Figs. 1.2B and C). These deposits fill shallow depressions in the bedrock, which explains the low local relief of the area.

Regional ice flow patterns

The regional Late Wisconsinan ice movements have been discussed in detail by Martineau et al. (1984), Prichonnet et al. (1984), Bouchard & Martineau (1985) and Prichonnet & Beaudry (1990). Four phases of ice flow have been deduced from the erosional record of the area. The oldest ice flow was directed toward the southeast and was followed by a southward flow (Fig. 1.2D). This ice movement was succeeded by a major southwestward flow and later by a late glacial ice flow toward west-southwest. As is shown later, the deposition of the regional De Geer moraines was controlled by the two youngest ice flows.

Description of the moraines

The morainic landforms are part of the Opémisca Belt (Shaw 1944). These could easily go unnoticed in the moraine field because they are found in close association with a great number of typical De Geer moraines, which have the same morphological features and the same spatial distribution. Only two series have been studied, both of which are located within 12 km of one another and are probably time transgressive unless crevasses extended into the glacier by the hundred (Fig.1.2A). Isolated forms have also been discovered southwest of Lake Lamarck, south of Lake Michwacho and south of Dolomieu Lake (Figs. 1.1B, 1.2A), but they will not be discussed here. This section describes the surficial morphology, the sedimentary facies, the internal structure and the lithological composition of the moraines.

Morphology and setting

A series of moraines, located south of Lake Lamarck, consists of at least eight successive segments separated by distances of between 90 and 400 m (Fig.1.2B). The spacing was measured on aerial photographs, perpendicularly to the crests. The maximum height varies between 1 and 10 m. The other moraines, located northwest of Lake Dolomieu (Fig.1.2C), consist of at least 15 segments separated by distances ranging from 60 to 260 m, with observed height varying from 1 to 5 m. However, the moraines are often partially covered by glaciolacustrine clay (up to 3 m) or by a thin offlap sequence of silt and sand (0.5 to 1.5 m).

The morphology of the analyzed segments is in all respects similar to that of adjacent De Geer moraines (Figs. 1.2B and C). Both are narrow and elongated, and their slopes may be symmetrical or asymmetrical. But some moraines are larger than others, especially in their central part. Their external geometry is chevron-shaped and they sometimes have appendages which are oblique or perpendicular to the main morainic segment. These segments are thus well integrated into the De Geer moraines field, which has the same spatial distribution. The spacing of the adjacent De Geer moraines is quite irregular, varying from 15 to 470 m with a mean spacing distance of 180 m. The moraines under study differ from the surrounding typical De Geer moraines on the basis of their internal constituents, being mainly composed of glaciofluvial material.

Sedimentary facies and internal structures

Lake Lamarck moraines. - Four vertical sections were excavated with a backhoe in the moraines located south of Lake Lamarck (Fig.1.2B). Their characteristics are presented in Table I.I. Three of the moraines are similar (ML1bis, ML2, ML3) and they consist of glaciofluvial material. The fourth moraine is mainly formed of till (ML1). Only ML1bis moraine is discussed in detail below.

The ML1bis cross-section, oriented perpendicular to the main axis of the moraine, is illustrated in Figure 1.3A. The cleared surface of the section has a length of 8.4 m and a height of at least 6 m. A trench excavated beneath the diamicton located on the proximal side shows that glaciofluvial material is found to a depth of 3 m below the lower surface. The ML1bis section revealed only glaciofluvial material which consists mainly of laminated coarse sand (Figs. 1.3B, 1.4A and B). All the laminations dip toward the south-southwest (Fig.1.3C). The dip of the laminations steepens progressively from the base of the section to the top. In the lower portion of the cross-section, displacements by faults is negligible. There, the dip of the laminations varies from 11° to 22°. The build-up of foresets, with increasing dip from the base (Fig.1.4A and B) combined with the pushing effect results in foresets dipping at greater than the maximum angle of repose (up to 57°). The truncation of structures on the stoss side of the moraine precludes reconstruction of the exact size of the cavity in which the sand was deposited, but small displacements along the faults may indicate only a minor effect of truncation.

The oblique laminations are folded and sheared in the upper two meters of the section (Fig.1.3A). The axial planes of folds dip upglacier and they are oblique to the moraine axis (Fig.1.3D and Table I.I); the fold axes are almost parallel to the elongation of the moraine, but most of them (75%) dip toward the southeastern sector of the moraine; the thrust faults have shear planes inclined upglacier, at angles up to 22°. The proximal side of the section also shows a pocket of diamictic gravel in which the dip of a-b planes measured on the lower surface of clasts do not show any definite preferred orientation. All units located on the proximal side are truncated by a gravel unit in which the clasts dip upglacier (3° to 33°), which is in agreement with the general slope (23°) of the upper surface of the moraine. This unit is part of the offlap sequence.

Some characteristics of ML1bis moraine have also been recognized in two of the three other sections excavated (Table I.I, ML1, 2 and 3): the ML2 and ML3 moraines show folded and sheared glaciofluvial material; a lens of till is also found on the proximal side of the ML3 section; but the ML1 moraine, a lateral extension of ML1bis, is mainly composed of till (60%).

Although the ML1 segment is continuous with the ML1bis segment (Fig.1.2B), it has a different facies. On its proximal side the ML1 section comprised a bevelled and deformed wedge of sand. This lens becomes thicker on the distal side of the section, where it occupies 40% of the total thickness. It is truncated by till. This till is composed of two units: a coarse lower unit partially winnowed of its fine particles, and a compact and fissile upper unit with a finer matrix. Sharp contacts dipping upglacier are observed both between the individual till units and between the lower till unit and the lower sand (Table I.I). The deformation has been restricted to the sand. Here, again, the axial planes of the folds dip upglacier.

Lake Dolomieu moraines. - Two vertical sections have been excavated in moraines located west of Lake Dolomieu (Fig.1.2C). Their characteristics are listed in Table

I.II. The MO2 section is restricted to the moraine observed above the surrounding surface (2.6 m), and the MO1A moraine has been excavated down to the presumed regional basal till (3.7 m). These two moraines show facies which differ from those of Lake Lamarck. However, glaciofluvial sediments constitute a significant proportion of the material (25% to 80%).

The MO2 section is 6.4 m in length and 2.6 m in height (Fig.1.5A). The moraine is composed of glaciofluvial material (80%) and till (20%).

The glaciofluvial material in contact with the till is composed of fine sand (Fig.1.5B) and the grain size increases toward the distal side (Fig.1.7). The sand in the core of the moraine exhibits inclined laminations dipping downglacier. Incorporated clast fabric (a-b planes) shows that they are oriented perpendicular to the moraine axis, and have been grouped into two modes (SW and W; Fig.1.7A). The material in the core of the moraine is folded and the axial planes dip upglacier (Fig.1.7B and Table I.II); the fold axes are parallel to the moraine crest and dip preferentially (83%) toward the southeastern sector of the moraine.

The covering diamictic gravel at the top of the section is composed of poorly oriented disk-shaped clasts embedded in a coarse sand matrix (Fig.1.5A). Till is restricted to the proximal side of the moraine, and it is thought that its emplacement was associated with the deformation of the surrounding sand.

The MO1A section is 9.3 m in length and 3.7 m in height (Fig.1.8A). The excavation reached the basal till. Here, the facies differ from the previous ones in that till is dominant (Fig.1.9A). The lower part of the section consists of a compact and fissile till whose matrix is fine sand (Fig.1.8B). The till is overlain by very fine stratified sand containing ripple marks which indicate a south-southeast to south-southwest paleocurrent direction (Figs. 1.10A and 1.9B) and by boulder rich till (Figs. 1.8A, 1.9A). The till forming the moraine has a coarser texture than the basal till. The lower units are truncated along their upper surface by gravel which pinches out toward the crest of the moraine and is considered to be a part of the offlap sequence.

On the distal side of the section the glaciofluvial sand is deformed. Very fine sand beds are occasionally bevelled and sheared. Minor deformation is part of a major fold which has a subhorizontal axis approximately parallel to the moraine axis (Figs. 1.8A and 1.10B). Surface contact between the diamicton and the folded sand was measured. It dips toward the northeast (Fig.1.10B and Table I.II).

<u>**Lithological composition of the morainic material**</u>

Five petrographic analysis (370 to 809 fragments) have been carried out on the 0.8 to 5 cm grain size fraction samples of the MO2 and MO1A moraines. The purpose was to evaluate possible variations in the origin of the material. As expected, material of local volcanic origin (Gobeil & Racicot 1983) dominates. This ranges from 66 to 77 % of the total count and erratics, mainly composed of far-travelled gneisses and granite, may reach up to 30% (Figs. 1.7C and 1.10C). Some pebbles found in the moraines originated from the Opémisca Pluton which is in agreement with regional dispersal patterns deduced from the abundance of this tracer in the surface till of this area (Beaudry & Prichonnet 1990). Some Proterozoic fragments have also been detected and included into unidentified material. This demonstrates that the sector is located within the western limit of the Lake Mistassini and Otish Mountains dispersal train identified by Bouchard & Martineau (1984).

Discussion

<u>**Characteristics of the Chapais glaciofluvial moraines**</u>

The moraines of the Chapais area exhibit different facies from one section to the other. The proportion of glaciofluvial material varies from 25 to 100%. Some characteristics are however consistantly observed in most of the moraines (Tables I.I and I.II). The inclined laminations always dip downglacier and the sedimentary structures have been deformed. The structures observed consist of thrust faults and overturned to recumbent folds that have planes inclined upglacier. When present, the till has always been deposited from the proximal side. Finally, the coarse material of the moraines is mostly of local origin.

Glaciofluvial moraines in other areas

The nature of the material of the moraines investigated in the Chapais area differs from that documented from other De Geer moraines in Finland (Zilliacus 1987a, 1987b, 1989), Sweden (Hoppe 1957, 1959; Borgström 1979), Norway (Sollid & Carlsson 1984), United States (Mickelson & Berkson 1974) and Canada (Mawdsley 1936; Norman 1938; Shaw 1944; Andrews 1963a, 1963b; Andrews & Smithson 1966; Barnett & Holdsworth 1974). For most of these, till is the major constituent of the moraines. When present, sorted sediments occur as smudges within the till. Only Zilliacus (1987b, fig.26) has described a moraine containing an unknown amount of glaciofluvial material. However, he did not present a detailed explanation for the glaciofluvial sediment.

A few studies have investigated De Geer moraine fields with facies similar to those encountered here. These facies are similar to the sediments of some "transverse eskers" described in Finland by Virkkala (1963). He described forms made of glaciofluvial material. These forms are perpendicular to ice flow and they contain glaciofluvial material. They are located between the Salpausselkä moraines, an area where many De Geer moraines have been identified. The transverse eskers are occasionally in transition to De Geer moraines which are named annual end moraines by Virkkala (1963). The constituent material of the transverse eskers has been folded and sheared, particularly on the proximal side of the forms, and till or glacial diamicton has been identified in some portion of the landforms. The inclined laminations dip in conformity with the distal slopes of the forms, that is downglacier. Virkkala (1963) links the genesis of the transverse eskers to the formation of basal crevasses at the glacier margin, such crevasses being controlled by topography. The interpretation is that sorted sediment would then have been deposited by meltwater and subsequently deformed by active ice. Other moraines similar to those described here have been described in Maine by Jong (1980) and Smith (1982) who suggested the landforms are associated either with eskers, with a major frontal moraine, or with a proglacial delta. Those moraines are composed of stratified coarse sediments which contain deformation structures such as thrust faults and recumbent folds (Smith 1982). These authors interpreted such features as small frontal moraines of De Geer type (Smith 1982: p.198), which were built up by an active glacier in contact with a body of water. The deformation structures were developed as the glacier continued to move outward, pushing whatever material that was available. As a consequence, some moraines are made of till while others are composed of ice-deformed glaciofluvial material.

Genesis of the Chapais glaciofluvial moraines

The De Geer moraines of the Chapais area have been described by Mawdsley (1936), Norman (1938), Shaw (1944) and Beaudry (1988). Only Beaudry (1988) has pointed out the presence of glaciofluvial material, and described the facies of one of them (cf.MO2). In the present paper, the term De Geer moraine is applied to all such forms which are found in close association with and characterized by a surface morphology analogous to De Geer moraines, thus the definition proposed in the introduction.

These forms are not distinct from the other regional De Geer moraines, being parallel to them and frequently forming a physical extension of them (Fig.1.2). They have the same spacing and same morphology. Both types are narrow and elongate forms perpendicular to the ice flow. The sinuous glaciofluvial moraines are in fact De Geer moraines and not transverse eskers.

General glacial context. - We now turn to the existing models for the genesis of the glaciofluvial moraines. Although their genesis is not completely understood, it is generally believed that these moraines were developed during the latest stage of deglaciation, at a time when the New Québec Glacier was in contact with Glacial Lake Ojibway (Kinojevis Phase of Vincent & Hardy 1977, 1979). Deglaciation of the studied area occurred c. 8 300 BP (Hardy 1976). Glacial Lake Ojibway covered a large area of south-central James Bay region. The ancient shoreline of this lake is now found at an elevation of at least 438 m (Norman 1938; Vincent & Hardy 1977, 1979), but other shoreline features have been observed up to 445 m (Prichonnet et al. 1984). Since the elevation of the surrounding area is in the order of 360 m, the minimum depth of the lake at the glacier front would then have been 78 to 85 m.

The axes of the moraines are roughly perpendicular to the two latest ice flow directions (Fig.1.2). The series of moraines located northwest of Lake Dolomieu is associated with glaciofluvial deposits forming an esker 3 km long downglacier and small mounds upglacier (Fig.1.2A). This suggests that the genesis of the moraines may be related to the glacial meltwater system and may require that deposition was channelled in subglacial cavities. This would explain the sinuosity of the moraines. A system of crevasses at a high angle to ice flow would allow formation of appendages oblique or perpendicular to the main axes of the moraines. If the moraines had been deposited in an open environment, at the glacier front, it is expected that the sediments would have formed small subaquatic alluvial cones, which are seen occasionally in the area adjacent to some eskers observed in the southern region of Chibougamau (Martineau 1984). Solheim & Pfirman (1985) have related the formation of rhombohedral ridge patterns, located in front of Bråsvellbreen Glacier on Svalbard, to squeezing-up of till inside bottom crevasses. Goldthwait (1974) and Mickelson & Berkson (1974) observed the formation of moraines in crevasses located at the bottom of McBride and Plateau Glaciers, in Alaska. Bottom crevasses have also been detected in areas of ice rises, and where higher ground glaciers feed the Ross Ice Shelf in Antarctica (Jezek & Bentley 1979, 1983). These conditions may not have been the same for the New Québec Glacier because of a reduced thickness of water beneath a generally grounded margin. Nevertheless, the mechanism of crevasse formation could be very similar. Along the Ross Ice Shelf, bottom crevasses are believed to result from the stress caused by ice rise and shear stress between fast moving outlet glaciers feeding zones of slower moving ice (Jezek & Bentley 1983).

Origin of sedimentary and glaciotectonic features.- In all the moraines investigated, the dip of the sedimentary structures indicates that water entering the crevasses flowed towards the ice margin. Openings of variable sizes located on the upglacier and downglacier sides of the crevasses allowed the flow of water perpendicular to the main axis of the future landform. Such openings could correspond to the linked cavity systems of Fowler's theory which predicts that when a glacier enters standing water, sliding velocity is increased and the drainage conduits are destabilized (Kamb 1987; Fyfe 1990). Closed cavities downglacier would have caused meltwater to run parallel to the main axis of the crevasse as is the case in an esker tunnel. In consequence, the sedimentary structures would have been distributed differently. Smaller cavities, located at the bottom of the glacier or in shear planes which channel water and sediments, could work alternatively to fill the cavity with sorted material much finer than the material (e.g. boulders) accumulated in the core of the regional eskers (Prichonnet et al. 1984). The finer texture of the material accumulated in the glaciofluvial moraines may be explained by less energy supplied to the hydrostatic system. From this, it can be deduced that all these cavities allowing the flow of water were relatively small.

The occurrence of glaciotectonic deformation structures indicates that the ice must have been slightly active, and analysis of the structures shows translocation downglacier. If these structures had been formed as a result of closing of subglacial cavities, the structures would then indicate compression from both sides of the moraines, which is not the case. Compression has not always produced shearing in the sediments. Because sediments were water-saturated they were easily deformed, and folding could develop to accommodate the different stress modes applied to the material. In MO1A moraine, stress and deformation seem to have been transmitted through a till layer located immediately above the saturated sediments (Fig.1.8A). In MO2 moraine, deformation probably resulted from the till being injected into the glaciofluvial sediments. But here again, the till lens is located on the proximal side of the moraine and it can be reasonably concluded that active ice caused this injection (Fig.1.5A). The till probably originated in a deforming subglacial bed as evidenced by the local nature of clasts included in the till (Fig.1.7C).

Facies variability may depend on the position of the subglacial cavities and be confined to zones where meltwater was channelled. There, the processes involved may have produced moraines composed predominantly of glaciofluvial material. Cavities located at the boundaries of these areas, where meltwater processes were somewhat restricted, have much less sorted material and more till (Beaudry & Prichonnet unpublished). Transitional environments may have existed and the present study detected a few of them.

Proposed model for deposition of glaciofluvial De Geer moraines.

The meltwater regime of Figure 1.11 presents the processes involved in the construction of the glaciofluvial De Geer moraines. That the glacier was in contact with a glacial lake must have had some influence on the height and the slope of the water table in the glacier. As is observed in modern ice sheets, meltwater would have been channelled in some areas (Sugden & John 1976). An increase in the input of meltwater would have steepened the slope of the water table. Water would then have flowed with higher velocity and it would have been capable of transporting sediments of variable grain size. Generally, in the areas where glaciofluvial De Geer moraines are encountered, it seems that either not enough meltwater was channelled or glacial activity disrupted the drainage through conduits in which an esker could have been formed. As a consequence, meltwater rather flowed through a net of small openings (Kamb 1987; Fyfe 1990), into bottom crevasses, diverting its flow as material filled existing cavities or as glacial activity again modified the drainage system. In the presence of subglacial cavities filled with water, such as crevasses parallel to the ice front, the velocity of the water flow would have been considerably diminished by a separated flow or sheet flow (Fig.1.11A); this would have caused a diminishing capacity of water to transport sediment. Glaciofluvial material could then have accumulated in an elongated moraine by accretion of material leeward. Shortly after the active sedimentation phase or sporadically when water flows were impeded, the glacial activity, being of some importance, would have deformed the primary sedimentary structures (Fig.11B). In some cases, till would then have been deposited on the surface of the sorted material, mostly on the proximal side, or even been injected into the glaciofluvial sediments. The present model allows for the simultaneous build up of several successive moraines behind the glacier front, in an area where the glacier was generally grounded. It is believed here that the moraines were formed in bottom crevasses located up to a few hundred meters behind the glacier front, and that the series of moraines were formed simultaneously in bottom crevasses. The formation of bottom crevasses would have been the result of the longitudinal stress caused by the reduction of shear stress in marginal zones buoyed by the frontal lake.

Comparison with other models.

The genesis for the glaciofluvial moraines appears to be very different from the model proposed by Virkkala (1963). He suggested that the opening of the bottom crevasses is related to topography. In fact, in the Chapais area, the landscape being highly peneplained, it is reasonable to believe that such a mechanism does not apply. Virkkala (1963) also pointed out that the "transverse eskers" were built up near the glacier front. This is discounted because water flow instead of being parallel to the landform was parallel to ice flow. Moreover, the glaciofluvial moraines were generally constructed at a certain distance behind the glacier front, in clusters of irregularly distributed crevasses. Smith (1982) suggested that such moraines were formed at the front of an active glacier that pushed available material. Such a mechanism cannot be applied to the glaciofluvial moraines of the Chapais area. Whereas these moraines were built up in confined areas, such as crevasses, that allowed the construction of elongated moraine segments. Deposition at the glacier front would have produced small alluvial cones. Also, the aspect of the sedimentary structures suggests that they are contemporaneous with moraine construction, and that the deformation processes affected sediments already in place. Finally, it is not likely that this mechanism of crevasse fillings corresponds to the model proposed by Zilliacus (1987a, 1987b, 1989) for the genesis of De Geer moraines in Finland. According to this author, till was seen as "flowing" toward crevasses, from both sides, after a phase of glacier surge (Zilliacus 1987b, fig. 54). The examined cross-sections in the Chapais area clearly demonstrate that the till lenses, when present, are found only on the proximal upglacier side of the moraines. This proximal deposition was also frequently identified in other moraines composed of till in the Opémisca and Fort George Belts (Beaudry & Prichonnet unpublished). Here and elsewhere, when observed, push structures indicate an outward and radial movement, more or less parallel to ice flow. Variations in this process are evidenced by comparing Figures 1.5A and 1.9A. In Figure 1.5A, it is quite obvious that the till was injected into the glaciofluvial material from the very base of the glacier. In Figure 1.9A, till is seen to override a smaller thickness of sorted material which confirms, according to the proposed model, a smaller quantity of meltwater.

Conclusion

The glaciofluvial De Geer moraines described in this paper might easily be undetected in a large De Geer moraine field such as the Opémisca Belt. Several series of moraines composed of glaciofluvial material have been positively identified among hundreds of moraines. Their characteristics can be summarized as follows. The moraines are narrow and elongated, and they sometimes have appendages. Their axes are perpendicular to the ice flow and they form series, in the downglacier direction, of up to 15 successive segments. The moraines are mainly composed of glaciofluvial material (25 to 100%) that includes inclined laminations always dipping downglacier. When till is present, it is located on the proximal side of the moraines, and it forms lenses either injected into the glaciofluvial material or covering the proximal surface of the moraines. Deformation structures are of glaciotectonic origin such as thrust faults and overturned to recumbent folds. Deformation structures have axial and thrust planes dipping upglacier.

The general characteristics of the moraines are compatible with the hypothesis that these forms are in fact true De Geer moraines and that they differ from similar moraines by their facies and by their mode of deposition.

The analysis of these moraines may allow a better understanding of minor moraine accumulation. Paleocurrent measurements clearly show that water flowed under pressure at the glacier sole, in a system of crevasses at the glacier margin. This water flowed perpendicularly to the main crevasses, generally depositing its charge as foreset laminations. Deformation of these sedimentary structures occurred after blocking of the deposition processes or during the sedimentation phase, when active ice folded and/or sheared the foreset laminations. The study of these deformation structures provides new insight into the dynamics of the New Québec Glacier during their formation. It reveals that the glacier was always active to a certain extent. It is, however, reasonable to believe that this activity had a limited effect, since cavities were developed and the moraines preserved. The observed deformation structures indicate that the movement which deformed the material must have been restricted to minor pushes. It is difficult to say whether this phenomenon had a recurrent or annual character, or if it was erratic. The observations seem to demonstrate that it was at least repetitive, but it is not believed here that deposition of a single moraine corresponds to a one-year retreat of the ice.

Finally, the material that constitutes the glaciofluvial moraines has the same provenance as the surrounding basal till, as evidenced by pebble composition of diamictons and tills analyzed in the moraines. The observations reported here complement other information from the analysis of De Geer moraines composed of till. The model outlined above is a component of a larger model for the genesis of all De Geer moraines and will be presented elsewhere.

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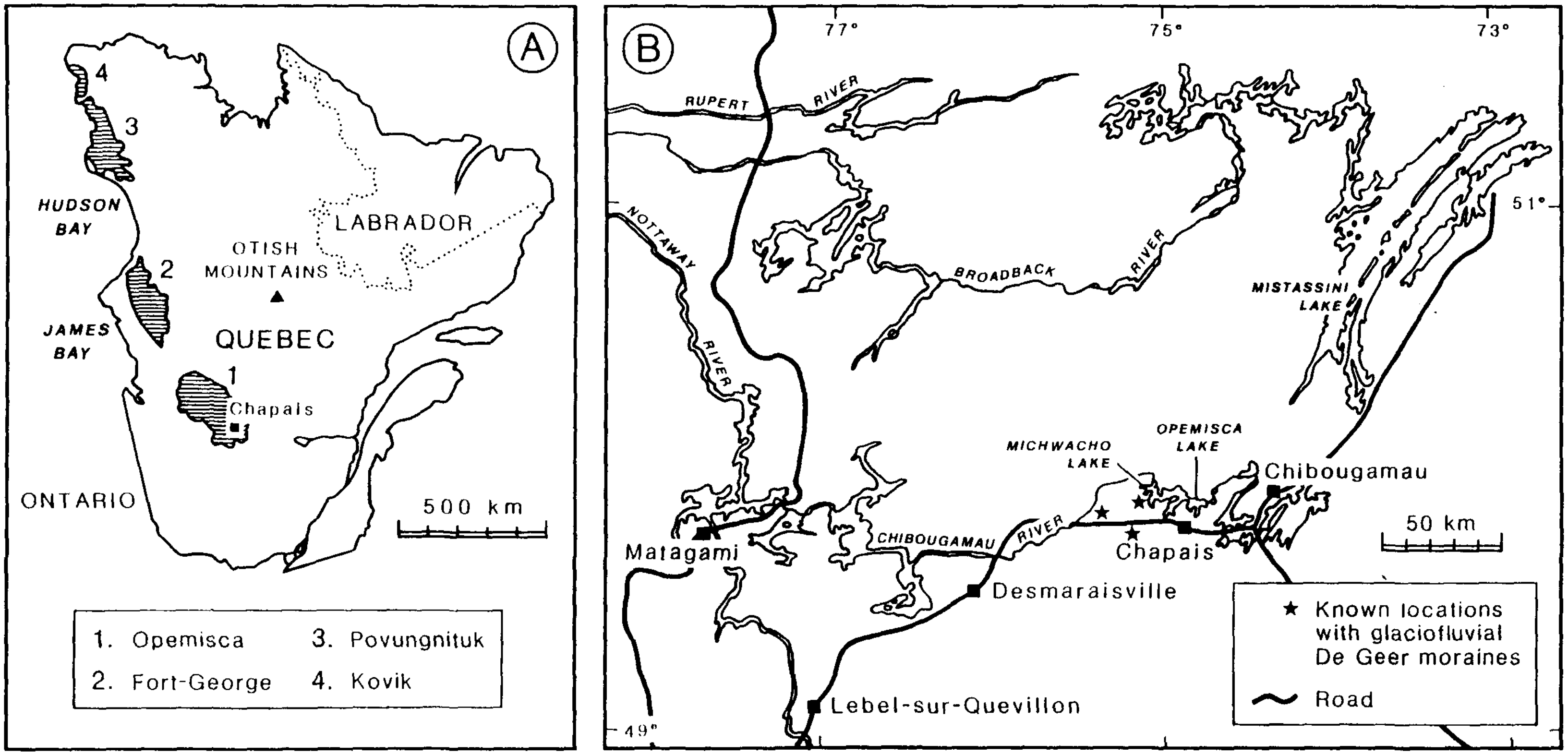


Fig.1.1. Location maps. A Chapais area in the southeastern part of the Opemisca Belt. The four hatchured areas indicate the known extent of the De Geer moraine belts as shown in Prest et al. (1968). B. Sites with De Geer moraines composed of glaciofluvial sediments.

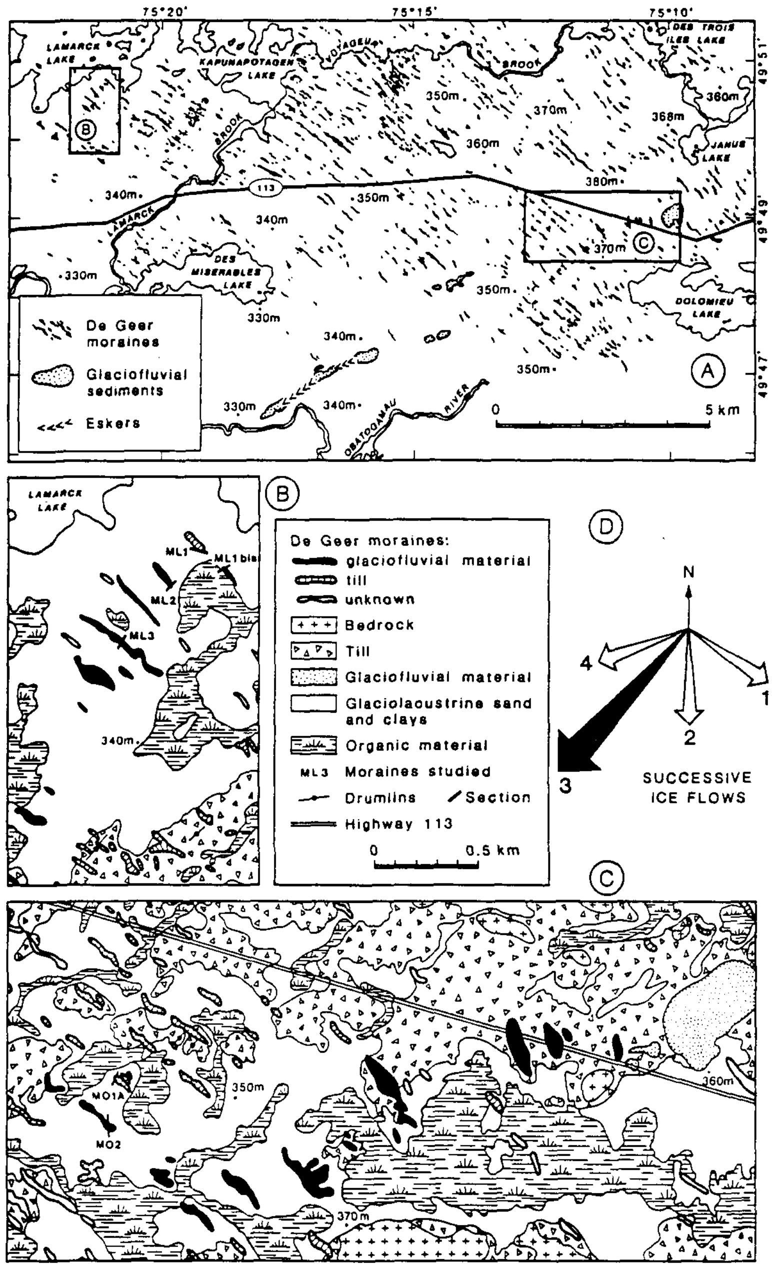


Fig.1.2. Distribution of De Geer moraines in the study area. A. Distribution of the De Geer moraines west of Chapais, with location of the two series studied and other major glaciofluvial accumulations. The sectors where no De Geer moraines were mapped are covered by a dense spruce forest. B. Lake Lamarck series. C. Lake Dolomieu series. D. Late Wisconsinan ice flows of the Chapais area (Prichonnet & Beaudry, 1990).

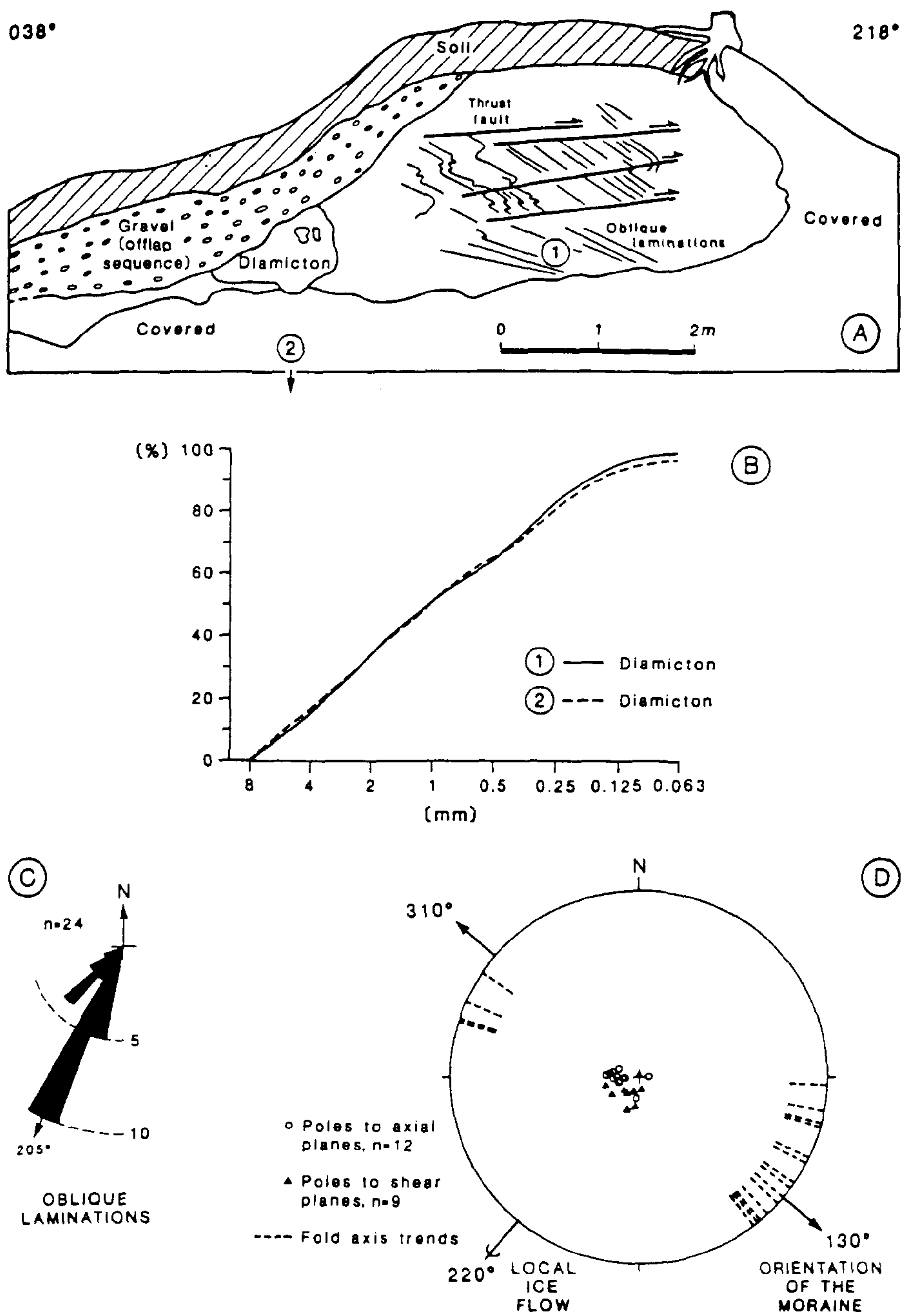


Fig.1.3. ML1bis moraine. A. Schematic cross-section. B. Granulometry of two samples of diamicton. Sample 2 was taken 3 m below the ground surface. C. Paleocurrents according to the dipping of inclined laminations. D. Analysis of deformation structures (Schmidt equal-area net, lower hemisphere).

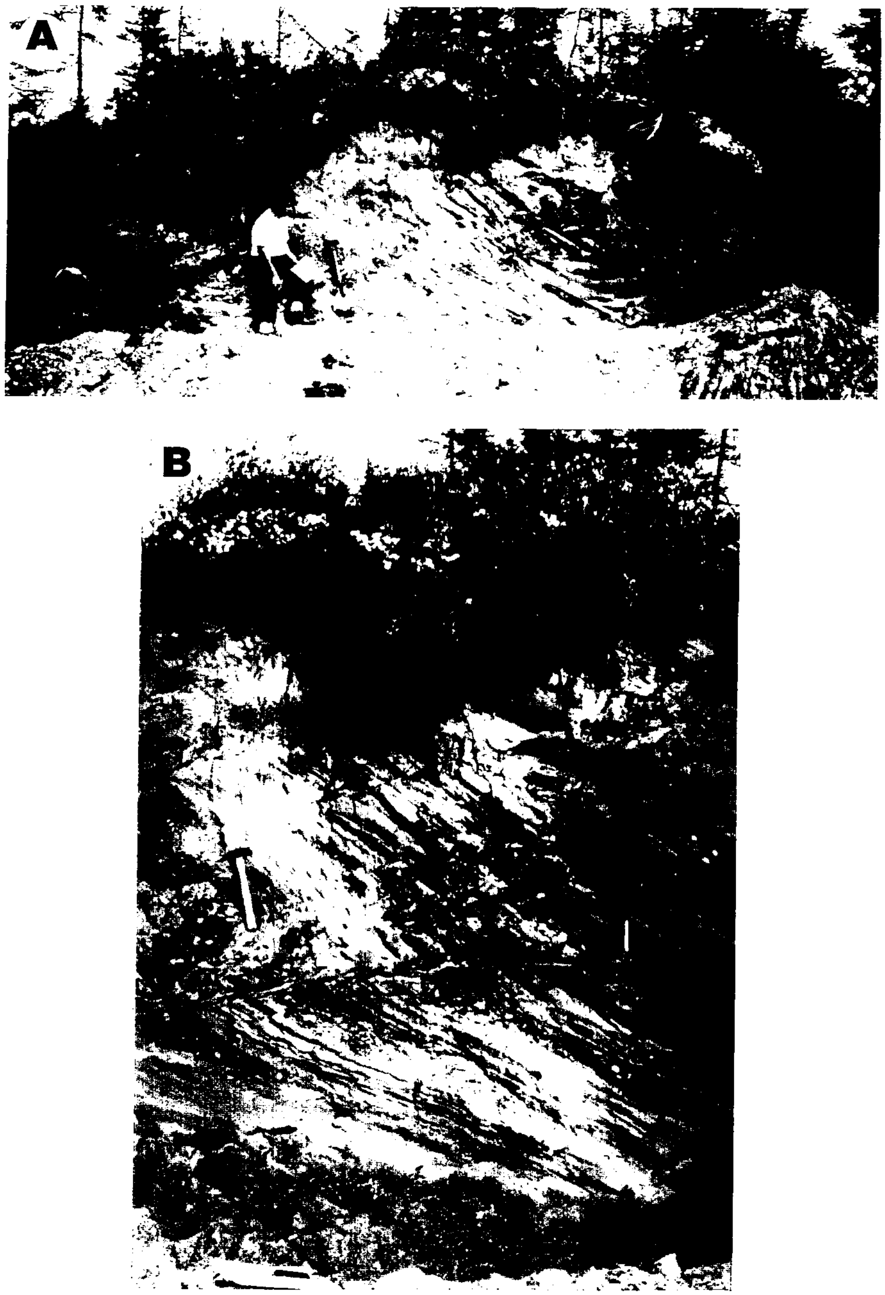
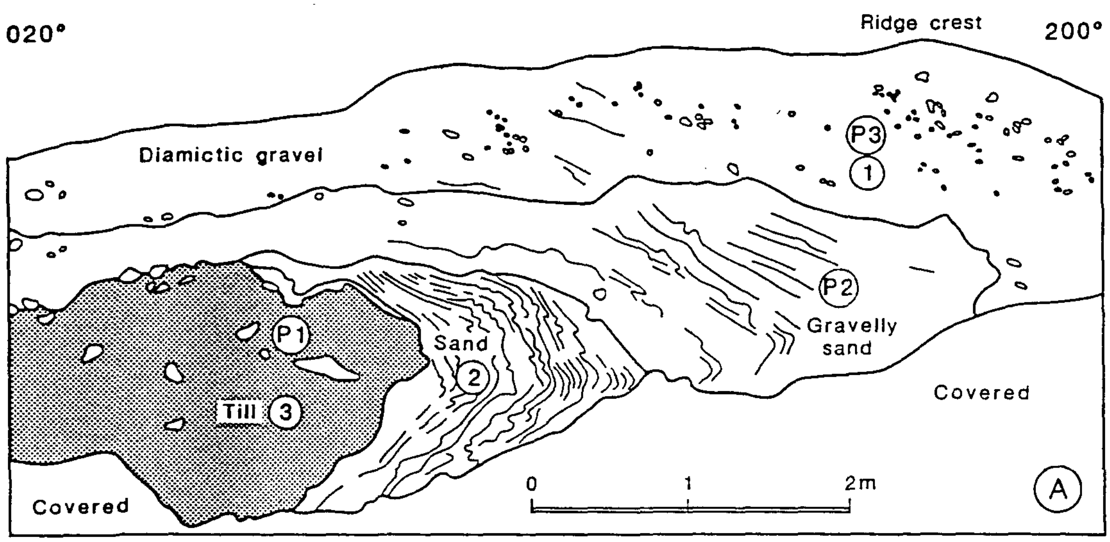


Fig.1.4. ML1bis section (Fig. 1.3A). A. View of the section. B. Close-up of the folded inclined laminations and thrust faults (hammer 39 cm long).



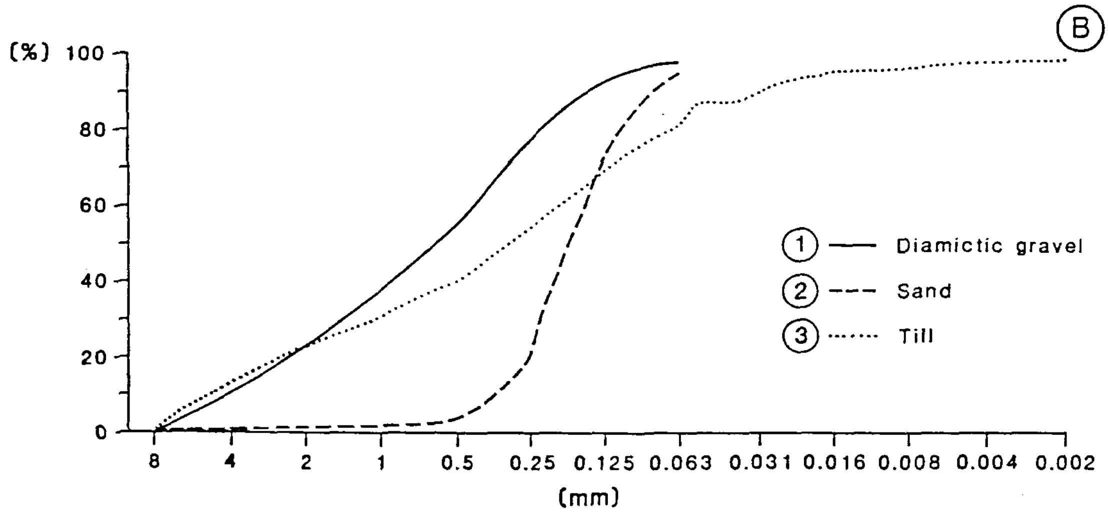


Fig.1.5. MO2 moraine. A. Schematic cross-section. B. Granulometry of diamictic gravel, sand and till.

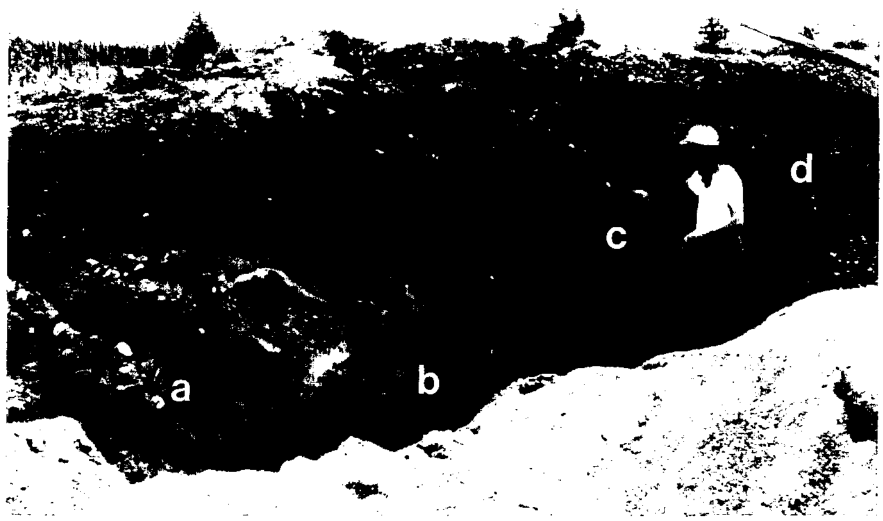


Fig.1.6. View of MO2 section: a, b, c and d are the four facies shown in Fig. 1.5A.

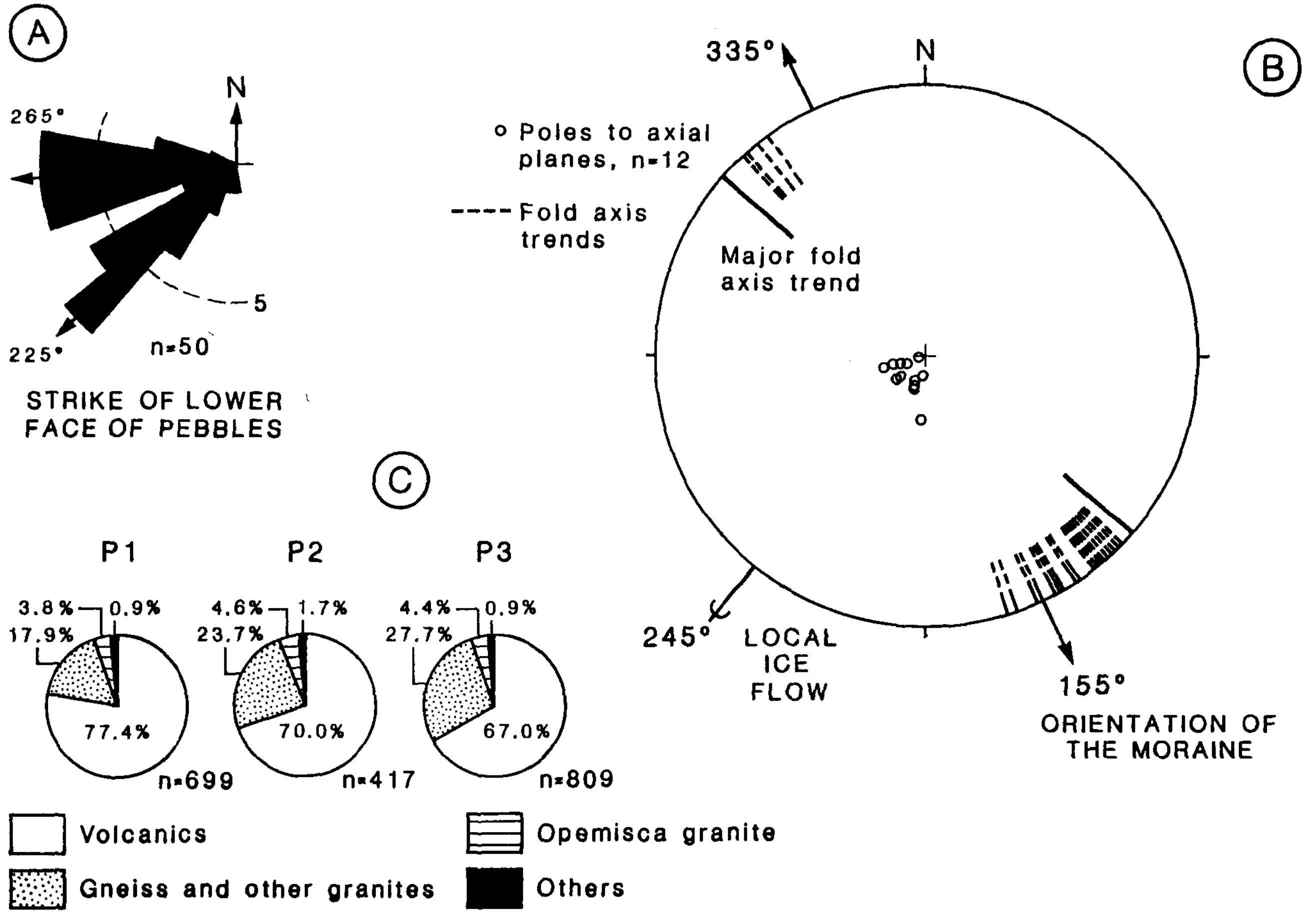


Fig.1.7. MO2 moraine. A. Paleocurrents as illustrated by the dipping of lower face of pebbles incorporated in the gravel unit. B. Analysis of sand unit deformation structures (Schmidt equal-area net, lower hemisphere). C. Pebble counts of the till, gravelly sand and diamictic gravel units.

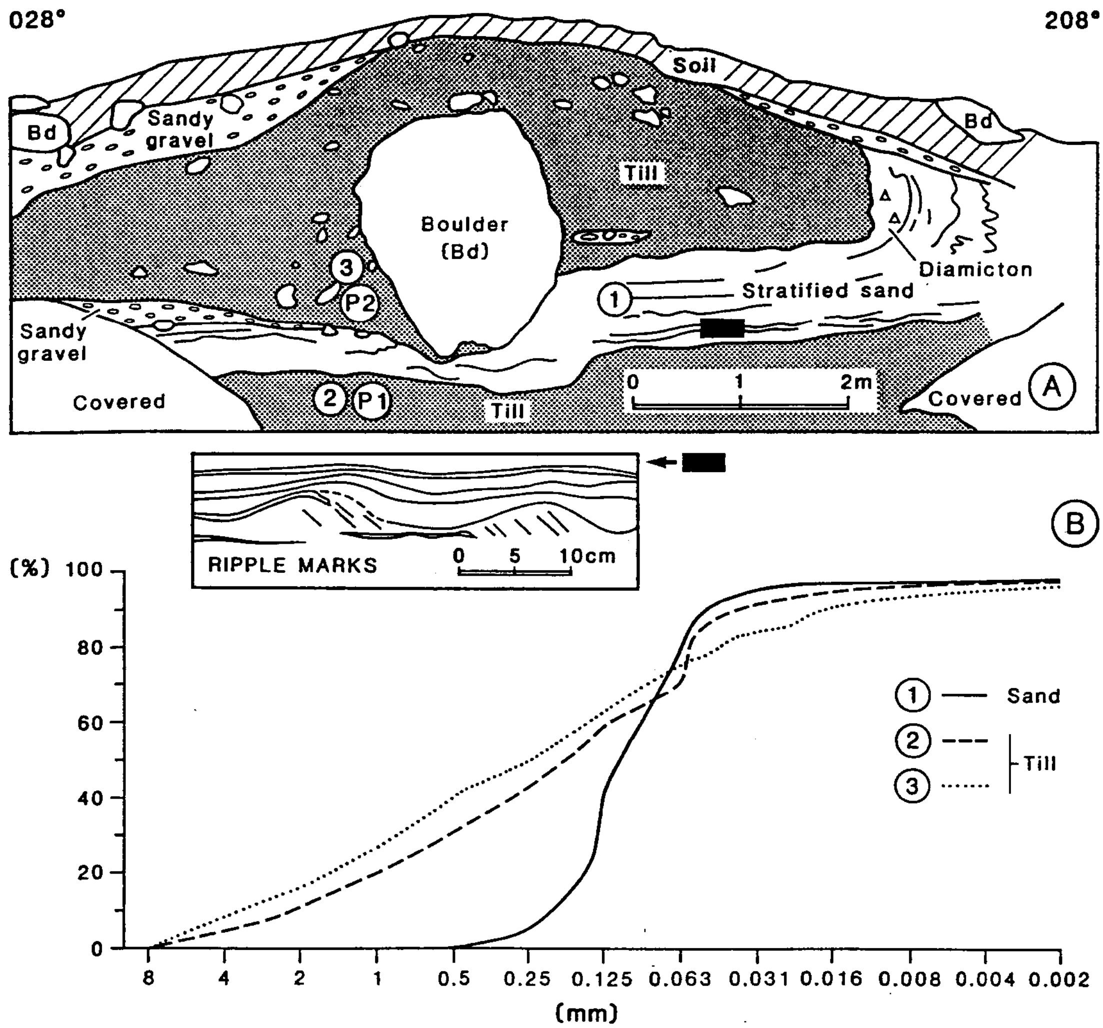


Fig.1.8. MO1A moraine. A. Schematic cross-section. B. Granulometry of the two till units and the intercalated stratified sand.

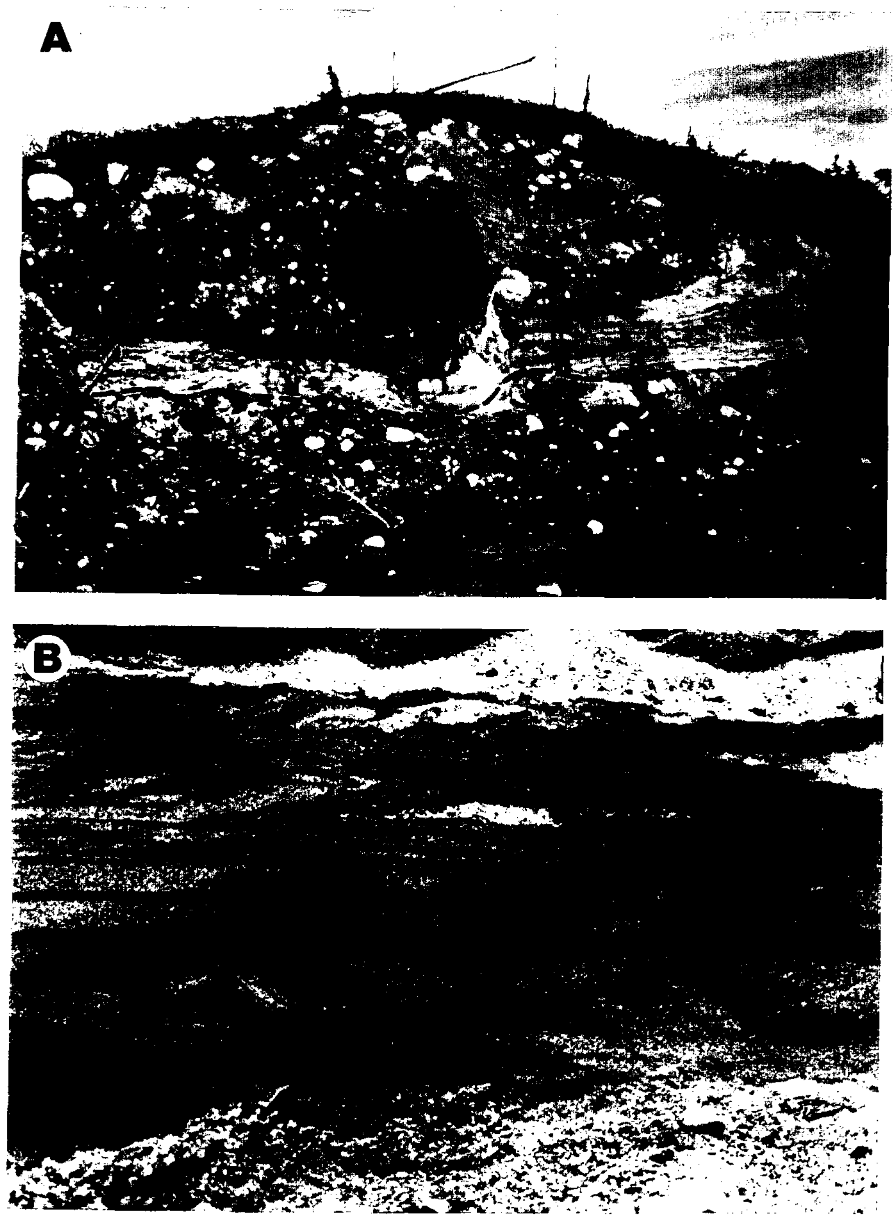


Fig.1.9. MO1A section (Fig. 1.8A). A. View of the section and of the till units a and b (boulder 3 m high). B. Detailed view of the stratified sand unit with ripple marks (λ(a - b) = 21 cm). Note the foresets toward the southern sector.

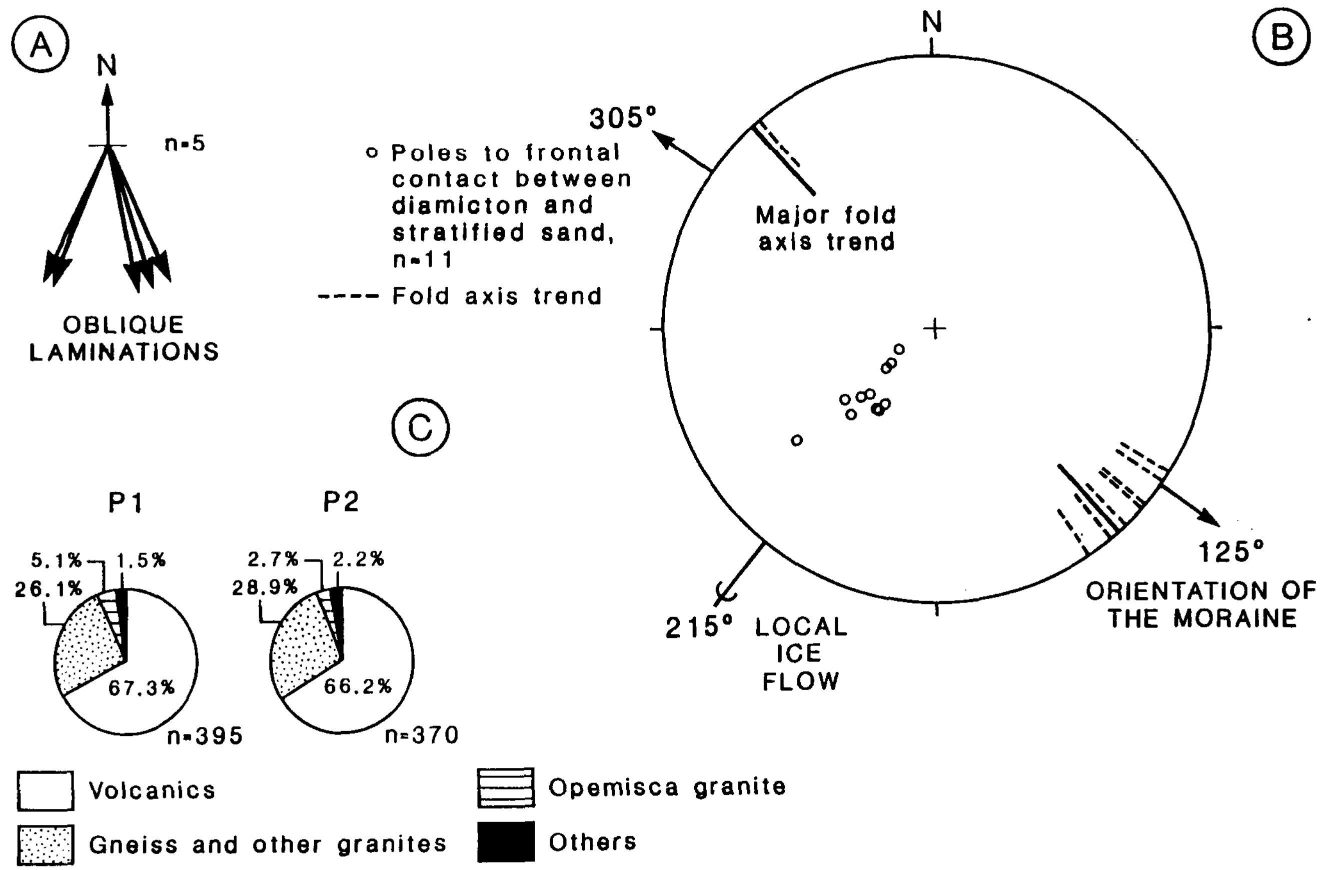


Fig.1.10. MO1A moraine. A. Paleocurrents according to inclined laminations in ripple marks. B. Analysis of deformation structures (Schmidt equal-area net, lower hemisphere). C. Pebble counts of the two till units.

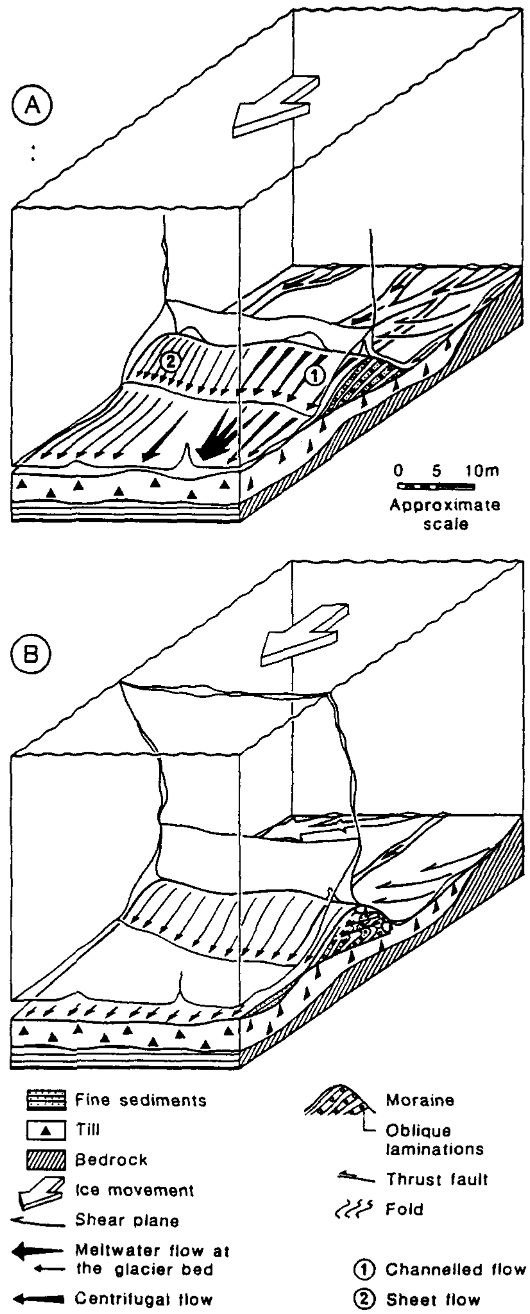


Fig.1.11. Model for the formation of the glaciofluvial De Geer moraines. Note that the surface of the diagrams does not represent the upper surface of the glacier. A. Build-up phase of the moraine: 1- channelled flow activity of water depositing sediments as horizontal or inclined laminations, and ripple marks; 2- sheet flow of less velocity. B. Glaciotectonic activity phase: deformation of sediments; injection of till lenses and/or deposition of diamictic material.

Table I.I. Characteristic features observed in sections of Lake Lamarck moraines.

MORAINE N°	ML1bis	ML2	ML3	ML1
Orientation	130° - 310°	126° - 306°	115° - 295°	100° - 280°
Cross section orientation height length	038° - 218° 2.9 m 8.4 m	029° - 209° 6.5 m 31.0 m	034° - 214° 2.0 m 20.0 m	075° - 255° 2.3 m 10.0 m
Proportion of glaciofluvial material	100 %	100 %	90 %	40 %
Sedimentary structures Oblique laminations Dip Strike	 n = 24 11° to 22° (lower part of section) 33° - 57° (upper part of section) mode at 205° Toward distal side of moraine	 n = 4 08° to 18° 155° to 172° Toward distal side of moraine	 n = 2 13° and 20° 175° and 221° Toward distal side of moraine	 not measured
Deformations (a) Axial planes of folds Dip Strike (b) Shear planes Dip Strike c) Fold axis trends Dip Strike Dip Strike (d) Contacts Dip Strike	 n = 12 05° to 21° 077° to 118° 263° and 012° Upglacier dip n = 9 01° to 22° 280° to 022° Upglacier dip n = 24 18 dip toward southeast; 03° to 30° 093° to 143° 6 dip toward northwest; 02° to 06° 287° to 303° Not observed	 Not measured n = 1 19° 059° Upglacier dip Not measured Sand/diamicton n = 7 09° to 45° 339° to 058° Upglacier dip	 Not measured n = 15 12° to 51° 319° to 095° Upglacier dip Not measured Sand/till n = 2 15° to 24° 032° to 040° Upglacier dip	 n = 2 05° and 08° 070° and 075° Upglacier dip Not observed Not measured Sand/till n = 4 13° to 55° 42° to 66° Upglacier dip
Other features	-No clear orientation of clasts in proximal diamicton -Clast measurement in offlap sequence (n=20) Dip: 03° to 62° Strike: 16 dip toward 005° to 091° 4 dip toward 183° to 241°	-Coarsening upward sequence toward surface -Folded and sheared sediments with maximum concentration on proximal side of the moraine	-Till lens injected on proximal side of moraine -Deformations limited to the sediments underlying the core and the proximal side of the moraine	-Compact and fissile till overlying deformed sand -Waterlain till in between sand and compact till

Table I.II. Characteristic features observed in sections of Lake Dolomieu moraines.

MORAINE N°	MO2	MO1A
Orientation	155° - 335°	125° - 305°
Cross-section orient. height length	020° - 200° 2.6 m 6.4 m	028° - 208° 3.7 m 9.3 m
Proportion of glacio-fluvial material	80 %	25 %
Sedimentary structures Oblique laminations Dip Strike	 measured on lower faces of disk-shaped clasts (n=50) 10° to 52° 2 modes at 225° and 265° Toward distal side of moraine.	 measured in ripple marks (n=5) 14° to 46° 158° to 204° Toward distal side of moraine.
Deformations (a) Axial planes of folds Dip Strike	 n = 12 03° to 26° 007° to 075° Upglacier dip	 Not measured
(b) Fold axis trends Dip Strike Dip Strike	n = 30 25 dip toward southeast 02° to 24° 134° to 163° 5 dip toward northwest 01° to 07° 317° to 324°	n = 10 7 dip toward southeast 03° to 20° 122° to 146° 3 dip toward northwest 02° to 07° 316° to 320°
(c) Contacts Dip Strike	Not measured	Sand/till n = 11 17° to 66° 035° to 060°
Other features	-Proximal lithologies dominating and diminishing toward surface of distal slope. -Highly folded sediment -Coarsening upward sequence	-Composition in pebble origin identical for both tills. -Folded glaciofluvial sediment -Offlap sequence on both slopes of moraine.

CHAPITRE II

SEDIMENTOLOGY, STRUCTURES AND GENESIS OF LATE GLACIAL DE GEER MORAINES FROM CENTRAL QUÉBEC, CANADA.

ABSTRACT

This paper presents a model for the genesis of De Geer moraines in the Chapais and Radisson areas, Québec. The model is based on geomorphological data, facies and deformation structure analysis, and other sedimentological data. Three facies associations have been identified: (1) sorted sediments that form foreset laminations dipping downglacier. Till lenses or glacial diamictons are found within the sorted sediments or form a surficial cover on the proximal side of the sections; (2) a non-fissile and poorly compacted till overlying and deforming sorted sediments. Laminae of finely sorted sediments may be incorporated in the till; (3) a fissile and compact till overlying and deforming sorted sediments, but more commonly lying on the basal till sheet. All three facies associations feature deformation structures (faults, folds, load and drag structures) with planes dipping upglacier.

The model proposed is an emplacement of De Geer moraines in bottom crevasses by an active glacier. In areas where meltwaters were channelized, sediments accumulated in the crevasses as foreset laminations. Laterally from those areas, meltwaters had a less important effect and mainly till accumulated. Glacial activity locally remobilized the basal till and pushed it toward the bottom crevasses located downglacier, or overturned large layers of till. Finally, in areas located even further laterally, meltwaters had almost no effect, the moraines were formed by

squeezing of till in the crevasses. The three facies associations are part of a continuum beginning with the moraines composed of sorted sediments and grading laterally into the moraines formed of fissile and compact till. This continuum is described herein for the first time.

RÉSUMÉ

Un modèle pour la genèse des moraines de De Geer des régions de Chapais et de Radisson, Québec a été mis au point. Il est basé sur des données géomorphologiques, sur une étude des faciès et des structures de déformation et sur d'autres données sédimentologiques. Trois associations de faciès ont été identifiées: (1) des sédiments triés formant des lits obliques inclinés vers l'aval glaciaire, avec des lentilles de till ou de diamicton interdigitées dans les sédiments triés ou drapant le versant proximal des moraines; (2) un till non fissile et peu compact recouvrant et déformant des sédiments triés avec, parfois, des laminations de sédiments fins triés incorporées au till; (3) un till fissile et compact recouvrant et déformant des sédiments triés ou reposant le plus souvent sur la nappe de till sous-jacente. Les trois associations de faciès présentent des structures de déformation (failles, plis, structures d'entraînement et figures de charge) dont les plans sont inclinés vers l'amont glaciaire.

Il est proposé que les moraines de De Geer se sont mises en place dans des crevasses basales d'un glacier actif. Dans les secteurs où s'écoulaient les eaux de fonte, des sédiments triés s'accumulaient dans des lits obliques. Latéralement à ces secteurs, les eaux de fonte avaient un impact mineur sur les sédiments et du till s'accumulait. Le glacier a localement remobilisé le till de fond et provoqué son

déplacement vers des crevasses localisées en aval, ou a retourné de larges lentilles de till. Finalement, dans les secteurs où les eaux de fonte n'avaient presque pas d'influence, les moraines se sont formées par placage de till dans les crevasses. Les trois associations de faciès font partie d'un continuum qui commence avec les séries de moraines composées de sédiment triés, puis passant latéralement à des moraines composées d'un till fissile et compact. Ce passage latéral est identifié pour la première fois.

INTRODUCTION

De Geer moraines have been defined as a type of minor moraine with moraine ridges which are parallel to one another (Elson, 1968). This landform usually forms a series of irregularly spaced ridges (Prichonnet et al., 1984; Beaudry and Prichonnet, 1991). Several authors have mentioned their presence in former postglacial lakes or shallow marine basins. The ridges are narrow and elongated, straight or sinuous, and some have appendages. Their profile may be symmetrical or asymmetrical. The material in the ridges may be till and/or sorted sediments. They were first described by De Geer (1889) and have since been known by different names such as: *annual moraines* (Norman, 1938; Shaw, 1944; Hoppe, 1948), *wash-board moraines* (Mawdsley, 1936; Hoppe, 1957), *cross-valley moraines* (Andrews, 1963a, 1963b; Andrews and Smithson, 1966) *sublacustrine moraines* (Barnett, 1967; Barnett and Holdsworth, 1974) and *lift-off moraines* (Gipp, 1992). Hoppe (1959) first proposed the name De Geer moraines for this type of landform.

Fields of De Geer moraines cover large areas of North America (Fig.1). In the United States, these landforms are found in Alaska and Maine. In Canada, De Geer moraines have been identified in most of the provinces and on the Scotian Shelf. These moraines, however, have been mostly studied in Québec, where they form four major belts covering areas varying from 5,000 km^2 to 43 000 km^2. These belts are located southeast and east of James Bay and Hudson Bay (Fig.2.1). A small number of De Geer moraines also occur in a few valleys on Anticosti Island (Painchaud et al., 1984), and south of Lake Saint-Jean (Tremblay, 1968).

This paper describes De Geer moraines from the Chapais and Radisson areas (Fig.2.1) that are respectively part of the Opémisca and Fort George Belts (Shaw, 1944). The objective is to develop a suitable model for the origin of these De Geer moraines. The conceptual approach used here is different from most of the previous studies, which have been mainly based on terrain morphology, spatial distribution and till fabric analysis. Many authors (see Zilliacus 1987b, for extensive discussion on the annual moraine problem) have concluded that De Geer moraines can be used to establish the relative chronology of deglaciation. The present study is focussed on the facies variations, the primary sedimentary structures, such as paleocurrent indicators, penecontemporaneous deformation structures and the lithological composition. The relationship between De Geer moraines and drumlins and the transition between De Geer moraines and Rogen moraines is also discussed. The traditional elements (moraine morphology, spatial distribution and till fabrics) are also used as criteria for analysis. The paper is completed with a discussion of the annual moraine problem and the place occupied by De Geer moraines in glacial landscapes.

In this study, no further reference will be made to the Opemisca and Fort-George Belts because these belts form an almost continuous field (Fig.2.1) and the areal extension of De Geer moraines is not yet known with certainty (some are covered by thick glaciolacustrine deposits). Nevertheless these moraine belts are separated by the Sakami moraine and are known to be diachronic (Fig.2.1). The moraines of the Chapais area, located south of the Sakami Moraine, were deposited when the Nouveau-Québec Glacier was in contact with Glacial Lake Ojibway around 8 300 years BP (Hardy, 1976). The moraines of the Radisson area, located east of the Sakami Moraine, developed around 8 000 years BP, after the drainage of this lake, when the Nouveau-Québec Glacier was in contact with the Tyrrell Sea (Hardy, 1976; 1977, 1982; Vincent, 1977; Vincent and Hardy, 1977, 1979; Hillaire-Marcel et al., 1981; Vincent et al., 1987). A few series of De Geer moraines have also been identified in the basin of Glacial Lake Mattawaskin (Bouchard, 1980). These moraines are probably contemporaneous with the first De Geer moraine series emplaced near Radisson to the north.

GEOLOGY AND PHYSIOGRAPHY OF THE AREAS STUDIED

The Chapais and Radisson areas are located on the Canadian Shield and are separated by a distance of 450 km (Fig.2.2). The area is underlain by Archean and Proterozoic rocks of the Superior Province (Avramtchev, 1985). The Archean lithologies include greenschist facies volcaniclastic rocks, granitic and gneissic rocks, and mafic and ultramafic rocks. The Proterozoic units are composed of slightly deformed sedimentary rocks (the Sakami and Chibougamau Formations; the Mistassini and Otish Groups). The studied moraines are located on metamorphosed volcaniclastic rocks.

The sediments from De Geer moraines have been used for road construction in both sectors and for the development of the La Grande Rivière Hydroelectric Complex. Hence, these landforms are often cut by excavations, especially in the Chapais sector, where they have only recently been exploited. In the Radisson sector, a few roads have been built across the moraines, but most of the sections have been reclaimed. Ten moraines in the Chapais sector and two moraines in the Radisson sector have been excavated and described in detail (Fig.2.2), from among approximately 30 observed sections.

The Chapais sector is an area of subdued relief. Elevations range from 340 to 400 m; the maximum elevations are to the northeast of the area and the terrain slopes to the southwest. Depressions in the bedrock are partially filled by Quaternary deposits. Glacial deposits are predominant, and include till, glaciofluvial sand and gravel, and glaciolacustrine sand and clay (Prichonnet et al., 1984). Locally, bogs cover extensive areas whereas bedrock outcrops over only 2% of the studied sector

(Beaudry and Prichonnet, 1991, Fig.1.2). A maximum overburden thickness of 33 m was observed during a large drilling program for mineral exploration (Burns et al., 1986; Brereton et al., 1987).

The Radisson sector is part of the James Bay Lowlands. Relief is slightly undulating with elevations varying from 210 to 150 m near the LG2 Reservoir and slowly decreasing westward. Quaternary deposits are composed of till, glaciofluvial sediments, marine sediments (Tyrrell Sea clay, littoral and tidal flat deposits) and of fluvial and organic sediments (Vincent, 1985 a, b). Bedrock outcrops form at least 50% of the ground surface.

GENERAL GLACIAL CONTEXT

The studied sectors were covered by the Nouveau-Québec Glacier several times during the Quaternary Period. In the Chapais area, the sequence of ice flows has been discussed by Martineau et al. (1984), Prichonnet et al. (1984), Bouchard and Martineau (1985). Prichonnet and Beaudry (1990) have described a sequence of four Wisconsinan ice flows. They relate the different ice flows to the migration of the Mistassini Ice Divide, as defined by Dyke and Prest (1987), from an area located to the northeast of Desmaraisville (Fig.2.2) toward Nouveau-Québec (Veillette and Pomares, 1991). In the Radisson area, only a west-southwest ice flow direction has been identified (Hardy, 1976; Vincent, 1977; Vincent et al., 1987; our data). In both sectors, the moraines are associated with the latest stages of deglaciation, and are therefore perpendicular to the latest ice flow directions which were southwest and west-southwest in the Chapais area and west-southwestward in the Radisson area.

GEOMORPHOLOGY OF THE STUDIED MORAINES

MORAINES OF THE RADISSON AREA

The moraines of the Radisson area have been called *annual moraines* by Shaw (1944) and *De Geer moraines* by Vincent (1977). They constitute series of parallel segments 30 to 900 m apart, with an average of 190 m. This spacing was measured on the surficial deposits maps of Vincent (1985a and b). Their height varies from one to ten meters, however the moraines are often partially buried under more than a meter of marine clay. Vincent (1977) has observed that the moraine widths vary from 5 to 150 m and their length from 50 to 1 500 m. According to this author (ibid., p.5 and 12), alignments of moraines many kilometers long would correspond to frontal positions of the retreating Nouveau-Québec Glacier. Another feature observed on the surficial deposit maps of Vincent (1985 a, b) is that the series of moraines is discontinuous. They form patches of moraines interrupted by areas of significant bedrock exposure.

The moraines of three sectors located north and south of Radisson have been mapped in detail (Fig.2.3a, b and d; for location see Fig.2.2). Although their morphology may at first seem regular, most of the moraines are chevron-shaped; the segments form angles lateraly. A few other moraines have appendages oriented at an angle or perpendicular to the main segment. These appendages seem to be contemporaneous with the emplacement of the main segment since no deformations or truncations were observed. Such a truncation of De Geer moraines by a frontal moraine emplaced during a readvance was mapped in Norway by Larsen et al. (1991). Another morphological feature illustrated in Figure 2.3c is the upglacier curve of the moraines in steeply sloping areas. This was also noted by Vincent (1977) north of La Grande Rivière.

MORAINES OF THE CHAPAIS AREA

The moraines of the Chapais area have been named *wash-board moraines* (Mawdsley, 1936), *annual moraines* (Norman, 1938; Shaw, 1944) and *De Geer moraines* (Martineau, 1984; Bisson, 1987; De Corta, 1988; Beaudry, 1988; Beaudry and Prichonnet, 1991). The moraines form a series of successive segments spaced at intervals between 15 and 550 m with an average of 180 m. This spacing was determined from aerial photographs and surficial deposit maps, and was measured perpendicular to the crest. Their height, measured in the field, varies from 1 to

15 m, but these landforms are often partially covered by glaciolacustrine clay (up to three meters) and/or by sand and gravel from an offlap sequence (0.5 to 1.5 m), so that the crests generally emerge from the deposits by 3 to 6 m. Their width varies from 5 to 100 m and their length from 20 to 1 400 m. Although some segments are perfectly aligned with others, reaching a total length of four to five kilometers, the spatial distribution of the moraines is often irregular. The moraines may be short and closely spaced, or also of variable length and separated by larger distances between crests (Beaudry, 1988, fig.2.5).

The external geometry of the moraines is variable (Fig.2.3d and e). Some segments are straight, whereas others are chevron-shaped or crescent-shaped. Most of the moraines observed in the field and on air photographs are in fact chevron-shaped and, as pointed out by Prichonnet et al. (1984, fig.17), the moraines seem to be composed of coalescent segments forming angles of around 25°. Many moraines consist of a main segment with perpendicular or oblique appendages. Field observations show that these appendages and the main segments were emplaced contemporaneously. No evidence of truncation or deformation were found. A section was also cut at the junction of a moraine and an appendage, and no deformation was observed in the primary sedimentary structures. Moraines forming a grid network have been identified north of Lake Opémisca (Fig.2.3d). At this locality, a few main segments are joined by an appendage that is parallel to ice flow.

Mawdsley (1936) also identified such a moraine network in the study area, and Strömberg (1965, fig.6) mapped a similar network in the Vänge area, in Sweden.

Most of the moraines in the Chapais area are perpendicular to the major southwestward ice flow. In some areas, the orientation of moraines was measured and compared to the orientation of striations. The moraines are generally perpendicular to the latest ice flow, although in two sectors, northwest of Lake Opémisca and southeast of Chapais (Fig.2.3e), the general orientation of the moraines is not perpendicular to the southwestward ice flow. The moraines have a north-northwest to south-southeast orientation. Striation measurements northwest of Lake Opémisca demonstrate prevalent ice flows towards the west-southwest during the emplacement of the moraines (Prichonnet and Beaudry, 1990). Southeast of Chapais (Fig.2.3e), no striations were measured, but the orientation of one of two short esker segments suggests that, here again, the moraines are perpendicular to the ice flows that prevailed when they were formed. Thus, the moraines could probably be used to evaluate the general direction of the ice flows that prevailed during deglaciation, and could be of considerable interest for ore-boulder tracing.

SPATIAL RELATIONSHIP WITH OTHER GLACIAL LANDFORMS

Relationship with drumlins

De Geer moraines cut drumlins at an oblique or perpendicular angle in both sectors (Figs.2.3a, b, c and 2.4; for location see Fig.2.2). Figure 2.5 (see Fig.2.2) illustrates the drumlins and De Geer moraines from a 5,200 km^2 surface of the Radisson area. De Geer moraines are lacking west of the Sakami Moraine whereas drumlins are numerous. Drumlin density is 26 drumlins/100 km^2. By contrast, east of the Sakami Moraine, De Geer moraines are abundant and the drumlin density drops to 4 drumlins/100 km^2.

In the Chapais area, another situation is observed. Near the eastward limit of Glacial Lake Ojibway, 45 km southeast of Chapais, the drumlin density calculated from the surficial deposit map of De Corta (1984), is 36 drumlins/100 km^2 and De Geer moraines are scarce. Thirteen kilometers east of Chapais the drumlin density, reported on the surficial deposit map of Bisson (1987), drops to 20 drumlins/100 km^2 whereas De Geer moraines are more numerous. West of Chapais, the drumlin density has not been calculated, but field observations show that these landforms are much less frequent while De Geer moraine density increases. Therefore the drumlin density decreases toward the interior of the Glacial Lake Ojibway basin whereas De

Geer moraines become more common.

Variations in the morphology of De Geer moraines when they cross drumlins have been discussed by Hardy (1976, fig.10). In some areas, he observed that the moraines are poorly formed and lie directly over the drumlins. Elsewhere, the moraines are more prominent and the sediments that constitute the drumlins seem to have been reworked to the point that the drumlins have been almost totally re-shaped.

In the sectors studied, the transition between drumlins and De Geer moraines (Figs.2.3a, b and c and 2.4a and b) is not the same as that which was observed by Hardy (1976). Near Radisson, the drumlins cut by De Geer moraines have a deformed outline (Fig.2.3a, b and c). The drumlins that are not cut by De Geer moraines keep their typical outline. In Figure 2.3a, a drumlin truncated just upglacier of a De Geer moraine has been observed on a large scale air photograph. The morphology of this drumlin clearly suggests that part of its sediments were remobilized by the glacier to form the local De Geer moraine. A similar phenomenon has been observed near Chapais (Fig.2.4a). Most of the moraines are located over areas where a drumlin appears to be deformed. A few situations where moraines are lying on the uplacier extremity of drumlins have been observed (Fig.2.4b). This portion of the drumlin appears to be truncated, and its material seems to have been pushed downglacier.

Prichonnet et al. (1984) observed push structures in the ablation till forming the surficial portion of a drumlin located 22 km east of Chapais. This till contains folded laminations of sand and silt. The identification of these structures and other stratified diamictons (Prichonnet, 1984, fig.11) suggest that the glacier was still active at the latest stages of deglaciation, when De Geer moraines were formed. This is also emphasized by the description of many push structures (folds, thrust faults) in moraines composed of stratified sediments (Beaudry and Prichonnet, 1991, Figs.1.3, 1.4, 1.5, 1.6 and 1.8).

The observations made in both sectors studied along with the data of Hardy (1976), Prichonnet (1984) and Prichonnet et al. (1984) might indicate that the sediments from many drumlins have been reworked by the glacier resulting in the development of a series of De Geer moraines.

Relationship with eskers

A few eskers cross the zones where De Geer moraines are numerous in both areas. Figure 2.3e illustrates a particular relationship between a one kilometer long esker segment, having a east-northeast/west-southwest orientation, and De Geer moraines. The forests were cut several years before the pictures were taken so that detailed mapping was facilitated on large scale air photos. On the figure, De Geer moraines appear to cut the esker. But detailed observations showed that the outline of the esker seems to be the result of the coalescence of a series of at least seven De Geer moraines. The crest of the esker is sharp but its slopes are undulating where the moraines cut the landform, and the moraines do not appear to have been deposited on the surface of the esker.

In a locality 27 km north-northwest of Chapais, close to the Chibougamau River, the orientation of the moraines differs from what is normally observed. At this site, the moraines are almost north-south because they curve upglacier toward an esker which is oriented east-west. This modification in the disposition of the moraines near eskers was previously identified in the Chapais area by Norman (1938) and has since been reported: in Nouveau-Québec (Prest, 1968), Norway (Sollid and Carlsson, 1984), and in Finland (Zilliacus, 1984, 1987a and b).

Relationship with Rogen moraines

Near Chapais, De Geer moraines are numerous and they exhibit the morphological characteristics described in the introduction since they form series of narrow and elongated ridges parallel to one another. Thirty kilometers east of Chapais, near the eastern limit of Glacial Lake Ojibway, De Geer moraines become more massive and they grade into Rogen moraines outside of the glacial lake basin

(De Corta, 1984).

Figure 2.6a illustrates the glacial landforms of a 60 km^2 area located 40 km south-southeast of Chapais (for location see Figure 2.2). The central depression of this area is occupied by Lake Caopatina. During deglaciation, the ice flowed toward the southwest. Transitional landforms between Rogen moraines and De Geer moraines have been mapped in detail. The terrain slopes toward the southwest and De Geer moraines are located on the upglacier side of the basin. These moraines are narrow and elongated and are oriented oblique to the local ice flow as shown by the orientation of the drumlins. Rogen moraines are located on the downglacier side of the basin where the terrain slopes toward the northeast. They are large and elongated, oriented transverse to ice flow, and have horns pointing downglacier. They also have a very characteristic feature of Rogen moraines since they are associated with drumlins located west of Lake Caopatina (Lundqvist, 1989; Bouchard, 1989). In the framed area located east of the Rogen moraines, another type of minor moraine has been mapped (Fig.2.6b). It does not have the characteristic morphological features of Rogen moraines or De Geer moraines. It is believed here that this type of minor moraine has not been previously described but no name is attributed to it in order to avoid complicating the minor moraine nomenclature. The most characteristic morphological feature of these minor moraines is that they are composed of segments pressed on one another. The individual segments of the landform appear to be similar in form to De Geer moraines, since they are narrow and elongated. Each segment has a very sharp crest and the moraines can be composed of up to three segments roughly parallel to one another. Their morphology and their transitional position between Rogen moraines and De Geer moraines suggest that they could correspond to De Geer moraine segments that were pushed into clusters. The geometry of the basin could have enhanced extensive flow where De Geer moraines are found and compressive flow where Rogen moraines are located. The transitional landforms could then represent the change from an extensive flow to a compressive flow.

DESCRIPTION OF THE FACIES AND INTERNAL STRUCTURES

In the following section, several terms are used to distinguish sediment types. A few of them are defined to avoid confusion. Diamicton is a descriptive word applied to a poorly sorted sediment composed of many size fractions. It may be nonsorted as in till (Dreimanis, 1982, 1988), but it may also have been partially or almost totally winnowed of its fine particles by water. Till is a nonsorted "sediment that has been transported and deposited by or from glacier ice, with little or no sorting by water" (Dreimanis, 1988, p.34). Till may also be described as a nonsorted sediment, compact or loose, fissile or non-fissile, occasionally containing lenses of sorted sediments, with striated clasts and boulders, that has not undergone significant sorting by water. The term till is used here in the context just defined and its use is based on detailed field and laboratory analysis. The term basal till is applied to the regional till sheet that may have been deposited by the action of active ice flow. Waterlain till corresponds to a sediment deposited directly by the glacier, but in water (Dreimanis, 1979). It has all the characteristics of a till, but its fine particles were washed out.

De Geer moraines were emplaced in glaciolacustrine or marine basins. When the water retreated either because of the isostatic uplift (Tyrrell Sea) or the northern drainage of Glacial Lake Ojibway, part of the sediments were reworked by wave action. These reworked sediments were deposited on the slopes of the moraines so that units of stratified sediments were emplaced. These units are referred to as the offlap sequence which generally has a maximum thickness of about one meter and pinches out toward the moraine crest; often it begins with a thin layer of sand grading into gravelly to bouldery coarser material. In many cases, these units are entirely composed of gravel. The coarsening upward sequence was caused by increasing wave energy as the water level decreased.

About 60 exposures were examined in the field in various degrees of detail, but only the moraines presenting significant data are discussed here. Three major facies associations have been recognized (Table 2.1). This distinction is based on their sediments, internal structures and their spatial relationships.

FACIES 1

The first facies corresponds to moraines composed of sorted sediments in proportions varying from 80 to 100%. This facies has been described and interpreted by Smith (1982) and by Beaudry and Prichonnet (1991). Thus, only its most important characteristics are described herein.

The moraines presenting this facies usually form a series of up to 15 successive segments parallel to one another, but they may also be found as isolated forms. In the Chapais area, it is estimated that this facies may represent about 15% of the De Geer moraines. In the Radisson area, no such estimate is possible because exposures are rare.

The sediments are stratified and the laminations always dip downglacier and extend perpendicular to the moraine axis (Fig.2.7a, b, c and d; for detailed data, see Beaudry and Prichonnet, 1991, Tables 1.1 and 1.2). In some sections, parts of the laminations are cut by thrust faults and modified by overturned to recumbent folds (Figs.2.7a, b and d). These deformation structures are generally limited to the uppermost proximal portion of the sections but in some cases deformation structures extend over the entire exposure. Several fault planes and axial planes of folds were measured and they all dip upglacier, perpendicular to the moraine axes. The thrust faults show translocation downglacier. Some sections contain diamicton and/or till on their proximal side (Fig.2.7a and b), forming lenses that were injected upwards in the stratified sediments or deposited as a surficial sheet thinning toward the central portion of the sections.

Lithological composition

Three petrographic analyses (417 to 809 clasts) were carried out on the moraines of Figure 2.7a (see also Beaudry and Prichonnet, 1991, Fig.1.6C). The samples were taken in different parts of the section, one from the till lens and two from the diamicton. The diamicton samples are located downglacier from the till lens, one at the same level as the till sample, in a younger unit than the till lens, and the other near the surface of the section in a unit younger than the two previous ones. The results show that volcaniclastic debris of a local origin predominate, but their proportion diminishes (whereas the proportions of granites and gneiss increase), from the till lens to the upper diamicton unit which proves that the clasts have been transported from longer distances.

FACIES 2

The second facies is represented by a non-fissile and loose till. Most of the observed sections expose this facies. This type of till occupies 75 to 100% of the sections while stratified fine or coarse sediments may form up to 25% of the entire surface. The till is sandy and its texture is similar to the underlying basal till, but it can be distinguished from the latter by its poor compactness and the absence of fissility. It contains striated boulders and clasts. Lenses and pockets of sorted sediments are frequent, but most of the moraines are structureless. Two of those sections are presented herein (Fig.2.8a and b).

Section 1

The first section is illustrated in Figure 2.8a. This section was cut in a moraine located 25 km west of Chapais (for location, see Fig.2.2 and MO1A in Fig.2.4). It can be separated into four principal units.

Unit A is formed of a compact and fissile till containing striated clasts and rare laminations or lenses of sorted sediments. This till is interpreted as being part of the regional basal till and it is overlain by unit B. The contact between units A and B is sharp.

Unit B is composed of stratified silt and fine sand of a thickness varying from 0.2 to 1.4 m. Ripple marks were identified in the fine sand. Paleocurrents measured on laminations of these ripple marks show that meltwaters flowed downglacier. On the distal side of the exposure, the entire unit B is folded. The fold curves upwards, and it partially envelops the upper units. Under a large boulder, the laminations of unit B are deformed by load and drag structures. This is shown on Figure 2.8a by the variation in thickness of unit B (from only 0.2 m upglacier to 1.3 m downglacier). The fold was probably formed by the bulldozing effect of the glacier during its forward flow.

Unit B is overlain by unit C and their contact is gradational, from a fine sand to a gravelly diamicton. The thickness of unit C may be as little as a few centimeters, so that it can be seen only on the right side of the section. The gravelly diamicton is partially winnowed of its fine particles.

Unit C grades into unit D which is a till. This till may be distinguished from the basal till of unit A by the absence of fissility and its poor compactness. It contains very small pockets of material winnowed of fine particles, which are concentrated in the lower part of the unit.

The sides of this section are covered by a unit of sandy gravel, absent over the crest but increasing in thickness away from it, to about one meter. This unit is part of the lacustrine and younger offlap sequence and it truncates all the underlying units, especially on the distal side of the section where the laminations of unit B curve upwards. The truncation explains why the folds are not complete. In Figure 2.8a, this truncation is hidden by organic material.

Section 2

The second section is illustrated on Figures 2.8b and 2.9. This section was exposed in a moraine located 42 km southeast of Radisson (for location, see Fig.2.2). It can be separated in two main units: a grey till and a complex unit consisting of four sub-units incorporated in the grey till (Fig.2.8b).

At the base, the grey till is poorly compacted and non fissile. It contains dispersed striated clasts and a few laminations of sorted fine sand. These laminations are deformed and all dip upglacier. The contact between the grey till unit and the stratigraphically younger unit is sharp but irregular. This contact forms a recumbent syncline.

The second unit may be separated in four sub-units. A typical sequence of these deposits includes (Fig.2.9a): (1) a reddish till 20 cm to one meter thick. It contains striated clasts, is compact and fissile and it may have a finer texture than the grey till (Fig.2.9b); (2) 25 cm of silt; (3) 10 cm of laminated sand which is folded and sheared. The axial planes of the folds are sub-horizontal. The shear plane dips upglacier and shows translocation downglacier (Fig.2.9c); (4) a gravelly diamicton. This diamicton extends to the downglacier portion of the section where it contains sub-horizontal laminations of sorted sediments.

This sequence is contained within the syncline formed by the grey till and it follows the contour of this syncline. Several features point toward an upglacier origin for those sediments: (a) the upglacier dip of the fine laminations incorporated in the grey till; (b) the similar dip of the shear plane measured on the normal face of the syncline and; (c) the evidence of translocation downglacier along this shear plane. This means that the upper face of the syncline was overturned on top of the sorted sediments of the second unit. The red till is interpreted as an allochtonous raft coming from an area located upglacier, where red quartzite outcrops are located.

Similarities between the two sections and interpretation

The two described sections show similar sequences, however the sequence described in the Chapais area is covered by till while the sequence of the Radisson area is covered by diamicton. This difference is not significant since it can be explained by the types of deformation structures: (1) in the first moraine, the sorted sediments that form a syncline partly envelop the upper till (Fig.2.8a); (2) in the second moraine, the till is deformed into an overturned syncline allowing the till to envelop the sorted sediments (Figs.2.8b and 2.9a). This difference could also be explained by the hypothesis that the red till and the overlying sub-units of the moraine of the Radisson area are part of an allochtonous raft incorporated into the grey till.

The coarsening upward sequence described herein is not an exception. It was observed in several other moraines of the Chapais area. In the Radisson area, the exposures are too rare to know the extent of this type of sequence in other moraines. The coarsening upward and the gradational contacts between the units of this sequence, except with the underlying basal till, indicate a diminishing influence of flowing meltwaters and an increasing influence of the glacier. That this glacier was active in the late stages of moraine formation is evidenced by the types of deformation structures: load and drag structures in the intercalated sorted sediments, deformation of the laminations incorporated in the till and folds and thrust faults in the sorted sediments.

Lithological composition

Four pebble counts (0.8-5 cm; 5-15 cm) allow a comparison between the till composing moraines of facies 2 and the underlying basal till (Table 2.2). Five lithological classes have been distinguished: (1) volcaniclastic rocks; (2) Opémisca Pluton granitic rocks; (3) gneiss and other granites; (4) sedimentary rocks of the Mistassini Group; (5) other clasts. The volcaniclastic rocks underlie the moraines while the other lithologies are located more than 13 km to the northeast (Gobeil and Racicot, 1983). Note that in the 5 to 15 cm fraction, the gneiss and other granites also include the rocks from the Opémisca Pluton.

Two classes of lithologies are dominant (Table 2.2): the volcaniclastic rocks (64.4 to 91.3%) and the gneiss and other granites (7.1 to 27.8 %). The sedimentary rocks are found only in very small quantities (less than 1.9%). In Table 2.2, the values of the first two classes are presented with brackets, calculated at a confidence level of 95% (±). These brackets are used to indicate if the difference between the samples are statistically significant. The width of the brackets vary with the total clast content of the samples. Samples containing large amounts of clasts give low values for the brackets. Thus, the differences observed between the pebble counts of all four moraines are not statistically significant. Consequently, the basal till and the till from the moraines are believed to have the same lithological composition. In three moraines, pebble counts were carried out on two fractions. In these cases, it appears that the fractions of 5 to 15 cm always contain more volcaniclastic clasts than the 0.8 to 5 cm fractions. The difference is not important, but it is consistent from one moraine to the other. This points to a low maturity of the sediments.

Till fabrics

Five till fabrics have been measured in the moraine of Chapais area (Fig.2.10) and two in the moraine of Radisson area (Fig.2.9d, for location of the till fabrics, see Figure 2.8a and Figure 2.9a respectively). The A and C axes of fifty prolate and bladed clasts were measured in each fabric, on a vertical face of 15 by 75 cm. Statistical evaluation of the data has been carried out according to the method proposed by Mark (1973, 1974). These fabrics show that A axes have no preferential orientation: their eigenvalues (S1) vary between 0.451 and 0.557 (Table 2.3). In Figure 2.10, the dip of the measured clasts is generally low and they show a weak concentration oriented parallel to ice flow and another perpendicular to ice flow. In Figure 2.9d, the dip of the measured clasts his higher, but there is no preferential orientation. The C axes are better oriented with eigenvalues (S1) between 0.571 and 0.831.

FACIES 3

The third facies is represented by a fissile and compact till. Around 10% of the observed cross-sections have shown this facies. Sorted sediments may occupy up to 40% of the exposures, but they may also be limited to very thin laminations incorporated in the till, thus forming less than 1% of the section. The texture of the till is similar to the underlying basal till. It is sandy, compact and fissile and it contains striated clasts. The laminations of fine sorted sediments incorporated in the till and the primary sedimentary structures of the sorted sediments underlying the till of the moraine are deformed. One section is presented here (Fig.2.11a).

This exposure is located 38 km west of Chapais (Fig.2.2). The section was cut in a moraine parallel to the moraine of Figure 2.7b. The two sections are separated by a distance of 200 m. The section of Fig.2.11a can be separated into four units.

The first unit is formed of a compact and fissile till with a sandy texture (Fig.2.11a and b1). It contains striated clasts. No laminations of sorted sediments were observed in this till. It is interpreted as being part of the regional basal till.

A sand lens overlies the first unit (Fig.2.11a and b2). The contact between the two units is sharp. The sand lens occupies 40% of the exposure. It is bevelled on the proximal side and it becomes thicker below the crest of the moraine where it has a thickness of 1.2 m. This sand lens is stratified and its primary sedimentary structures are deformed by small folds. An axial plane measured in the folds dips upglacier (Fig.2.11c). On the distal side of the moraine, this unit is replaced by a gravelly diamicton not shown on Figure 2.11a. The transition between the sand lens and the gravelly diamicton has not been observed. The upper portion of the sand lens contains till pebbles.

The sand lens grades into a unit identified as a waterlain till of variable thickness (up to 70 cm), thus forming a gradational contact. The sediments of this unit have a coarser texture than the underlying basal till (Fig.2.11a and b3). It is compact and contains striated clasts. It seems to be somewhat deficient in fine particles, which suggests that it was probably deposited in water. Those characteristics are typical of a waterlain till (Dreimanis, 1979).

Finally, the waterlain till grades into a upper unit of compact and fissile till having a similar texture to that of the underlying basal till (Fig.2.11a and b4). The till of the upper unit contains striated clasts, but no laminations of fine sorted sediments. The lower face of this unit and of the waterlain till dip upglacier (Fig.2.11c).

Lithological composition.

Two pebble counts (0.8-5 cm; 5-15 cm) allow a comparison of the lithological composition of the till forming the moraines of facies 3 with the underlying basal till (Table 2.2). Two classes are dominant: the volcaniclastic lithologies (64.4 to 74.2%) and the gneiss and other granites (19.9 to 33.2%). In the fraction of 0.8 to 5 cm, for both moraines, the till of the moraine contains significantly more volcaniclastic lithologies than the underlying basal till, this being calculated at a confidence level of 95% (±). The bedrock underlying those moraines being composed of volcaniclastic rocks, this shows that the moraines containing this facies are composed of a till having a more local origin than the underlying basal till. A moraine containing locally derived debris has also been observed in the area of Lake Scott, east of Chapais (Bisson, 1987). This aspect should be investigated further because of its obvious relevance to mineral exploration.

Although the till of the moraine is composed of more locally derived debris than the underlying basal till, its composition follows variations in that of the basal till. This is highlighted by the comparison of the lithological composition of the pebble counts of moraines MO5 and MO6 (for location of the sections, see Fig.2.4). The exposures were cut in two moraines parallel to one another and the sections are separated by a distance of 230 m. The lithological composition of the basal till in these sites is quite different (Table 2.3). In the area adjacent to moraine MO5, the local lithologies are dominant in the basal till (0.8-5 cm, 83.9%; 5-15 cm, 85.5%) while the basal till near moraine MO6 contains fewer local clasts (0.8-5 cm, 66.5%; 5-15 cm, 72.3%). At both sites, similar variations are observed in the lithological composition of the till coming from the moraines. Thus, variations can be observed in the origin of the basal till over short distances, and the till composing the moraines tends to have similar variations in its lithological composition.

Till fabric.

One till fabric has been measured in the moraine of Figure 2.11a. The A axes of the measured clasts preferentially dip upglacier (Fig.2.11d). The calculated eigenvector for the A axes is parallel to the last ice flow (V1 = 035°/12.0°) and its eigenvalue confirms the strong clustering of poles around this value (S1 = 0.831). The C axes of the measured clasts are perpendicular to the ice flow (V1 = 325.7°/81.3°; S1 = 0.876). The clasts incorporated in the till of this moraine thus show a preferential orientation in the direction of ice flow, thus meaning that this till formed under an active glacier.

RELATIONSHIP BETWEEN FACIES

The spatial distribution of the three facies identified show that they grade into one another. Figure 2.4a is a surficial deposit map on which a series of at least 15 successive moraines composed of sediments of facies 1 can be recognized (glaciofluvial sediments). This series is parallel to the direction of ice flow and Beaudry and Prichonnet (1991, Fig.1.2A) showed that it may be associated with an esker system located about 5 km in a downglacier direction.

The section illustrated in Figure 2.7a was dug in a moraine from this series (see MO2 in Fig.2.4a). In this moraine, water played an important part in the emplacement of the landform in which sorted sediments form 80% of the section. The section of Figure 2.8a shows a facies arrangement typical of facies 2. This section is located 200 m north of the previous exposure (see MO1A in Fig.2.4a). Here, the sorted sediments only form 25% of the section and the till is not fissile and is poorly compacted. Finally, another moraine located 225 m further north from the previous one (see MO6 in Fig.2.4a) is entirely composed of a compact and fissile till typical of facies 3. This moraine is located at an elevation about 10m higher than the two previous ones.

This facies relationship shows that meltwaters were probably concentrated in a sheet whose width corresponded to the length of the moraines that are part of the series of glaciofluvial moraines. Laterally, as we go to facies 2, water played a less important part as is shown not only by the smaller proportion of the section occupied by sorted sediments, but also by the texture of the sorted sediments which are coarser in facies 1 than in facies 2. As we go even further from the series, meltwaters do not seem to have been present in significant amounts. This is shown by the absence of sorted sediments in moraine MO6.

THE PROPOSED MODEL

The model proposed here is illustrated on Figure 2.12. Part of this model has been presented in an earlier paper discussing of De Geer moraines composed of stratified sediments (Beaudry and Prichonnet, 1991, Fig.1.11). It is proposed that series of De Geer moraines were emplaced simultaneously into bottom crevasses located up to a few hundred meters behind the ice front. The present model is more complete since it encompasses all three facies, but it is only applied to the moraines studied. No attempt is made to propose a model that could explain the genesis of all De Geer moraines since it is recognized here that different processes may lead to the development of similar landforms.

GENERAL GLACIAL CONTEXT

Deglaciation in the Chapais area occurred around 8300 BP (Hardy, 1976). The Nouveau-Québec Glacier was then in contact with Glacial Lake Ojibway (Fig.2.2). Norman (1938) established the maximum lake level at 438 m near Chapais, Ignatius (1956) proposed a level of 427 m southwest of Chibougamau, while Prichonnet et al. (1984) suggested a level of at least 445 m east of Chibougamau. The site studied by Norman (1938) is located west of Lake Opémisca and is thus nearer the moraines described herein. The depth of Glacial Lake Ojibway would then have been about 80 m when these moraines were emplaced.

In the Radisson area, deglaciation would have proceeded with ice being in contact with Glacial Lake Ojibway when the ice front was west of the Sakami Moraine position and in contact with the Tyrrel Sea east of the moraine (Fig.2.2). The moraines of the Radisson sector developed when the Nouveau-Québec Glacier was in contact with the Tyrrell Sea whose minimum depth varied from 55 m over topographic highs to 115 m in valleys (Vincent, 1977). No De Geer moraines were apparently deposited west of the Sakami Moraine. Lake Ojibway was probably too deep for the moraines to be emplaced (Hardy, 1976; Vincent, 1977). In fact, Hardy (1976) proposed that no De Geer moraines were deposited in areas where the lake was deeper than 180 m.

GENESIS OF THE MORAINES STUDIED

Opening of the bottom crevasses

The Nouveau-Québec Glacier was in contact with large bodies of water such as Glacial Lake Ojibway or the Tyrrell Sea. It is expected that the glacier terminus would be somewhat buoyant. Seasonal increases in water levels or tides could have engendered even more buoyancy. This buoyancy would have caused an increase in the tensile stress at the glacier grounding line. Herterich (1987, fig.11) presented a model where the stresses were calculated over the entire ice column within the transition zone between a grounded glacier and an ice shelf. Behind the grounding line, the buoyancy would cause compressional stresses near the glacier's surface and tensile stresses near the base of the glacier. Using this model, Herterich predicted that, in response to those tensile stresses, open bottom crevasses should be created behind the grounding line.

Bottom crevasses forming in this context have been identified inside Ice Stream B and the Ross Ice Shelf, in Antarctica by Jezek and Bentley (1979, 1983). These authors have demonstrated the existence of a system of crevasses perpendicular to ice flow and a second system of smaller crevasses crosscutting the first. Jezek and Bentley (1983) suggested that the crevasses are caused by the effect of tension in the ice, related to its buoyancy or by shear stresses between fast moving outlet glaciers feeding zones of slower moving ice.

It is proposed that the opening of bottom crevasses in the Nouveau-Québec Glacier, fringing a large body of water, would have been caused by the buoyancy of the glacier terminus. The series of bottom crevasses would have opened, behind the grounding line, in response to the basal tensile stresses such as those predicted by Herterich's (1987) model. Seasonal variations of water levels in Glacial Lake Ojibway or tidal variations in the Tyrrell Sea would enhance this process. It is even possible that these variations in water levels would be the main process responsible for the increase in tensile stresses necessary for the opening of the series of bottom crevasses. It is believed here that the glacier was under an extended flow regime rather than a compressive flow regime since the latter would have closed the crevasses.

The geomorphology of the moraines and their spatial distribution may be explained by deposition in a system of bottom crevasses rather than by emplacement at the ice front. The development of angularity in the principal moraine segment (Prichonnet et al., 1984, fig.17; Figs.2.3 and 2.4), of oblique to perpendicular appendages and of a grid net pattern (Fig.2.3d) would be the result of the original spatial distribution of the crevasses. Jezek and Bentley (1979, fig.10) have identified such patterns in the bottom crevasses of Ice Stream B in Antarctica. Beaudry and Prichonnet (1990) stressed that the moraines composed of stratified sediments had to have formed in bottom crevasses. It is believed that if the moraines had been emplaced at the ice front, they would not have produced sharp crested moraines such as the ones described herein. It is expected that the sediments would rather have formed small linear accumulations extending in the direction of the ice flow in the same manner as the large eskers of the area (Prichonnet et al., 1984). The morphology of the short esker of Figure 2.3e suggests that it resulted from the coalescence of a series of De Geer moraines forming simultaneously in at least six successive bottom crevasses. The length of this esker also suggests that crevasses opened at least up to a distance of 1 km behind the ice front.

The transition between De Geer moraines and Rogen moraines in the area of Lake Caopatina also supports a genesis in bottom crevasses. Here, however, the crevasses would have been formed by a different process, that is extensional crevasses. In Figure 2.6, De Geer moraines are located on the upglacier extremity of a depression where extended flow should have occurred (Sugden and John, 1976). The transition from an extended flow to a compressive flow regime produced transitional landforms and, eventually, under compressive flow, Rogen moraines were formed. Bouchard (1980, 1989) proposed that Rogen moraines of the area were emplaced by "stacking of slices of debris-laden ice" (Bouchard, 1989, p.303). In the particular case of Figure 2.6, those slices seem to have been composed of De Geer moraines formed into bottom crevasses opened under an extensive flow regime and subsequently deformed under a compressive flow regime. This situation where De Geer moraines seem to have been formed into crevasses opened under an extensive flow regime is rare but it is not exceptional. Figure 2.3c shows De Geer moraines curving upglacier near a steep slope. This slope may have caused extended flow and the subsequent opening of bottom crevasses. In the two examples just described, the moraines are not perpendicular to the ice flow determined by the surrounding drumlins. They are in fact oblique to the ice flow, a pattern expected for crevasses forming under extended flow (Vornberger and Whillans, 1990, fig.7).

Emplacement of the moraines into bottom crevasses

The proposed emplacement of the moraines is based on the facies analysis and on their spatial distribution. Beaudry and Prichonnet (1991) have suggested that De Geer moraines composed of sediments from facies 1 were formed into bottom crevasses, in areas where meltwaters were channelized. Those meltwaters probably flowed into subglacial channels and/or through small conduits into the lower column of ice. This could correspond to the linked cavity system of Fowler's theory (Kamb, 1987; Fyfe, 1990). The subglacial channels could also correspond to the ones presented in the model of the drainage system, inside the ablation zone of the ice sheet, proposed by Brodzikowski and Van Loon (1987, fig.17; 1991, fig.133). The width of those channels probably corresponded to the length of the moraines forming these series. For example, in Figure 2.4, the width of the channel where De Geer moraines composed of glaciofluvial sediments were emplaced must have been at least 400 m. The subglacial channels were probably located in low-lying areas since it is mostly there that the series are found. The subglacial channels were probably too small and the sedimentation phase too short to allow the formation of a continuous esker such as the one identified 5 km downglacier from the series of moraines of Figure 2.4 (Beaudry and Prichonnet, 1991, Fig.1.2A). But in other cases, the sedimentation phase was long enough for the moraines to coalesce into an esker (for example see Fig.2.3e).

The present model proposes that meltwaters flowed perpendicularly to the elongation of the crevasses as evidenced by the stratification. Before entering the crevasses, the meltwaters flowed under pressure and thus transported a load of sediments. When it entered into the crevasses, the velocity of the flowing meltwaters was diminished. This allowed the deposition of sorted sediments into foreset laminations generally dipping downglacier (Beaudry and Prichonnet, 1991, Fig.1.11A). The meltwaters probably escaped downglacier, through a subglacial channel. Since the ice was active, the pressure again increased and coarse sediments were transported to the next crevasse located downglacier. Sorted sediments then accumulated simultaneously in series of parallel crevasses, in a downglacier direction, thus forming series of De Geer moraines composed of stratified sediments (Fig.2.4). The sedimentation phase probably ended upon migration of the subglacial channels, their closure by ice activity or upon calving of that section of the glacier.

During the sedimentation phase or shortly after, the glacier still being active, the upglacier wall of the crevasse probably came into contact with the morainic sediments. This together with the forward movement of the glacier partially deformed the primary sedimentary structures. Till and/or diamicton were then deposited as a surficial cover on the proximal side, or as lenses injected into the sorted sediments. This model is different from the one of Smith (1982) who proposed that similar moraines were formed by bulldozing at the ice front.

Laterally from the subglacial channels, in areas where meltwater activity was decreasing, less debris could be sorted and the glacier squeezed moraines composed mainly of till (Fig.2.12b and c). Those moraines correspond to facies 2. Near the subglacial channels, or in areas where meltwaters flowed as thin sheets, fine sediments accumulated into horizontal laminations inside bottom crevasses, thus covering the basal till (Fig.2.8a). These laminations have the characteristics of sediments deposited in more or less stagnant water (Brodzikowski and Van Loon, 1987). When, subsequently, the glacier came into contact with the bed, a surficial layer of the basal till was deformed and remobilized. This till was transported in a downglacier direction, toward basal crevasses. When the till began accumulating in the crevasses, the influence of meltwater decreased. This is shown by the vertical transition from sorted sediments occasionally containing till pebbles (Fig.2.11a), into a coarse diamicton winnowed of its fine particles, and into a true till (Fig.2.8a). The chaotic aspect of the till fabrics (Figs.2.9d and 2.10) show that this till was not emplaced in direct contact with the active glacier. As this loose till was deposited, the underlying sorted sediments were deformed by fold, load and drag structures. Here again, the glacier being active, more deformation (folds and thrust faults) occurred both in the sorted sediments and in the overlying till. This deformation was probably generated by the contact of the upglacier wall of the crevasse with the morainic sediments and this process stopped upon calving.

Till deformation has been inferred by seismic analysis of conditions at the bottom of Ice Stream B in Antarctica (Alley et al., 1986, 1987; Blankenship et al., 1986; Menzies, 1989). Hart and Boulton (1991) observed that subglacial deformation is not unusual. The thickness of till affected by the deformation processes may attain six meters. This till is interpreted to be water-saturated and plastic (water contents of up to 40% have been identified in areas recently uncovered by ice; Menzies, 1989).

Based on the till fabric data, it appears that the till was probably extruded into cavities. Analysis of the deformation structures demonstrate that the glacier was active and that the till was moving in the direction of ice flow.

This model may also explain the scarcity of drumlins in areas where De Geer moraines are numerous (Fig.2.5). Not all drumlins would have been deformed by the glacier to form De Geer moraines, but it clearly appears that some of them had their profile modified (Figs.2.3a and b, 2.4a and b). Also, some drumlins appear to have been truncated and their material pushed downglacier to form a moraine (see truncated drumlins of Figs.2.3a and 2.4b).

In other sectors meltwater activity was even less pronounced so that it had a minor effect. Here, moraines of facies 3 were emplaced. Some sorted fine sediments may have been deposited (Fig.2.11a), but till was more often deposited directly over the basal till. The mechanism of deposition for the till composing these moraines probably involved many processes (Fig.2.12). Part of this till could have been deposited by deformation and remobilization of the surficial portion of the basal till sheet as proposed for the moraines of the facies 2. However, the overconsolidation of the till and its fissility indicate subglacial deposition (Krüger, 1979). The subglacial deposition is also evidenced by the strong fabric (Fig.2.11d). These factors suggest an accumulation mechanism where lodgement and basal meltout predominated.

The emplacement of moraines into bottom crevasses may seem difficult to prove since it is often believed that those crevasses tend to close rapidly. But the formation of moraines composed of till has been identified inside bottom crevasses of the McBride and Plateau Glaciers in Alaska (Goldthwait, 1974; Mickelson and Berkson, 1974). Rhombohedral ridge patterns located in front of the Bråsvellbreen Glacier on Svalbard have also been related to a squeezing-up of till inside bottom crevasses (Solheim and Pfirman, 1985).

COMPARISON WITH OTHER MODELS

Several models have been proposed to explain the formation of De Geer moraines. In a detailed review of those models, Beaudry (1988) grouped them according to the area where the moraines were emplaced relative to the ice front: 1) in several papers, it was proposed that De Geer moraines were formed at the ice front or a few meters behind the ice front, where it was buoyed up by the hydrostatic pressure of the frontal water body; 2) other authors argued that the moraines were emplaced into bottom crevasses. All those models, except for the ones of Beaudry and Prichonnet (1990) and Larsen et al. (1991), were based mainly on geomorphology and on the analysis of till fabrics. Little attention was given to facies analysis. In the present model, the facies analysis is used to identify the processes responsible for the emplacement of the sediments and the processes active subglacially. The geomorphology also contributes to the explanation of the processes of formation, but it is mostly used in support of an emplacement into a series of bottom crevasses.

The proposed mechanism of crevasse formation differs from the model of Zilliacus (1987a and b, 1989). This author suggested that the crevasses opened during surges of the Scandinavian Glacier. In the Chapais and Radisson areas, no evidence of surges was identified in the sectors where De Geer moraines are found. The only known surges are the Cochrane and Rupert surges in the James Bay Lowlands (Hardy, 1976), and a surge following drainage of Lake Ojibway, at the south end of Lake Mistassini (Bouchard, 1980; Dilabio, 1981). It is believed here that the crevasses opened in response to the stresses caused by the buoying up of the glacier by the frontal water body, such as is proposed for Ice Stream B in Antarctica (Jezek and Bentley, 1979, 1983; Herterich, 1987).

The moraines described here could not have been formed by a short re-advance of the glacier's terminus (Andrews and Smithson, 1966; Smith 1982; Sollid and Carlsson, 1984; Larsen et al., 1991). Such a mechanism would have deformed all the primary sedimentary structures, especially in those De Geer moraines composed of stratified sediments. Instead, in the studied moraines, deformation structures are limited to the sediments located just below the crest and around injected lenses of till and/or diamicton. This suggests that the deformation structures resulted from a minor push by the upglacier wall of the crevasse.

The present model does not allow accumulation by flowage of water-soaked till toward the ice terminus (Hoppe, 1957, 1959; Loken and Leahy, 1964). The morphology of the moraines such as angularity in the segments, presence of appendages and grid-net patterns, rather suggests that the till flowed toward bottom crevasses in which the sediments have been moulded. In fact, the morphology of the moraines corresponds exactly to the reconstituted patterns of bottom crevasses inside Ice Stream B, in Antarctica (Jezek and Bentley, 1979, fig.10).

The hypothesis that the moraines were formed by accumulation, at the base of an ice cliff, of debris released by melting ice (Norman, 1938; Shaw, 1944; Holdsworth, 1973; Barnett and Holdsworth, 1974) can be rejected based on the facies data described above. Sediments falling from the ice cliff, into water, would probably have been sorted somewhat, which is not what is observed in the till forming most of the moraines. Those are composed of a till similar in granulometry and lithological composition to the underlying basal till. Moreover, material coming from higher positions in the ice column has usually been transported over longer distances than the material coming from a basal position (Shilts, 1976). The lithological composition of the studied moraines is in fact similar to the one of the underlying basal till and some moraines contain more local lithologies than the basal till (Table 2.2). This suggests that the sediments were derived from the basal part of the ice column.

The mechanism of moraine deposition proposed by Mawdsley (1936) for the Opawica-Chibougamau area cannot be applied to the moraines presented here. The primary sedimentary structures and the deformation structures imply genesis by remobilization of part of the till sheet and its movement toward bottom crevasses rather than accumulation of debris washed into open crevasses.

Andrews (1963a and b) and Andrews and Smithson (1966) suggested that their *simple-linear* and *S-shaped moraines* were formed by injection of water-soaked till into bottom crevasses. Their proposed mechanism is very similar to the one suggested here.

Zilliacus (1987a and b, 1989) suggested that the moraines were emplaced into bottom crevasses by flowage of till from both sides of the crevasses. He based his conclusions on the analysis of till fabrics showing that clasts dip in accordance with both slopes of the moraines. In the present study, all deformation structures (folds, thrust faults, load and drag structures) show that the till originates from the upglacier side of the crevasses only. This is also supported by the truncated drumlins of Figures 2.3a and 2.4b which suggest that the drumlins were deformed and their material transported downglacier to form a moraine.

DISCUSSION

In this section, two aspects regarding De Geer moraines will be discussed briefly: 1) the annual moraine problem; 2) the place of De Geer moraines in glacial landform successions.

THE ANNUAL MORAINE PROBLEM.

Much of the discussion by previous authors concerning the genesis of De Geer moraines focused on their value as relative geochronological markers. This idea is based on their distribution which suggests a regular, although sporadic, mechanism of deposition. Many authors have supported an annual rate of deposition for the moraines (Norman, 1938; Shaw, 1944; Möller, 1962; Sollid and Carlsson, 1984; Larsen et al., 1991) while others rather suggested a more erratic phenomenon (Hoppe, 1957, 1959; Strömberg, 1965). Most of the recent studies on De Geer moraines propose simultaneous deposition of many successive moraine segments (Zilliacus, 1987a and b, 1989; Beaudry, 1988; Beaudry and Prichonnet, 1991).

Based on geomorphological data, Boulton (1986) proposed that push-moraines emplaced in a marine environment were probably deposited annually at the ice front. In this paper, the geomorphology of the moraines and their facies suggest that the moraines were deposited simultaneously into a series of bottom crevasses extending at least 1 km behind the ice front. It is believed here that the studied De Geer moraines were not deposited annually and that this landform should not be used as relative geochronological marker.

In Scandinavia, Strömberg (1965) and Zilliacus (1987a and b, 1989) compared the spacing of De Geer moraines to the varve chronology established for their area. Both authors concluded, based on their comparison, that De Geer moraines could not be shown to be annual. In the sectors studied in the present paper, no varve chronology is available. But Bouchard (1980) studied two sites located 42 km northeast of Chapais and 40 km north-northeast of Chapais respectively, within the basin of Glacial Lake Ojibway. He calculated a maximum annual retreat of the ice front of 200 and 330 m respectively. The mean spacing of De Geer moraines in the Chapais area (180 m) is much too different for them to be considered as correlated. Based on this comparison and on the present model, it is concluded that De Geer moraines cannot be shown to be annual. Even if the spacing of De Geer moraines were similar to the annual retreat of the ice front as calculated with varve chronology, this cannot be considered as being conclusive since it appears that the moraines are deposited in [a series of basal] crevasses and not at the ice front.

Even if the moraines cannot be used as geochronological markers, it was demonstrated earlier that their general orientation is always perpendicular to the ice flows that prevailed during deglaciation. From another point of view De Geer moraines thus give a good idea of these ice flow directions and thus are useful in the initial stages of mineral prospection.

DE GEER MORAINES IN GLACIAL LANDFORMS SUCCESSION

Subglacial landforms, and especially their succession in glacial landscapes give a good idea of the conditions that prevailed under the last continental ice sheets (Sugden and John, 1976; Menzies and Rose, 1989). In Canada, models of glacial landscapes have been proposed for the Keewatin Ice Divide (Aylsworth and Shilts, 1989a, b) and for the Nouveau-Québec Ice Divide (Bouchard 1989). De Geer moraines cover extensive areas of the regions considered by those models, but they are not included in the succession. This could be explained by the poor understanding of the processes responsible for their formation and also by the fact that many authors still consider them as frontal and annual moraines. One attempt was made in Québec to include De Geer moraines in such a succession (Gray and Lauriol 1985). De Geer moraines were identified as the end member of the succession and the authors correlated these landforms with the hummocky moraine member of the succession proposed by Sugden and John (1976).

One difficulty that arises in identifying the place of De Geer moraines in the glacial landscape succession is that they are found in close association with many landforms. In the Northwest Territories, De Geer moraines are located in the outer drift zone and in the ribbed moraine zone of Aylsworth and Shilts (1989 a, b). In Québec, these moraines cover very extensive areas of the outer streamlined zone of Bouchard (1989). They are also found in close association with esker systems (see Beaudry and Prichonnet, 1991) and are transitional to Rogen moraines.

As was discussed in the proposed model for the emplacement of De Geer moraines, the presence of a frontal water body caused the glacier's terminus to be buoyed up. Variations in water levels caused an increase in the tensile stress present in the ice along its grounding zone. It is this stress that would have been responsible for the opening of the bottom crevasses. Since the glacier was still active, as evidenced by facies analysis data, the basal till sheet could have been remobilized to fill the open crevasses. This could explain why De Geer moraines are often seen associated with drumlin fields. Drumlins having a positive topography, their material is remobilized more easily than the surrounding basal till sheet. This does not mean that all drumlins would have been deformed into De Geer moraines since zones of bottom crevasses were probably formed, separated by sectors where few or no bottom crevasses at all were opened.

The identified transition between De Geer moraines and Rogen moraines east of Chapais is also related to the presence of a frontal water body. The best example of this transition is illustrated on Figure 2.6a. Here, the mechanism responsible for the opening of the bottom crevasses is probably different. The transition observed suggests that all these moraines were emplaced simultaneously in a subglacial position. The bottom crevasses in which De Geer moraines were emplaced are probably opened by tensile forces on the upglacier side of a small basin. This is supported by the fact that De Geer moraines are often oblique to the last ice flows, a situation expected for extension crevasses (Fig.2.3c and e). On the downglacier side of the basin, since the glacier was in compressive flow, the crevasses were closed and the moraines occupying the cavities were pressed onto one another as slabs of sediment. This formed the transitional moraines and, further downglacier, Rogen moraines (Fig.2.6a). This sequence could probably have been observed in other basins where Rogen moraines formed, but the absence of a frontal water body or the presence of a water body which was too shallow relative to the ice thickness precluded the preservation of De Geer moraines so that only Rogen moraines are seen. The sequence of Figure 6a therefore suggests: (1) that the frontal water body modifies the dynamic of the glacier since calving favors a rapid retreat of the ice front; (2) that the glacier was still active when the landforms were emplaced.

This transition can probably only be observed near the eastern edge of Glacial Lake Ojibway where water was shallow so that crevasses would have opened under an extensive regime. The Chapais area is located well within the glaciolacustrine basin (Fig.2.2). There, the lacustrine waters being deeper, they had more influence on the glacier margin so that only De Geer moraines could form. The bottom crevasses would have opened according to the mechanism proposed in this paper. Thus, the transition between De Geer moraines and Rogen moraines of the Chapais area would result from: a) processes induced by the lake waters inside the basin; b) processes where the impact of the lake waters diminished leading to a predominance of other factors such as the bedrock topography.

Based on the above discussion, it is proposed that De Geer moraines should be included in the glacial landscape model of Sugden and John (1976, fig.13.16) as being part of at least the last four end members (Fig.2.13). It is believed that the moraines could have formed as one of those members if a frontal water body influenced the dynamic of the glacier margin. The model proposed here constitutes a base for discussion and it could be modified as new data is accumulated.

This raises another question since in large areas of Québec, the Nouveau-Québec Glacier retreated in contact with frontal water bodies and yet no De Geer moraines formed. This is the case in Ungava Bay, in the James Bay Lowlands west of the Sakami Moraine and in most of the Champlain Sea basin. In those sectors, the depth of the water body relative to the ice thickness probably had a large influence on the dynamic of the glacier, thus not allowing the emplacement of De Geer moraines. If the glacier is too thick in comparison to the water depth, the glacier cannot be buoyed up so that bottom crevasses could form. In sectors where the water depth was too great relative to the glacier thickness, this probably enhanced rapid ice flows, thus precluding the preservation of bottom crevasses. A similar situation would be expected in areas where the ground slope is too high.

In summary, it is believed that frontal water bodies have a large influence on the glacier's dynamic, and De Geer moraines could form given that the conditions described above are favourable. In order to better understand those processes, more research should be done in the transition zones such as the one illustrated in Figure 2.6a. This should lead to increased understanding of the dynamic of the glacier and enable the real position of De Geer moraines in the glacial landscape succession to be defined.

CONCLUSIONS

The present paper, based in large part on facies and deformation structure analysis, has provided new insight on the genetic processes involved in the emplacement of De Geer moraines from the Chapais and Radisson areas.

Geomorphological data was presented such as the morphology of the moraine segments and the relationship between De Geer moraines and: (1) drumlins. Many drumlins appear to be truncated and their material remobilized to form moraines; (2) eskers. A least one series of De Geer moraines composed of sorted sediments seems to be associated with an esker system located downglacier; (3) Rogen moraines. A transitional sequence was identified in the area of Lake Caopatina (Fig.2.6a).

Three facies associations have been detailed: (1) sorted sediments; (2) non-fissile and loose till; (3) fissile and compact till. Those three facies associations form a continuum beginning with the series of moraines composed of sorted sediments, and grading laterally into the moraines formed of a fissile and compact till. This transition is identified for the first time.

Deformation structures were measured in all the analyzed facies associations. They consist of overturned to recumbent folds, thrust faults, load and drag structures.

Those deformation structures are evidence that the glacier was still active when the moraines formed.

The model presented here suggests that the material composing the De Geer moraines of the Chapais and Radisson sectors were deposited in bottom crevasses by an active glacier (Fig.2.12). In the areas where large amounts of meltwater were channelized, sorted sediments were deposited as foreset laminations in the crevasses. In the areas where less water was present, till was deposited. The glacier locally remobilized the basal till, thus deforming existing drumlins, to push it toward crevasses located nearby. In the areas where little meltwater was channelized, the glacier constructed the moraines by squeezing of till. The origin of De Geer moraines is therefore polygenetic and other processes may be identified in future studies. Finally, De Geer moraines have no relative geochronological value.

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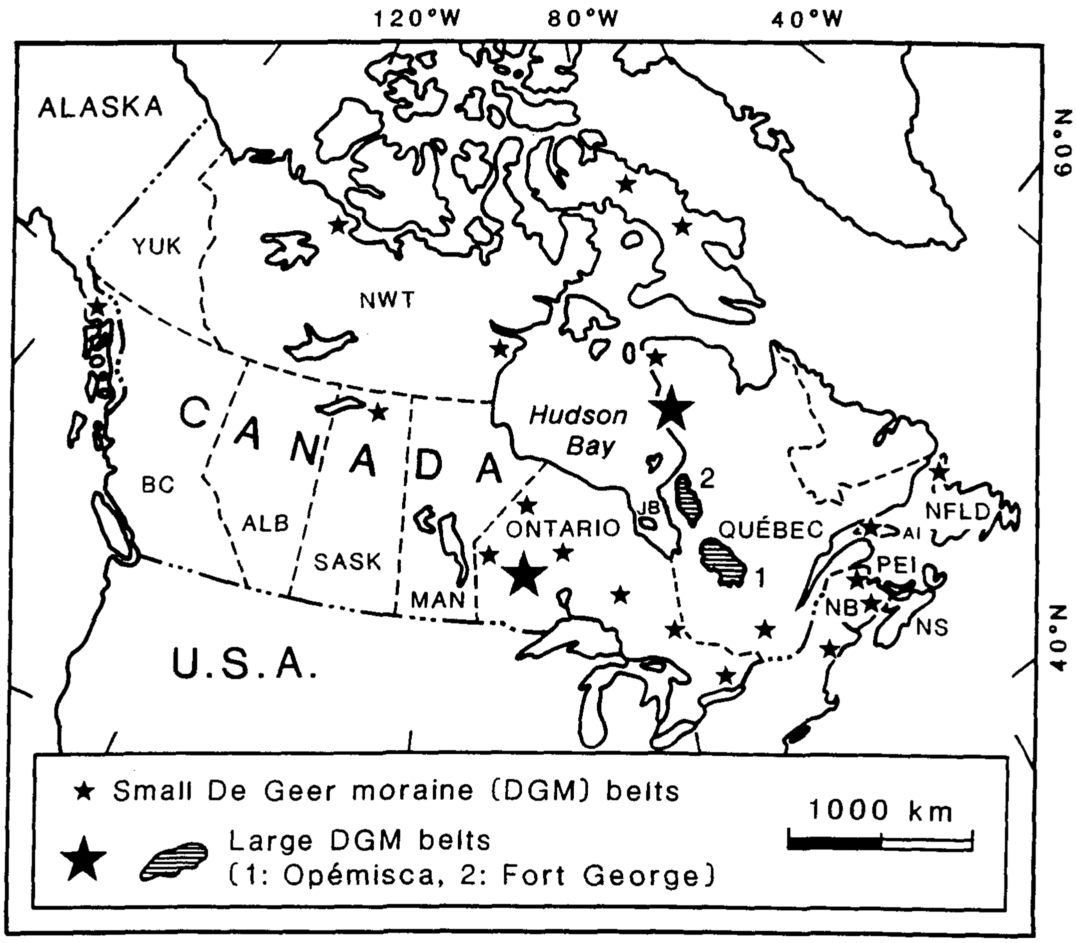

Fig.2.1 Known location of De Geer moraine belts in North America. Abbreviations: Yuk=Yukon; NWT=Northwest Territories; BC=British Columbia; ALB=Alberta; SASK=Saskatchewan; MAN=Manitoba; JB=James Bay; NB=New Brunswick; NS=Nova Scotia; PEI=Prince Edward Island; NFLD=Newfoundland; AI=Anticosti Island; U.S.A=United States of America; SM= Sakami Moraine.

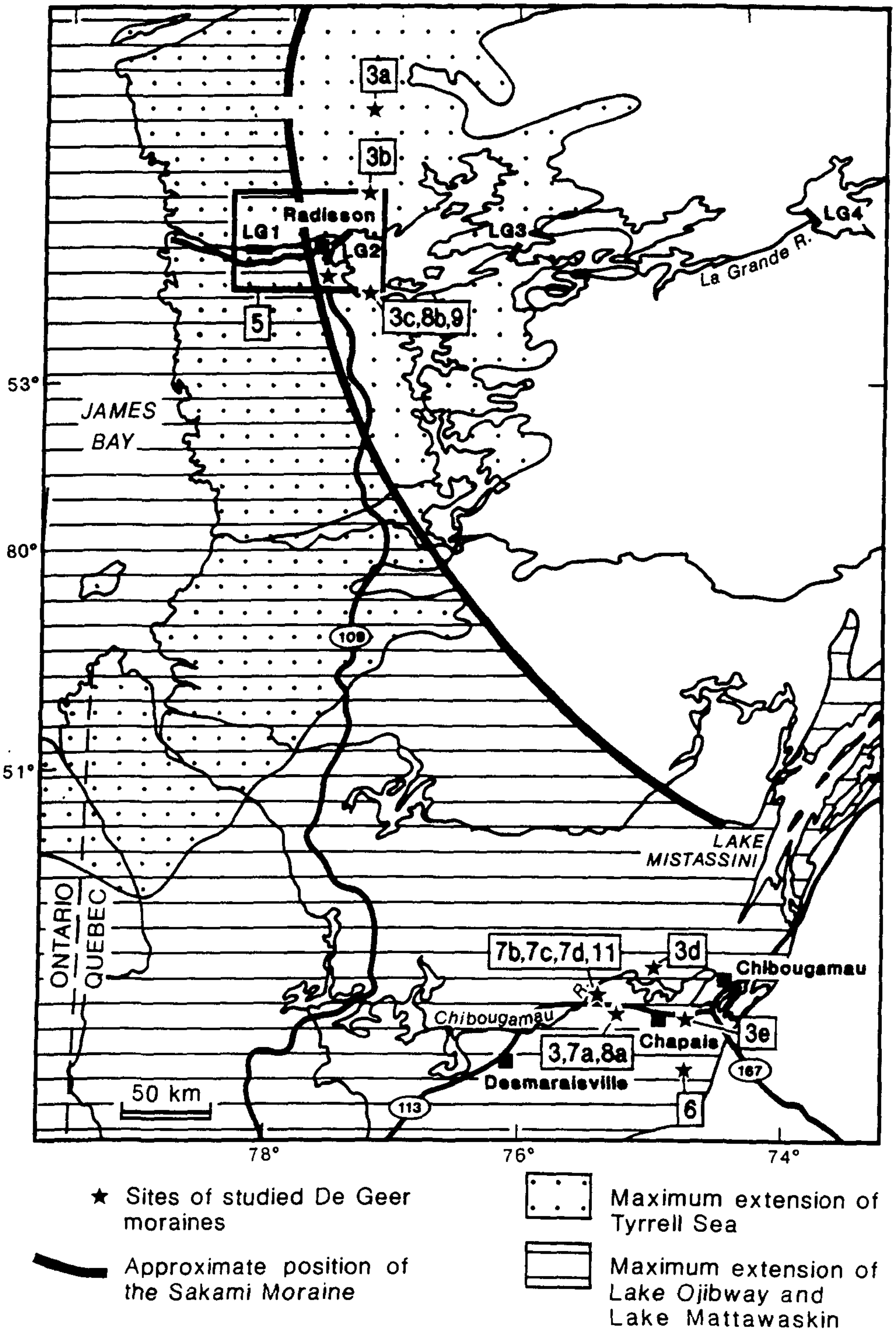

Fig.2.2 Location of the studied De Geer moraines and of the figures cited in the text (modified from Vincent 1989, fig.3.47). LG1, LG2, LG3 and LG4 locate the dams of the La Grande Rivière Hydroelectric Complex.

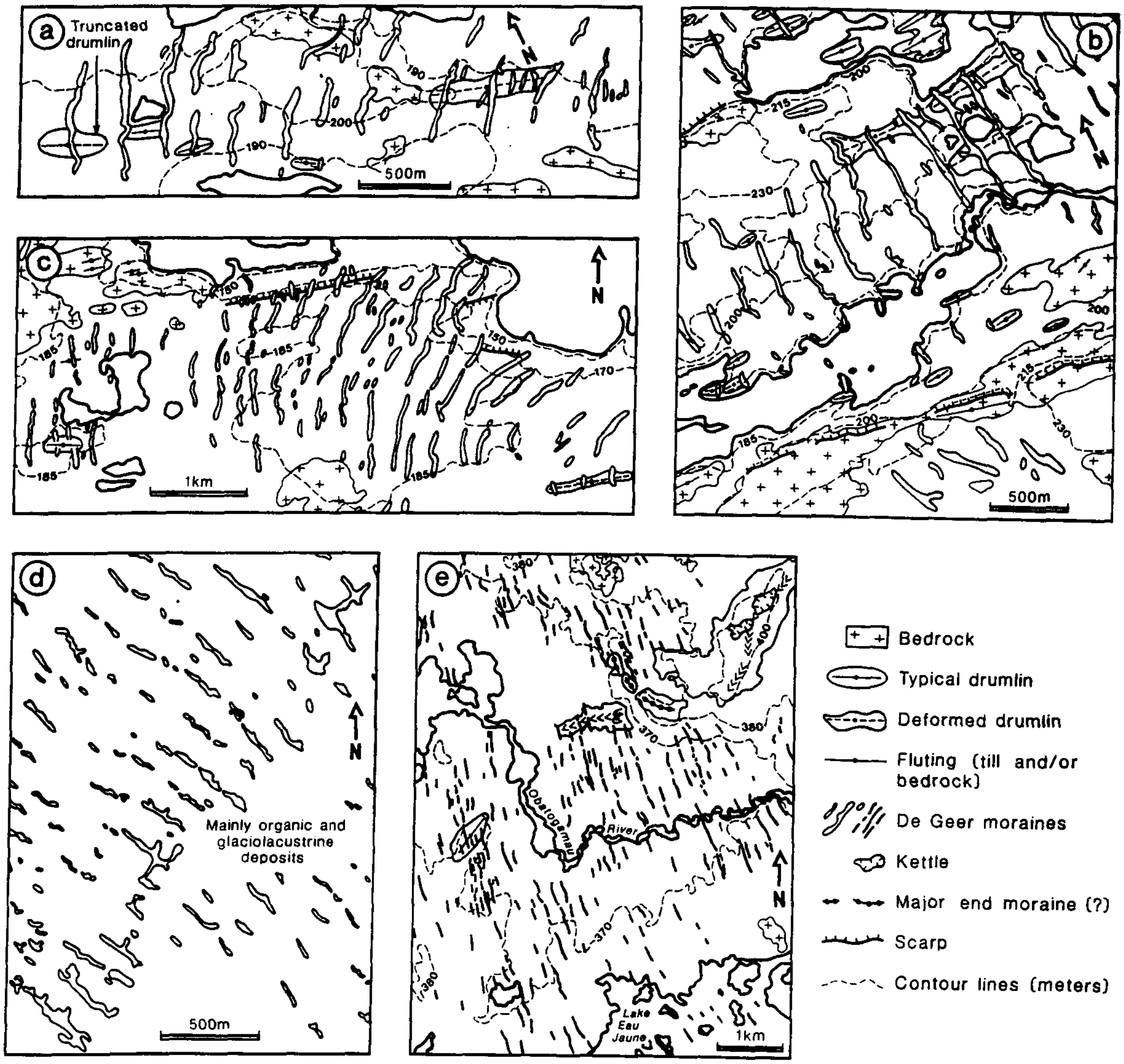

Fig.2.3 Detailed maps of De Geer moraines and other important geomorphological features of the Radisson sector (a, b and c) and Chapais sector (d and e). For location, see Figure 2.2.

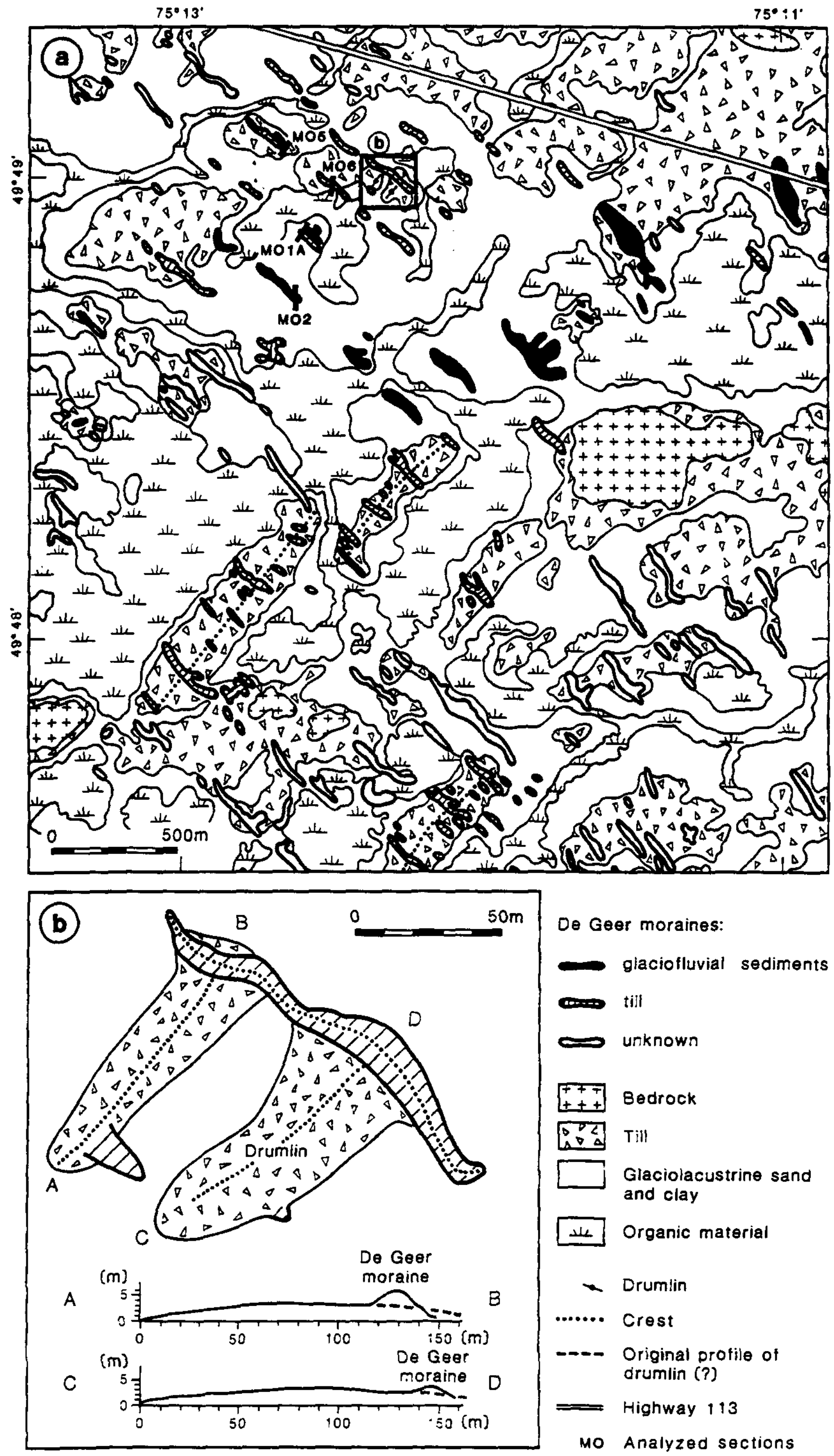

Fig.2.4 a- Surficial deposit map of a sector located 25 km west of Chapais. Note the series of De Geer moraines composed of sorted sediments and the relationship with deformed drumlins; b- detailed morphology of De Geer moraines crosscutting drumlins (see box in Figure 2.4a). For location, see Figure 2.2.

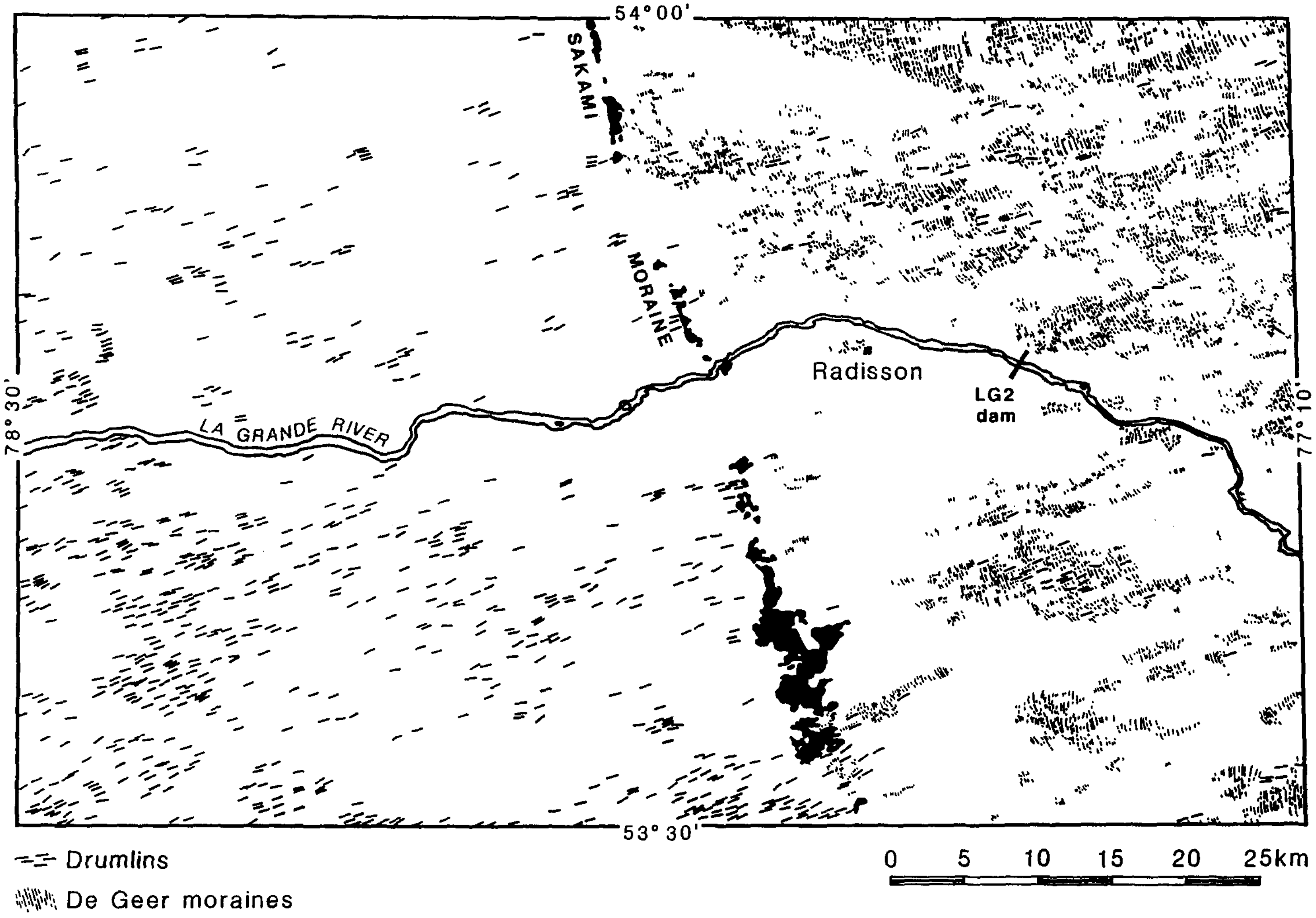

Fig.2.5 Map of the drumlins and De Geer moraines on both sides of the Sakami Moraine (modified from Vincent 1985a and b). West of the moraine, the drumlin density is 26 drumlins/100 km^2. East of the moraine, the drumlin density is 4 drumlins/100 km^2. For location, see box in Figure 2.2.

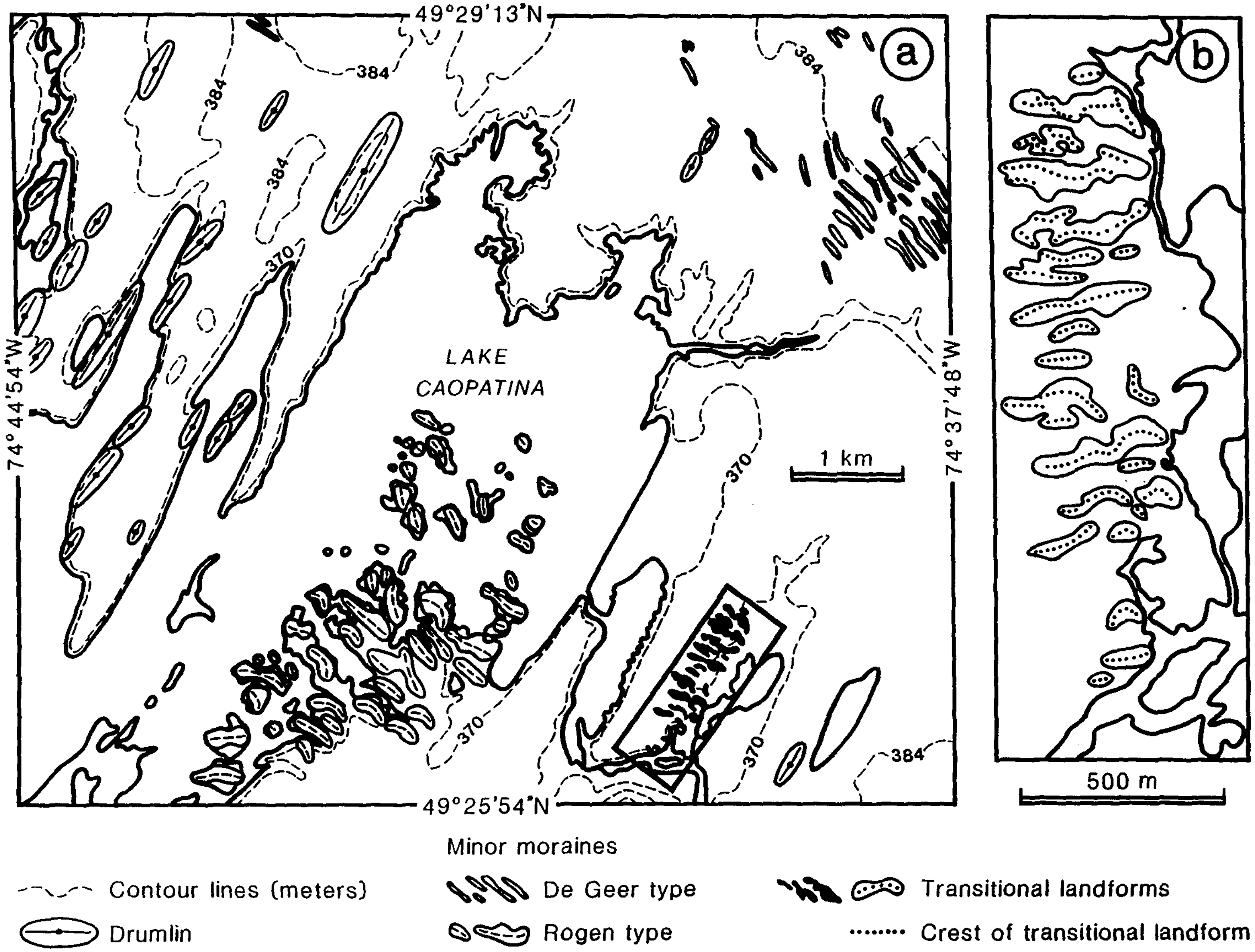

Fig.2.6 a- Map of the main geomorphological features of the area of Lake Caopatina; b- Detailed morphology of the transitional moraines (see box in Figure 2.6a). For location, see Figure 2.2.

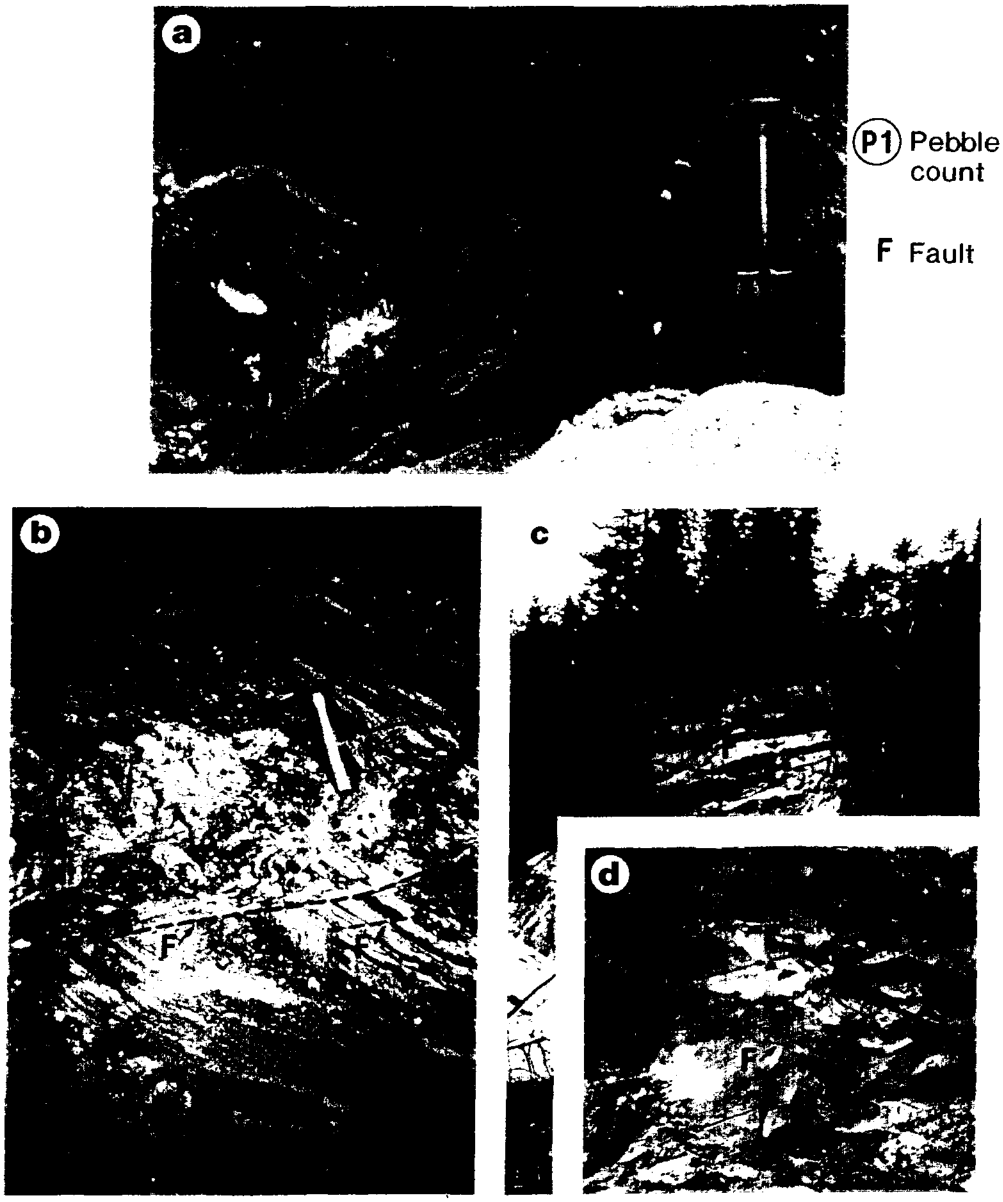

Fig.2.7 De Geer moraines composed of sorted sediments (Chapais sector): a- MO2 section. Note the till lens injected in the sorted sediments; b- ML1*bis* section. Close-up on the folded and sheared foreset laminations (hammer is 39 cm long); c- ML2 section. General view of the section; d- ML2 section. Close-up on deformation structures. Upglacier is either on the left (a and b), or on the right side (c and d). For location, see figure 2.2.

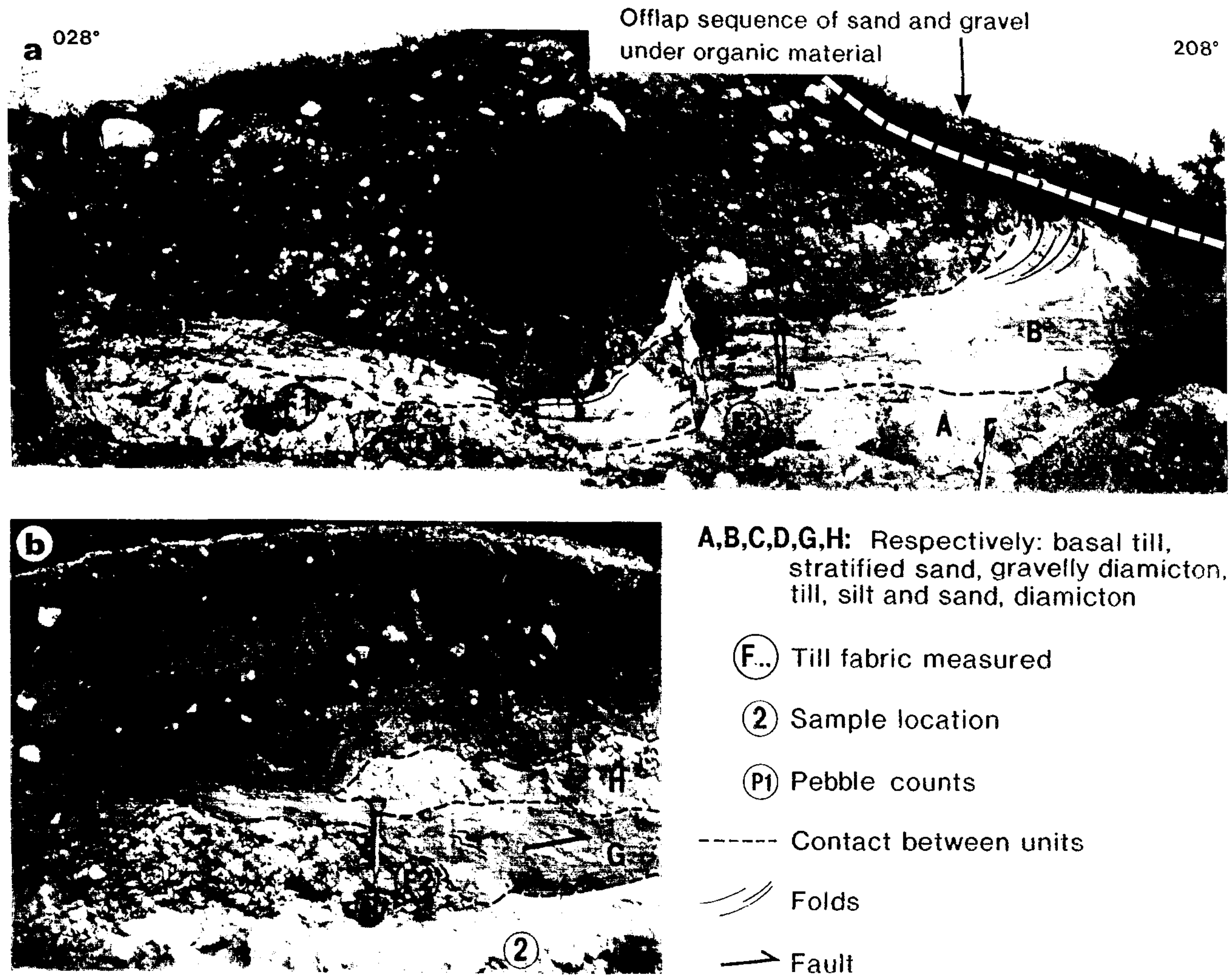

Fig.2.8 De Geer moraines composed of a non fissile and loose till. a- MO1A section (Chapais sector). General view of the section (boulder in centre of photograph is 3 m high): (A) basal till, (B) sorted sediments, (C) diamicton, (D) till; b- BJ1 section (Radisson sector). Close-up on the overturned syncline (see also Figures 2.9a and b). Upglacier is on the left side of both sections. For location, see Figure 2.2.

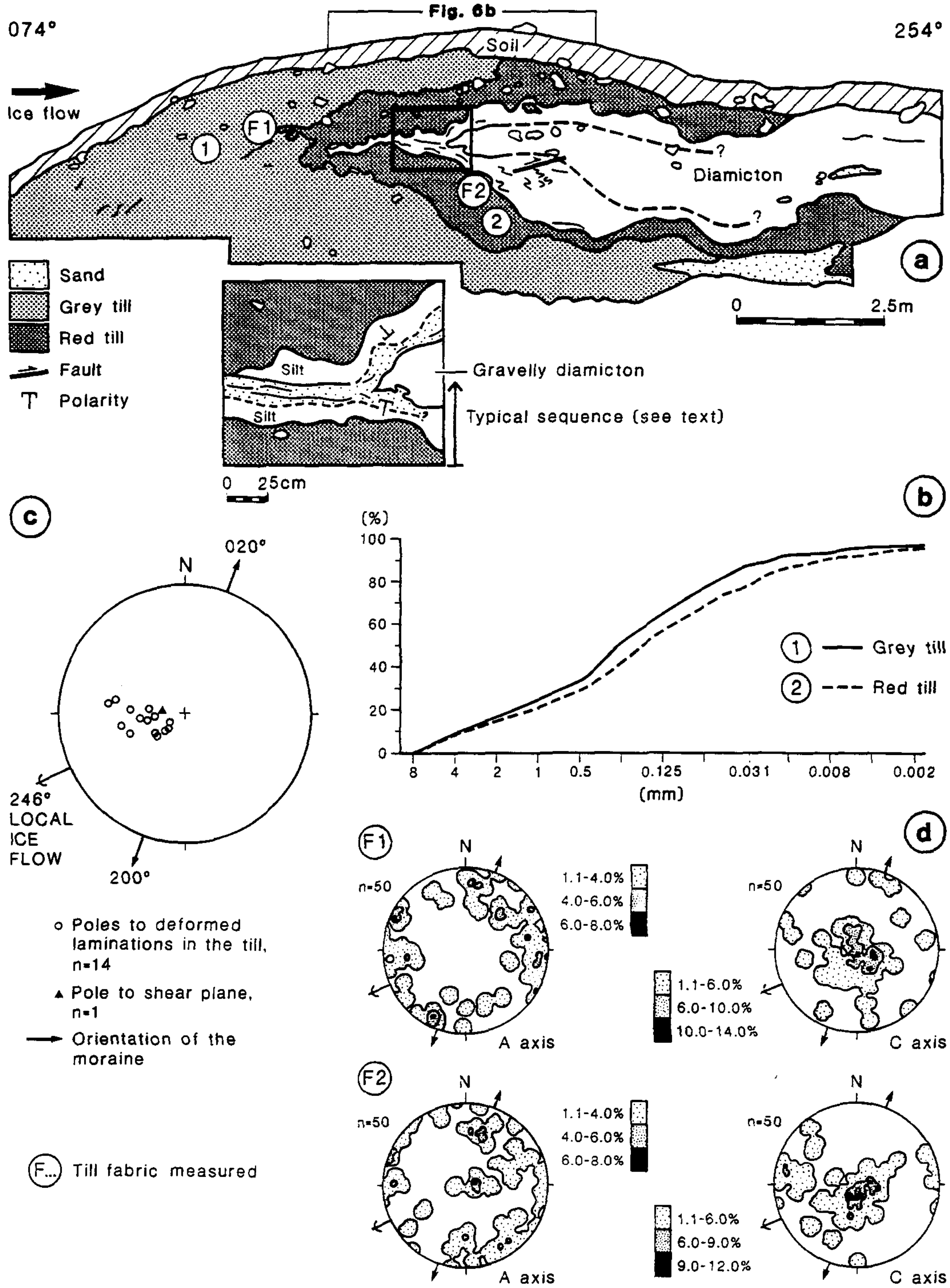

Fig.2.9 BJ1 moraine: a- schematic cross-section; b- grain-size distribution of the two tills; c- analysis of deformation structures (Schmidt equal area net, lower hemisphere); d- till fabrics (a axis and c axis).

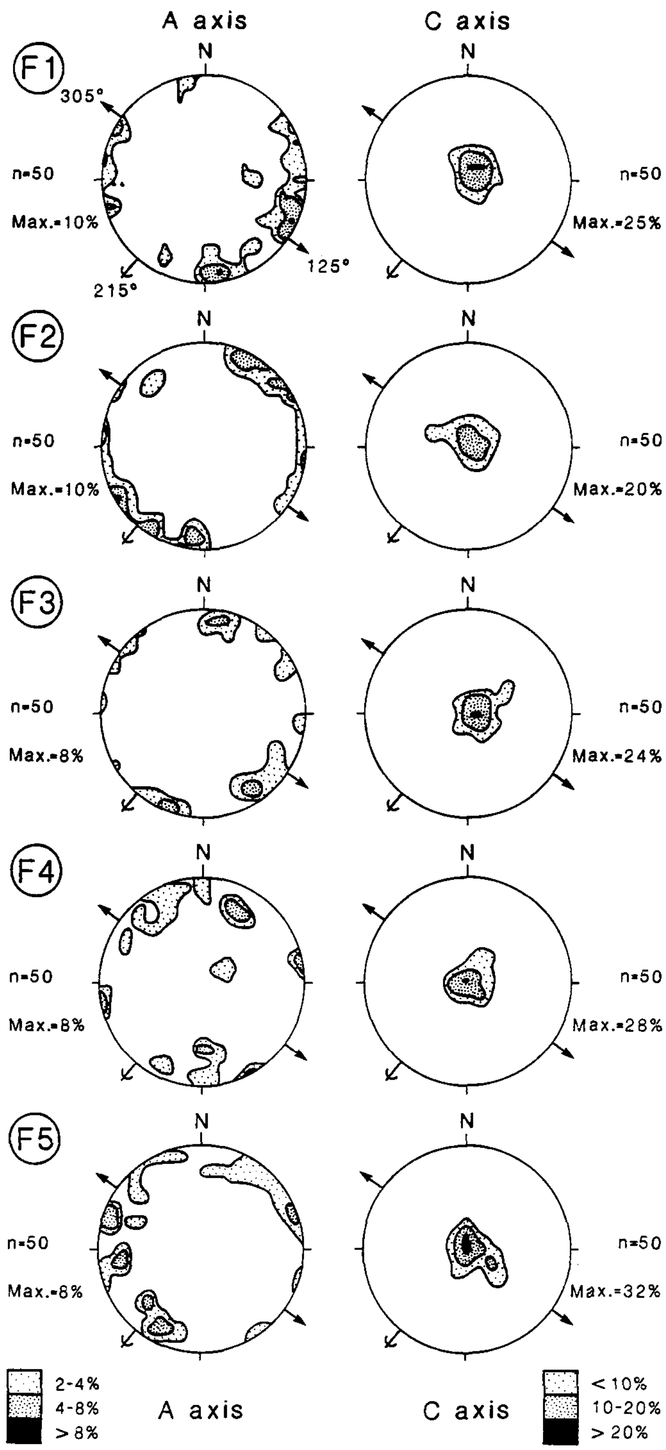

Fig.2.10 Till fabrics of MO1A section (a axis and c axis). For location of samples, see Figure 2.8a.

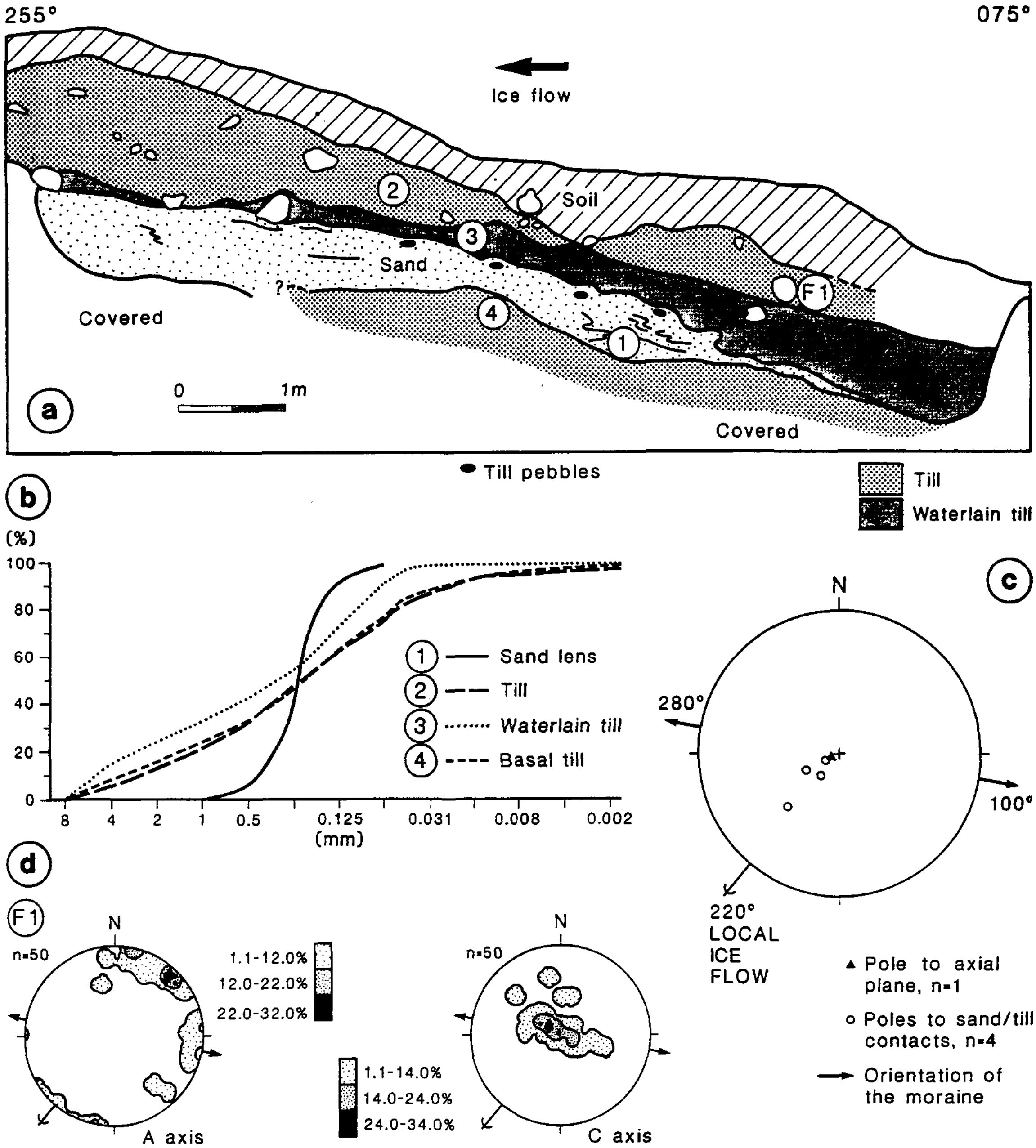

Fig.2.11 ML1 section: a- schematic cross-section; b- grain-size distribution of the four units; c- analysis of deformation structures (Schmidt equal-area net, lower hemisphere); d- till fabric (a axis and c axis). Upglacier is to the right. For location, see Figure 2.2.

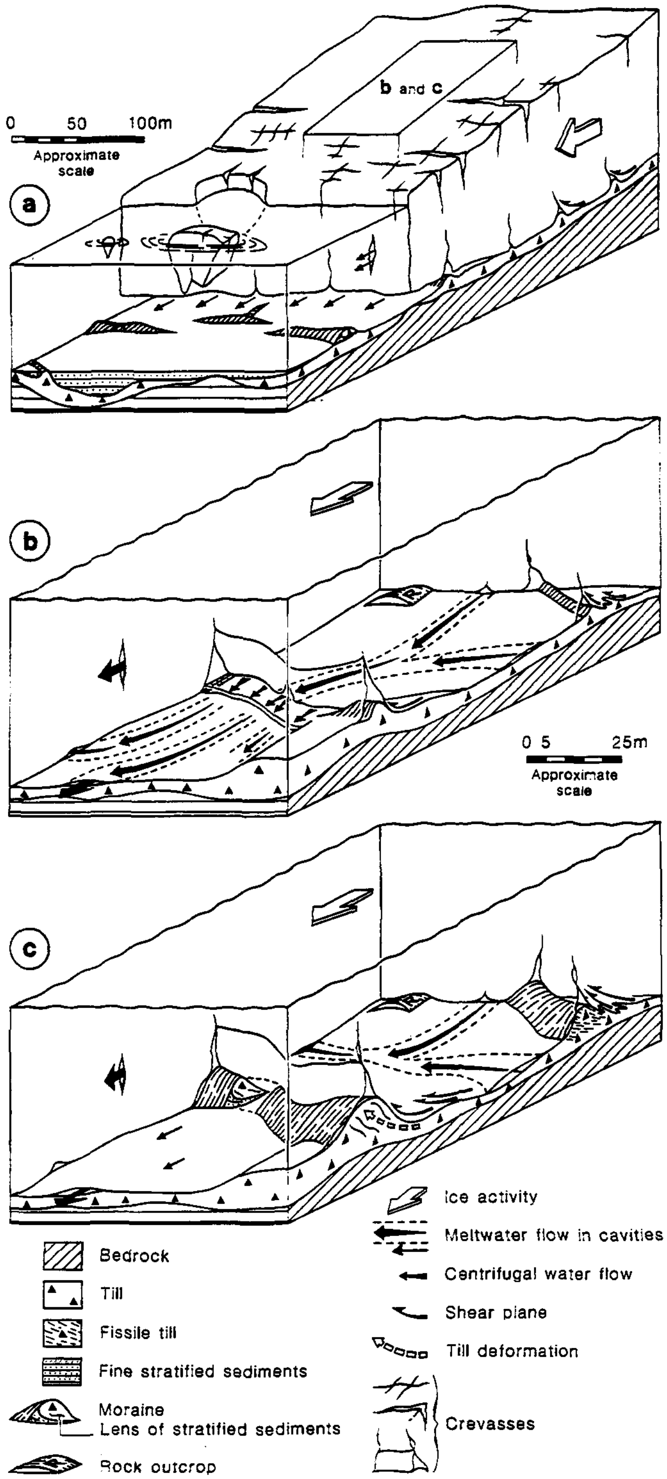

Fig.2.12 Model for the emplacement of De Geer moraines. Note that the surface of diagrams b and c do not represent the upper surface of the glacier: a- general glacial context. The terminus of the glacier is slightly buoyed up by the frontal water body. Crevasses open because of the stress created by the buoyancy at the grounding line; b- opening of the crevasses and initiation of the deposition phase by deformation of the basal till and squeezing. In areas of channelled meltwater flow, sorted fine sediments accumulate in crevasses (see Beaudry and Prichonnet, 1991, Fig.1.11); c- accumulation of till and deformation of the sorted sediments. Meltwater conduits are destabilized and meltwaters flow elsewhere.

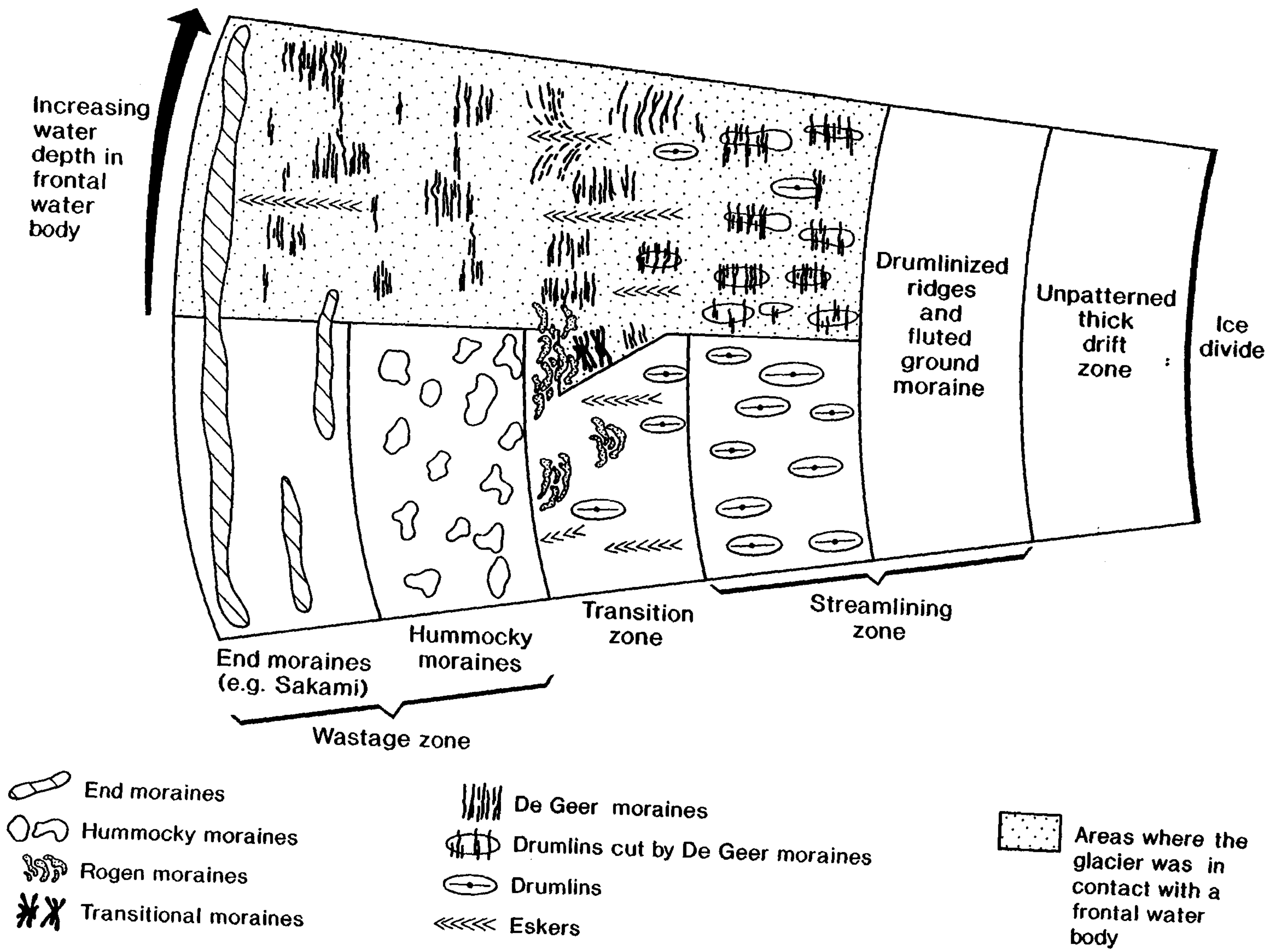

Fig.2.13 Model illustrating the place of De Geer moraines in the glacial landforms succession (modified from Sugden and John 1976, and Bouchard 1989).

Table II.II Lithological composition of the moraine till and adjacent basal till in the 0.8 to 5 cm and 5 to 15 cm fractions.

Moraine N°	Volcani-clastics	Gneiss and other granites	Opemisca granite	Ultra-distal	Others	Total
MO1A						
0.8-5cm						
Moraine till	68.4 ± 4.7	26.7 ± 4.5	2.7	1.9	0.3	370
Lodgement till	68.8 ± 4.5	24.5 ± 4.3	5.1	1.3	0.3	395
MO5						
0.8-5cm						
Moraine till	80.4 ± 4.5	16.0 ± 4.1	2.0	1.3	0.3	301
Lodgement till	83.9 ± 3.5	12.6 ± 3.3	3.2	---	0.3	397
5-15cm						
Moraine till	91.3 ± 3.3	7.1 ± 3.1	---	0.8	0.8	265
Lodgement till	85.5 ± 4.7	13.5 ± 4.5	---	0.5	0.5	221
MO6						
0.8-5cm						
Moraine till	74.1 ± 4.3	19.9 ± 3.9	4.5	1.5	---	402
Lodgement till	66.5 ± 4.7	28.6 ± 4.5	3.5	1.1	0.3	374
5-15cm						
Moraine till	73.2 ± 5.5	24.5 ± 5.3	---	2.3	---	257
Lodgement till	72.3 ± 4.5	25.7 ± 4.5	---	1.2	0.8	374
ML1						
0.8-5cm						
Moraine till	74.2 ± 4.3	24.9 ± 4.1	---	0.7	0.2	406
Lodgement till	64.4 ± 4.9	33.2 ± 4.9	0.8	0.8	0.8	356
MBF1						
0.8-5cm						
Moraine till	72.1 ± 5.3	24.7 ± 5.1	1.4	1.1	0.7	283
Lodgement till	76.0 ± 5.1	19.9 ± 4.9	1.9	1.1	1.1	262
5-15cm						
Moraine till	77.3 ± 5.7	21.3 ± 5.5	---	1.4	---	216
Lodgement till	75.3 ± 6.3	22.5 ± 6.1	---	1.7	0.5	182
MK1						
0.8-5cm						
Moraine till	70.4 ± 5.3	27.8 ± 5.3	0.7	0.4	0.7	277
Lodgement till	77.2 ± 4.5	18.8 ± 4.3	1.9	0.9	1.2	324
5-15cm						
Moraine till	79.6 ± 5.3	17.3 ± 4.9	---	1.8	1.3	225
Lodgement till	77.0 ± 5.7	22.0 ± 5.7	---	0.5	0.5	209

Table II.III Description of the till fabrics data. V1 and V3 are eigenvectors. S1 and S3 are the corresponding eigenvalues.

Moraine Number	Sample Number	Axis Measured	N	V1 Azimuth Plunge	S1	V3 Azimuth Plunge	S3
MO1A	F1	A	50	110.5° 11.1°	0.521	330.3° 76.6°	0.104
MO1A	F1	C	50	045.1° 81.1°	0.823	262.7° 7.0°	0.068
MO1A	F2	A	50	041.8° 0.7°	0.557	285.7° 88.4°	0.073
MO1A	F2	C	50	025.6° 83.4°	0.779	228.9° 6.0°	0.074
MO1A	F3	A	50	153.0° 7.7°	0.488	279.0° 77.1°	0.096
MO1A	F3	C	50	054.4° 80.7°	0.819	308.4° 2.6°	0.066
MO1A	F4	A	50	351.1° 7.2°	0.489	152.2° 82.4°	0.195
MO1A	F4	C	50	077.4° 82.8°	0.776	336.1° 1.4°	0.078
MO1A	F5	A	50	230.2° 4.7°	0.519	122.4° 74.9°	0.103
MO1A	F5	C	50	114.3° 80.6°	0.831	225.6° 3.5°	0.046
ML1	F1	A	50	035.2° 12.0°	0.807	244.2° 76.4°	0.026
ML1	F1	C	50	325.7° 81.3°	0.876	206.5° 4.3°	0.031
BJ1	F1	A	50	068.0° 8.4°	0.520	227.9° 81.0°	0.151
BJ1	F1	C	50	167.9° 79.5°	0.662	284.0° 4.6°	0.161
BJ1	F2	A	50	116.5° 22.1°	0.451	259.7° 63.1°	0.204
BJ1	F2	C	50	235.6° 71.4°	0.571	359.8° 10.7°	0.118

CHAPITRE III

GLACIAL DISPERSAL FROM THE OPÉMISCA PLUTON IN THE CHAPAIS AREA, CENTRAL QUÉBEC.

Abstract

This paper presents the dispersal trains of granitoid debris from the Opémisca Pluton in the surficial till sheet of the Chapais area, Québec. The clasts of three size-fractions were counted (0.8 to 5 cm, 193 sites; 5 to 15 cm and 15 to 25 cm, 21 sites). The samples have been taken either from the upper part of the basal till or from the till of De Geer moraines in an area of 3 700 km^2. Debris contents are shown on a contour line map and a dispersal curve. A major southwestward dispersal train with a length of at least 90 km is documented. This dispersal train is parallel to the last southwestward ice flow. A residual southeastward dispersal pattern is also identified at the eastern edge of the pluton. Its main branch is 15 km long and is parallel to the oldest regional ice flow identified. The tip of this dispersal train seems to be diverted toward the SSW. The patterns of these two dispersal trains support the relative chronology of the two main regional ice movements previously recognized. They should be considered seriously in mineral exploration programs using any size fractions of glacial sediments as a tool for tracing mineralized outcrops.

Résumé

Cet article présente les patrons de dispersion des débris de granitoïde provenant du Pluton d'Opémisca, dans la nappe de till de fond de la région de Chapais, Québec. Les débris de trois fractions granulométriques ont été comptés (0,8 à 5 cm, 193 sites; 5 à 15 cm et 15 à 25 cm, 21 sites). Les échantillons proviennent de la partie supérieure du till de fond ou du till des moraines de De Geer, dans une région couvrant une superficie de 3 700 km^2. Le contenu en débris du pluton d'Opémisca est représenté par une carte d'isolignes et par une courbe de dispersion. Un train de dispersion majeur vers le sud-ouest, et d'une longueur d'au moins 90 km, est documenté. Ce train de dispersion est parallèle au mouvement glaciaire tardif vers le sud-ouest. Un train de dispersion résiduel est aussi mis en évidence à l'est du pluton. Son axe principal atteint une longueur de 15 km et il est parallèle à l'écoulement glaciaire le plus ancien, soit en direction du sud-est. La terminaison de ce train de dispersion résiduel semble déviée vers le sud-sud-ouest. Les patrons de ces deux trains de dispersion semblent confirmer la chronologie relative des principaux écoulements glaciaires régionaux. Ceux-ci devraient être considérés sérieusement dans les programmes d'exploration minérale basés sur l'étude de n'importe quelle fraction granulométrique, lorsqu'utilisée pour retracer la source de minéraux commerciaux.

Introduction

In the Chapais area, Central Québec (Fig.3.1a), recent investigations have shown that, during the Late Wisconsinan, the area was subjected to different ice flow directions. This had an impact on the alignment of the glacial landforms and also on the emplacement of the dispersal trains.

Till is the most useful medium for tracing clastic dispersal in glaciated terrains as shown by several studies from Scandinavia, Great Britain, and Canada (see Shilts 1984). East of Chapais, a major southwestward dispersal train has been documented by Bouchard and Martineau (1984), Bisson (1987) and De Corta (1988). This dispersal train was laid down by the youngest regional ice flow. However, an older southeastward ice flow is conspicuous from observation of glacially eroded and truncated bedrock surfaces (Martineau et al. 1984; Prichonnet et al. 1984; Bouchard and Martineau 1984, 1985; Prichonnet and Beaudry 1990; Veillette and Pomares 1991).

This paper describes the glacial dispersal of clasts from the granitoid rocks of the Opémisca Pluton in the Chapais area (Fig.3.1b) and suggests constraints on the interpretation of detailed geochemical surveys in mineral exploration programs. The identified dispersal trains and data from previous regional studies will be used in a short discussion on the configuration of the Labradorean sector of the Laurentide Ice

Sheet.

Geology and physiography

The Chapais area is part of the Abitibi Greenstone Belt and its bedrock is composed of Precambrian rocks from the Superior Province (Gobeil and Racicot 1983; Avramtchev 1985; Fig.3.1b). A large portion of the regional bedrock is composed of green schist facies volcaniclastic rocks. Except for some ultramafic and mafic intrusives and stratiform anorthositic complexes, the largest part of the bedrock is composed of syn- to late-tectonic granitoid rocks. These are mainly granites and gneisses. Some granitoid plutons are pre- to syn-tectonic in origin. Among those, the Opémisca Pluton covers an area of 260 km^2 (Fig.3.1b). It presents an elliptical shape, oriented WNW-ESE. This granitoid is rather uniform, but it grades into a syenite on its boundaries (Wolhuter 1971).

The studied area, which includes the Opémisca Pluton, covers a surface of 3 700 km^2 (Fig.3.1b). The relief is subdued and most of the area lies generally below 400 m (Fig.3c). The maximum elevation is reached at Michwacho Mountain (560 m). Quaternary deposits fill shallow depressions in the bedrock. Their thickness is generally only a few meters, but locally up to 4 m for ground moraine and up to 15 m for De Geer moraines. According to Burns et al. (1986) and Brereton et al.

(1987), it may reach 33 m in some shallow depressions. A large part of these deposits is composed of glaciolacustrine sand and clay, and organic deposits overlying the ubiquitous till. Till sheet forms include ground moraine, drumlins and De Geer moraines. Glaciofluvial deposits are found in large esker systems (Prichonnet et al. 1984) and in clusters of De Geer moraines (Beaudry and Prichonnet 1991; Beaudry and Prichonnet, submitted).

Ice flows

Four successive ice movement directions have been documented from ice flow indicators (Fig.3.2). The oldest ice flow was toward the southeast. Outcrops bearing erosional marks from this movement have been mapped from Desmaraisville to the continental divide, 44 km east of Chapais, and from the southern tip of Lake Mistassini to at least 45 km south of Chapais (Ignatius 1956; Gillett 1966; Murphy 1966; Bouchard and Martineau 1984, 1985; Bouchard et al. 1984; Martineau et al. 1984; Prichonnet et al. 1984; De Corta 1988; Prichonnet and Beaudry 1990; Veillette and Pomares 1991).

No till sheet emplaced by this ice movement has yet been identified. However, Bisson (1987) and De Corta (1988) have traced indicator clasts in the till sheet that they have tentatively related to the southeastward ice flow.

The southeastward ice movement was followed by (1) a southward ice flow, as indicated by striations and grooves (Prichonnet and Beaudry 1990), (2) a south-southwestward and (3) a more conspicuous southwestward ice movement. This last movement has carved the bedrock as shown by the striations, rat tails, grooves, *roches moutonnées* and crag and tail forms of different sizes. Landforms composed of different types of glacial sediments, such as drumlins and eskers, are parallel to this ice movement while landforms perpendicular to the ice flow, such as Rogen and De Geer moraines, are also indicative of this major movement. This southwestward ice flow is responsible for most of the glacial dispersal of clasts as shown by a few dispersal trains documented by Laverdière (1971), Dilabio (1981), Bouchard and Martineau (1984), Bisson (1987) and De Corta (1988). Near the continental divide, in the eastern part of the region, the orientation of the drumlins gradually changes from south-southwest toward the south (De Corta 1988). This movement is contemporary to the southwestward ice flow identified in the western part of the area studied.

Finally, in some areas, these three main ice movements were followed by a late west-southwest ice flow that has slightly eroded the bedrock (Prichonnet et al. 1984; Prichonnet and Beaudry 1990). This shift in the ice flows at deglaciation is also illustrated in some areas by NNW-SSE De Geer moraines (Fig.3.3): see for instance the area located north of Lake Michwacho where WSW-ENE striations and rat tails are perpendicular to the moraines (Fig.3.2, site 9). In another sector located 10 km southeast of Chapais (Fig.3.3), no striations have been observed because of a limited access, but NNW-SSE De Geer moraines crosscut a NE-SW drumlin. These features as well as a short esker segment oriented ENE-WSW suggest a shift of the very late ice flows.

Methodology

In the larger grain-size fractions, the Opémisca Pluton granitoid can easily be recognized from other granites, being of light pink color. It is mainly composed of plagioclase, potassic feldspar, hornblende and quartz (Wolhuter 1971). Field observations of other granitoid intrusions suggest that a similar granite outcrops 25 km southwest of the Opémisca Pluton. However this granite is only found in small dykes, inside the Lapparent Pluton (Fig.3.1b). A similar intrusion was identified by Nantel (1985) inside the Lapparent Pluton, 36 km southwest of Chapais.

A total of 193 samples of till were collected around the Opémisca Pluton (1 sample for 19 km^2; Fig.3.4): they were collected from basal till and De Geer moraines (respectively 127 and 66 sites), both tills generally having the same lithological composition (Beaudry and Prichonnet submitted). Clasts in the 0,8 to 5 cm fraction (number of clasts: minimum, 185; maximum, 704; mean, 377) were

Table II.I Characteristic features of the three facies described (N = number of moraines in which the features were observed and measured).

Facies	1	2	3
Number of described moraines	4	6	2
Long axis orientation Chapais Radisson	 115° to 155°-295° to 335° not observed	 125° to 130°-305° to 310° 110° to 290°-020° to 200°	 100° to 280°-130° to 310° not observed
Length of sections Chapais Radisson	 6.4 to 31.0 m not observed	 5.0 to 13.0 m 12.0 to 16.0 m	 5.0 and 10.0 m not observed
Main features	sandy to gravelly sorted sediments forming foreset laminations	poorly compacted and non fissile till till overlying and deforming stratified sediments (N=4)	compact and fissile till sometimes overlying and deforming sorted sediments
Percentage in section of sorted sediments of till	 80 to 100% up to 20%	 up to 40% 60 to 100%	 up to 40% 56 to 100%
Primary structures Paleocurrents Laminations in till	 inclined laminations and incorporated clasts dip toward distal side of moraine (N=4) not observed	 inclined laminations in fine stratified sediments dip toward distal side of moraine (N=1) upglacier dip (N=2)	 not observed not observed
Deformation structures contacts between facies axial plane of folds shear planes	 upglacier dip (N=3) upglacier dip (N=2) upglacier dip (N=3)	 upglacier dip (N=4) sub-horizontal (N=1) upglacier dip (N=1)	 upglacier dip (N=1) upglacier dip (N=1) not observed
Other features	-till lens injected on proximal side of section (N=2) -lens of diamicton on proximal side of section (N=2)	-fine sediments wrapped in a till syncline (N=1) -gradual contact between sorted sediments and overlying till	-well developped fissility -waterlain till between sorted sediments and till (N=1)

taken at depths ranging from 75 cm to 1,5 m, at the base of the B horizon, along logging roads. Gaps thus resulted in the sampling, notably on the Opémisca Pluton and south of Chapais (Fig.3.4). At 21 sites, pebble counts were made in the field, on the 5 to 15 and 15 to 25 cm fractions (mean of 318 and 215 clasts per sample). These were located at different distances from the pluton for comparison purposes. Finally, the 0.8-5 cm clasts were identified in the laboratory. In this process, samples were taken randomly and their exact location was ignored to avoid any presumption.

A few granitoid clasts collected southeast of the Opémisca Pluton and believed to originate from the pluton were examined by coloration and micrographic analysis to verify the visual identification.

The 0,8 to 5 cm size fraction was used to draft contour lines of the component of Opémisca Pluton clasts in the surface till, according to the nodal point method (see Bouchard and Martineau 1984): in this method, contour lines are drawn according to mean values calculated for a surface area of 100 km^2. By this procedure, it is possible to smooth differences between adjacent sites. Dispersal curves are drawn for the southwestward dispersal train. In the 0,8 to 5 cm fraction, 132 samples were used to build this curve (Fig.3.5a). Samples were grouped in bands 2,5 km wide, and mean values were obtained. Distribution curves based on the 21 sites of the 5 to 15 cm and 15 to 25 cm size fractions are constructed using the same method.

Results

On the northeastern side of the pluton, in 16 samples out of 24, the till generally has no clasts from the Opémisca Pluton (Fig.3.4). However, a few samples with concentrations from 0,4 to 2,9% of this granite, are located near streams and also very close to the pluton.

Within the Opémisca Pluton limits, the twelve studied sites are located on the northwestern extremity of the pluton because of limited road access. In these samples, the granites form 20,6 to 73,1% of the total clasts. These values diminish abruptly outside of the Opémisca Pluton limits, in the southwestern direction (Fig.3.5a). The 30% contour line extends to a maximum distance of 4 km downglacier on the westernmost portion of the pluton. On the southeastern section, the 30% contour line cannot be established because of the scarcity of sampled sites.

Southwest of the pluton, the mean values decrease rapidly to less than 10%, after a transport distance of 10 to 18 km (Fig.3.5a). The pattern of the 10% and 20% contour lines seems different in the southeastern and the northwestern portions of the dispersal train. These contour lines have a lobate shape: one lobe is parallel to the northwestern side of the pluton, and the other to the southwestern branch of Lake Opémisca. The mean content decreases more rapidly on the southeastern portion than on the northwestern portion and this may be an artifact resulting from a low sample density. But this difference disappears with the 5% contour line which is rather uniform. Southwest of this contour line, there are apparently three zones where the till contains more than 5% of granitoids from the Opémisca Pluton: two of them are probably limited in extent, although a third one covers a large surface of the Lapparent Pluton.

Another pattern is outlined by the contour lines of 2 and 1%, southeast of the Opémisca Pluton; in fact, 29 samples out of 31 contain clasts from this granite. The maximum content is 3,7%. This pattern extends toward the southeast over a distance of 15 km. The 2% contour line is oriented toward the southeast for 6 km, and then it turns south-southwest.

The dispersal curve of the 0,8 to 5 cm size fraction shows the following pattern (Fig.3.5b): on the proximal contact of the pluton, the till is enriched very rapidly in granitoid debris, up to about 39% after a transport distance of only 1,3 km, an increase of 30%/km. Then the granitoid content increases slowly to 46% toward the distal contact of the pluton, with a gradient of 0,8%/km. Southwest of the pluton, the curve is negatively exponential downglacier, with a few irregularities.

Immediately beyond the distal margin of the pluton, the granite content drops to 28% over 1,3 km, a decrease of -13,8%/km. The tail of the dispersal curve forms an asymptote decreasing at 0,07%/km. If a theoretical projection was calculated, it would be expected that the 1% mean content in the surface till would be reached only after a glacial transport of 90 km.

The dispersal curves for the 5 to 15 cm and 15 to 25 cm size fractions show a pattern similar to the 0.8-5 cm clasts curve (Fig.3.5b), but the enrichment over the Opémisca Pluton are more pronounced, reaching respectively 65% and 67%. Percentages are generally higher in these coarser fractions and it is only after a glacial transport of at least 40 km that the values of the three fractions become similar.

Discussion

The Opémisca Pluton as a tracer

Many studies carried out in Canada used specific tracers that were easily recognizable from other lithologies: e.g. Dubawnt Group in Northwest Territories (Shilts 1980, 1982; Shilts et al. 1979), Chibougamau and Albanel Formations north of Chibougamau (Bouchard and Martineau 1984). Here, the Opémisca granite can be used as a tracer because north and west of the Opémisca Pluton, clasts of this granitoid are rarely found in the surface till (Fig.3.4). As mentioned above, granitoid clasts are usually found near the contact of the pluton or near small creeks. This precludes contamination by a similar granitoid located to the northeast, and their sporadic presence may be interpreted as the result of an early fluvial transport before the last glaciation.

Several types of granites outcrop over large surfaces around Chapais (Fig.3.1b), but they do not affect the results. A local granite that is similar to the Opémisca Pluton is found 25 km to the southwest, and it is limited to small dykes inside the Lapparent Pluton. On the Streickeisen diagram (Fig.3.6), a sample from an outcrop of this granite corresponds to the empty circle found inside the cluster zone of samples from Wolhuter (1971). As a result there is an apparent slight increase in the content of debris from the Opémisca Pluton in the surface till, especially on the western portion of the Lapparent Pluton (Fig.3.5a). An increase in the content of debris from the Opémisca Pluton is also observed 4 km downglacier from a similar intrusion mapped by Nantel (1985).

During sampling east of the pluton, the presence of Opémisca Pluton clasts larger than 5 cm was noted and a few were brought back to the laboratory (empty circles in Fig.3.4). A few clasts were analyzed by coloration and the results were reported on a Streckeisen diagram (Streckeisen 1976) along with data from Wolhuter (1971, his Table I) and analysis from other granites found in the area (Fig.3.6). The samples of Wolhuter come from different sectors of the Opémisca Pluton. According to the Streckeisen diagram, these are granodiorite to monzodiorite. The clasts found in the surface till southeast of the pluton all fall into the cluster formed by the samples analyzed by Wolhuter. Photographs of thin sections illustrate a sample of the bedrock (Fig.3.7a) and a sample of a clast from the till (Fig.3.7b). Both samples show the same mineralogical assemblage and contain the same accessory minerals such as sphene, chlorite, epidote and apatite, although the last two minerals are not illustrated on Figure 3.7b.

The Chibougamau Pluton, located east of the Opémisca Pluton, is a tonalitic intrusion and it does not contain potassic feldspar (Gobeil and Racicot 1983), instead the Opémisca Pluton contains up to 27% of potassic feldspar (Wolhuter 1971). As a consequence, Opémisca Pluton clasts found southeast of its eastern limits are attributed to glacial dispersal and the pattern of the distribution is believed to represent a residual southeastward dispersal train.

According to laboratory controls, it is concluded that the use of the Opémisca Pluton as a tracer is justified since it can be distinguished macroscopically from the other granites of the Chapais area with a high level of confidence.

The southeastern dispersal train

Granitoid clasts derived from the Opémisca Pluton were found in the surface till east of the pluton (Figs. 3.5, 3.6 and 3.7). The Opémisca Pluton debris content in this direction shows a pattern that seems parallel to the oldest southeastward ice flow. It is therefore suggested that this pattern is a remnant of a presumably former and larger southeastward dispersal train. The low content in clasts from the Opémisca Pluton could be explained by a dilution caused by the southwestward ice flow (Shilts 1976; Puranen 1990).

South of Chibougamau, 40 km ESE from the studied area, De Corta (1988, fig.21c) has documented a southeastward pattern from a pebble analysis of the granite from La Dauversiere Stock, in the surface till. De Corta proposed that this pattern could be the result of the oldest ice flow. Bisson (1987) also identified a site located 14 km east of Chapais, where the lithological composition of the till was best explained by a southeastward transport of clasts. This data constitute independent support for the interpretation of the residual southeastward dispersal train.

The southwestern dispersal train

The southwestern dispersal train is of a major interest. It is parallel to the last southwestward ice flow and to other dispersal fans documented in this part of Québec (Laverdière 1971; Dilabio 1981; Bouchard and Martineau 1984; Bisson 1987; De Corta 1988). This final ice flow is exactly parallel to the drumlins and crag-and-tails and was still active at the time the eskers were formed (Prichonnet et al. 1984, fig.2). The dispersal fan presented here is finger-shaped and apparently displays two lobes extending southwestward. The lobate shape of the dispersal train may be due to multiple processes such as: (1) elevated hills on the western side of the pluton which have induced high-level transport in the ice (cf. Shilts 1976); (2) deeply scoured basins in the southwestern part of Lake Opémisca which could have promoted higher basal ice velocity and/or; (3) subdued relief of the eastern side of the pluton which did not allow material to be plucked and transported in the ice in the same quantity than on the western side.

Two main features are evidenced by the dispersal curves of Figure 3.5b: (a) over the pluton, the coarser-grained fractions are enriched in clasts from the Opémisca Pluton comparatively to the finer-grained fraction. The difference noted on the pluton can be attributed to the fact that this granitoid has been plucked in larger size particles. The density of joints in the granite is probably the main factor controlling the size of the eroded clasts (Bouchard and Salonen 1990); (b) downglacier, it is only after a distance of 40 km that the three fractions have about the same amount of clasts. This can be interpreted as an evidence that abrasion of the particles during comminution predominated in glacial transport (Shilts 1976).

Implications for mineral exploration

A few mineral exploration programs using overburden sediments as geochemical medium have been conducted in the Chapais area (Burns et al. 1986; Brereton et al. 1987). The till sheet can result from at least two directions of ice flow. Burns et al. (1986) adequately interpreted that the regional surface till was emplaced by ice flowing toward south-southwest (210°-220°). They also have associated an ice flow toward southwest (225°-240°) with the deposition of a lower till unit which has been identified only by reverse circulation drilling. Such a sequence of ice flows is known from Abitibi (Veillette 1986, 1989), an area some distance (310 km) from Chapais. But in the Chapais area, no such old ice flow was deduced in earlier work (Prichonnet and Beaudry 1990). On the contrary, the oldest ice flow observed in the Chapais area is toward the southeast. An ice flow toward 225°-240° has been identified, but it has been attributed to the deglaciation and is believed to result from the downdraw effect of Lake Ojibway on the New Quebec or Labrador Glacier margin (Prichonnet et al. 1984); moreover, this interpretation is supported by the crosscutting of striae (see also Prichonnet and Beaudry 1990).

The dispersal study carried around Opémisca Pluton shows that the southwestward ice flow is responsible for most of the glacial transport within the surface till. The till sheet being relatively thin (generally less than 4 m), the effect of the earlier southeastward ice flow has probably been diluted by the later ice movement, but, as shown here, southeastward glacial transport is still observed locally. These glacial transport data support the chronology deduced from the striation record of the area as pointed out by studies already quoted. In the Chapais area, mineral exploration programs focus commonly on the till/bed interface. Therefore, this older southeastward ice flow should be considered as a primary geological constraint in the interpretation. It could be expected that in areas of thick till cover the late southwestward ice flow may not have reworked the entire till sheet. Consequently, correlation of Burns et al. (1986) of the stratigraphy of the area with ice flows identified in Abitibi is questionnable.

Implications for the configuration of the Laurentide Ice Sheet

Many hypotheses have been proposed for the configuration of the Laurentide Ice Sheet during the Wisconsinan, especially for the Late Wisconsinan. Tyrrell (1898) first proposed that the ice sheet was composed of four domes located over Keewatin, northern Ontario, Labrador and Baffin Island. Flint (1943, 1947, 1971), Ives et al. (1975) and Denton and Hughes (1981) rather supported a single dome centered over Hudson Bay. Their hypotheses were based on isostatic rebound. But morphological features of the Glacial Map of Canada (Prest et al. 1968) and more recent data on ice flows and dispersal trains have led to the proposition of a multiple dome Laurentide Ice Sheet (Shilts et al. 1979; Andrews and Miller 1979; Shilts 1980; Dyke et al. 1982; Dyke and Prest 1987; Dyke et al. 1989).

The ice flows indicators documented in the Chapais-Chibougamau and Abitibi sectors emphasize a more complex history of shifting domes or ice divides during the Late Wisconsinan (Martineau et al. 1984; Prichonnet et al. 1984; Bouchard and Martineau 1985; Veillette 1986, 1989; Prichonnet and Beaudry 1990; Veillette and Pomares 1991). The model of Dyke and Prest (1989) probably best explains the history of ice flows for this area. These authors have proposed the Mistassini ice divide, located west of Chapais, ca 18ka BP. The ice flows issuing from this divide may correspond on one side to the ancient southwestward ice flow measured in Abitibi by Veillette (1986, 1989) and on the other side to the ancient southeastward ice flow of the Chapais-Chibougamau area: the residual southeastward dispersal train identified here can be attributed to this specific ice flow. On the other hand, the ancient northwestward ice flow identified by Veillette and Pomares (1991), north and northwest of Desmaraisville, and correlated by these authors to the southeastward ice flow of Bouchard and Martineau (1985) and Prichonnet and Beaudry (1990) may constrain the exact location of this divide. As a consequence, on the western side of the Mistassini ice divide the ice was probably flowing toward the Abitibi on its southern portion, and toward James Bay on its northern portion. This precludes the existence, at that time, of a major ice divide crossing James Bay at its northern tip, namely the Hudson ice divide. And to allow an ice flow toward James Bay from the Mistassini ice divide, there must have been a saddle over this area. The field data presented here and the work of Veillette and Pomares (1991) support the presence of an ice dispersal center or an ice divide located southwest of Hudson Bay.

Conclusion

The results presented here constitute a framework for future studies of mineral exploration and of Quaternary stratigraphy in the Chapais area. Striations, crag-and-tails, and drumlins give the best idea of the last ice movements that prevailed in this area. A major southwestward dispersal train from the Opémisca Pluton, which is in agreement with geomorphological features, has been identified and documented (Fig.3.5a). The dispersal train has a lobate pattern and the distribution of the clasts can be explained both by the positive topography of outcrops on the western side of the Opémisca Pluton (Fig.3.1c), and by deeper glacial erosion of the southwestern branch of Lake Opémisca. The eastern sector of the pluton being relatively peneplained, the resulting dispersal train is more uniform.

A residual southeastward dispersal train is observed for the first time at the eastern edge of the Opémisca Pluton (Fig.3.5a): this fan contains much less debris from the Opémisca Pluton than the southwestern dispersal train, and its low content could be a consequence of a dilution by the southwestward ice flow.

The pattern of the dispersal trains support the relative chronology of the ice movements proposed by several authors for the Chapais area (see Prichonnet and Beaudry 1990). Moreover, this sequence of ice movements and the ice flows observed in the Desmaraisville-Matagami region by Veillette and Pomares (1991) suggest that the Hudson ice divide of Dyke and Prest (1989) did not extend over James Bay during the Late Wisconsinan maximum.

Multiple ice flows constitute a geological constraint in the mineral programs using till or erratics as an exploration tool. Future programs should focus more precisely on their effects over successive till sheets, presuming their existence in some protected zones, where the till sheet is thick.

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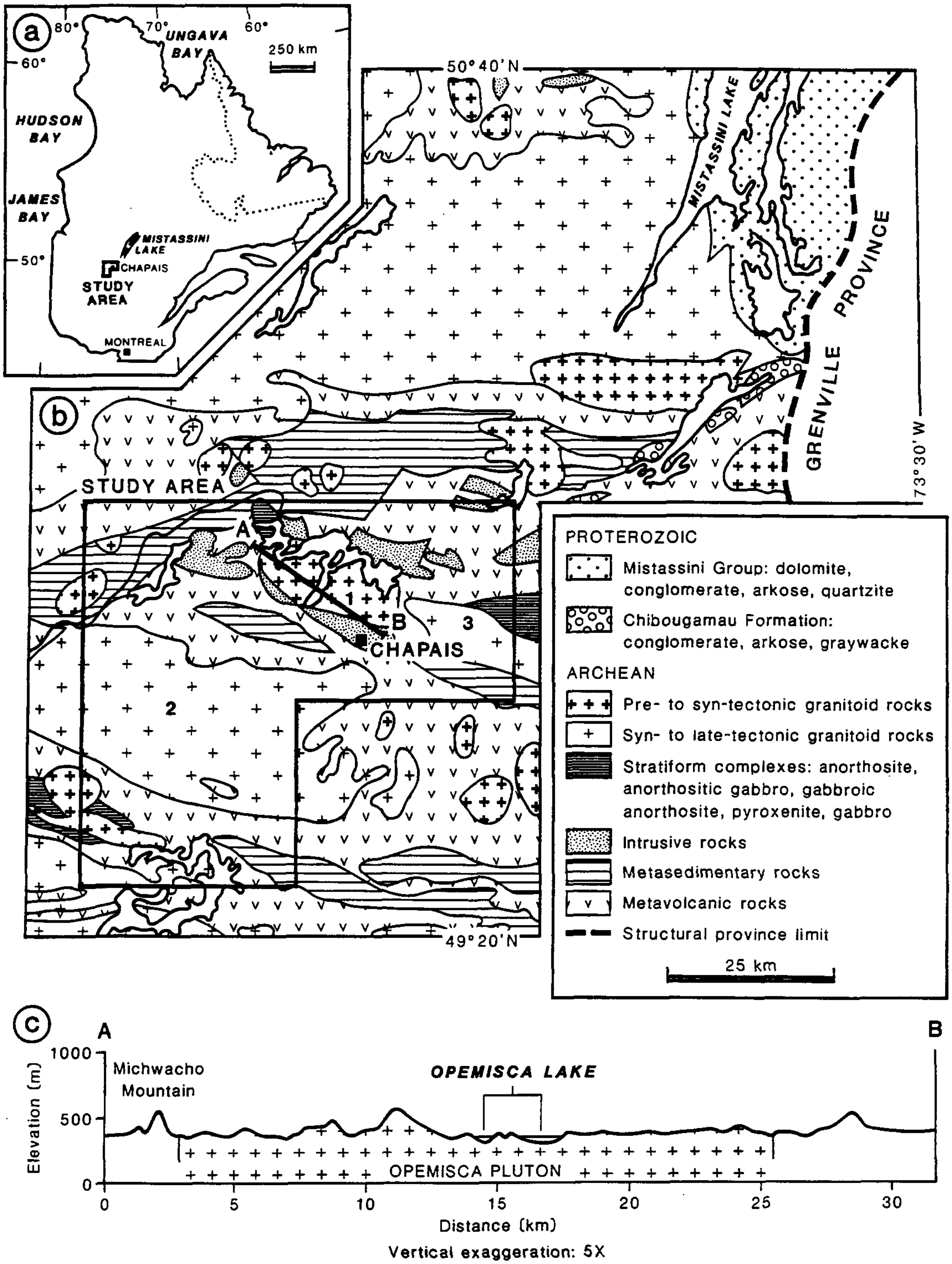

Fig.3.1 a. Location map. b. Generalized geological map of the studied area and surrounding terrain (modified from Avramtchev, 1985): 1- Opémisca Pluton, 2- Lapparent Pluton, 3- Chibougamau Pluton. C. Topographic profile (A-B) of the Opémisca Pluton.

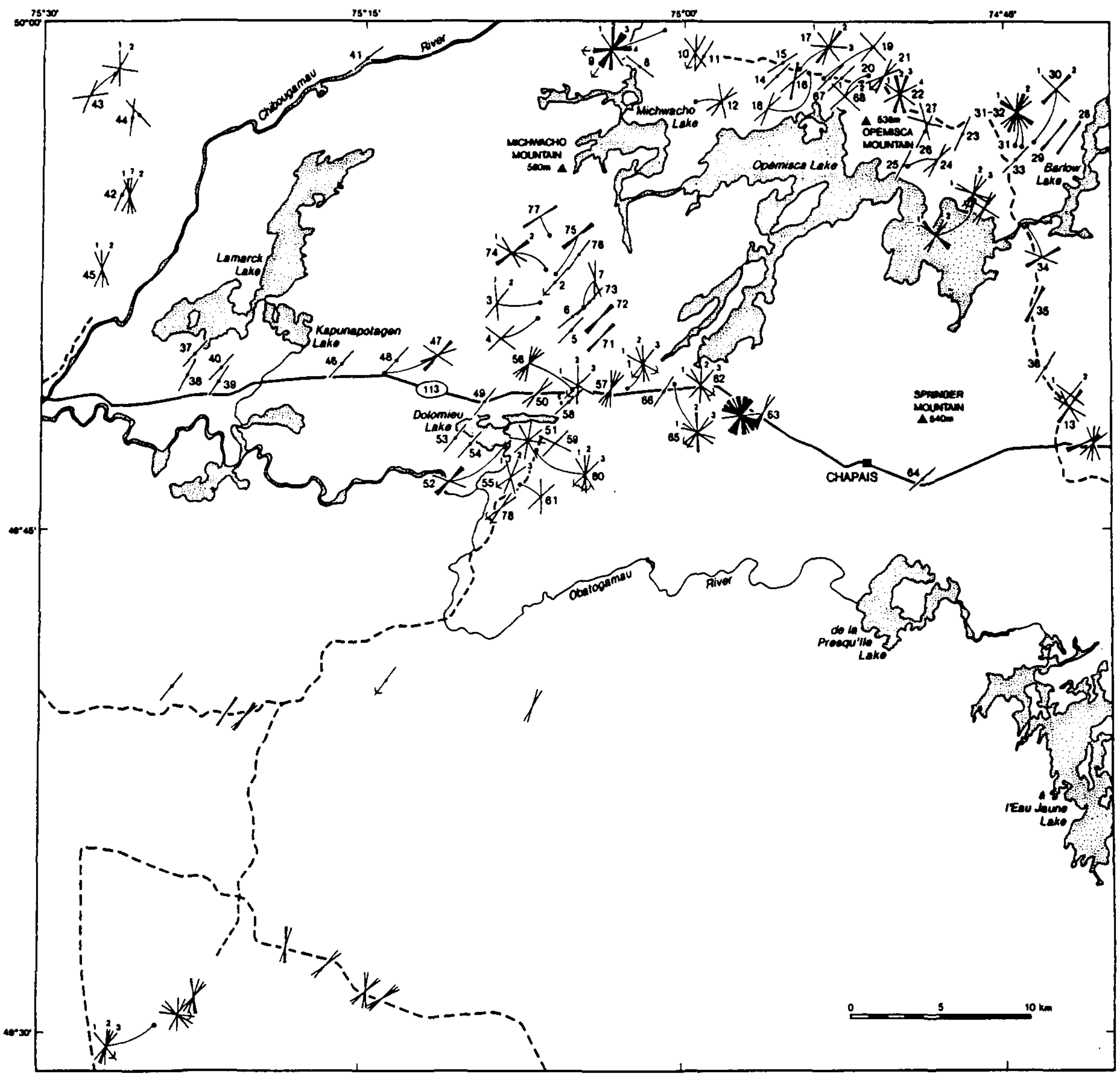

Fig.3.2 Location of the measured erosional marks in the Chapais area (modified from Prichonnet and Beaudry 1990).

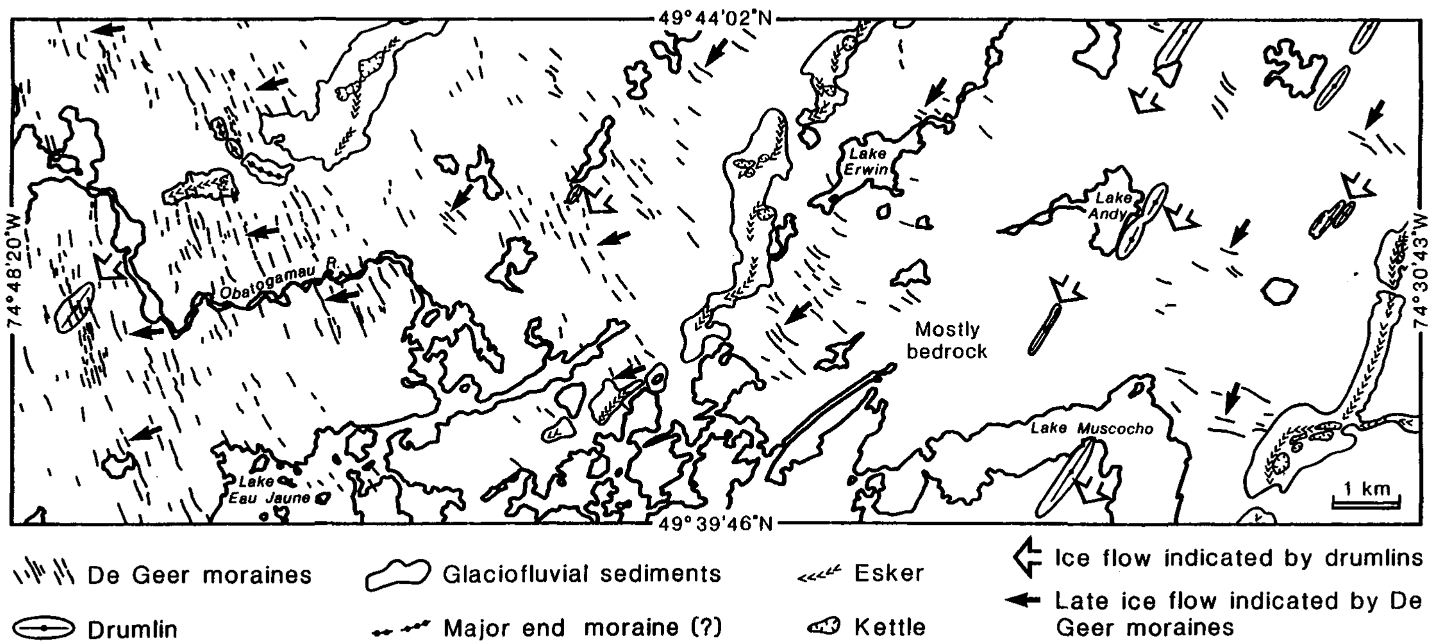

Fig.3.3 Map of De Geer moraines and other important geomorphological features of a sector located 10 km southeast of Chapais. Note the shift in the orientation of De Geer moraines in the western part of the map.

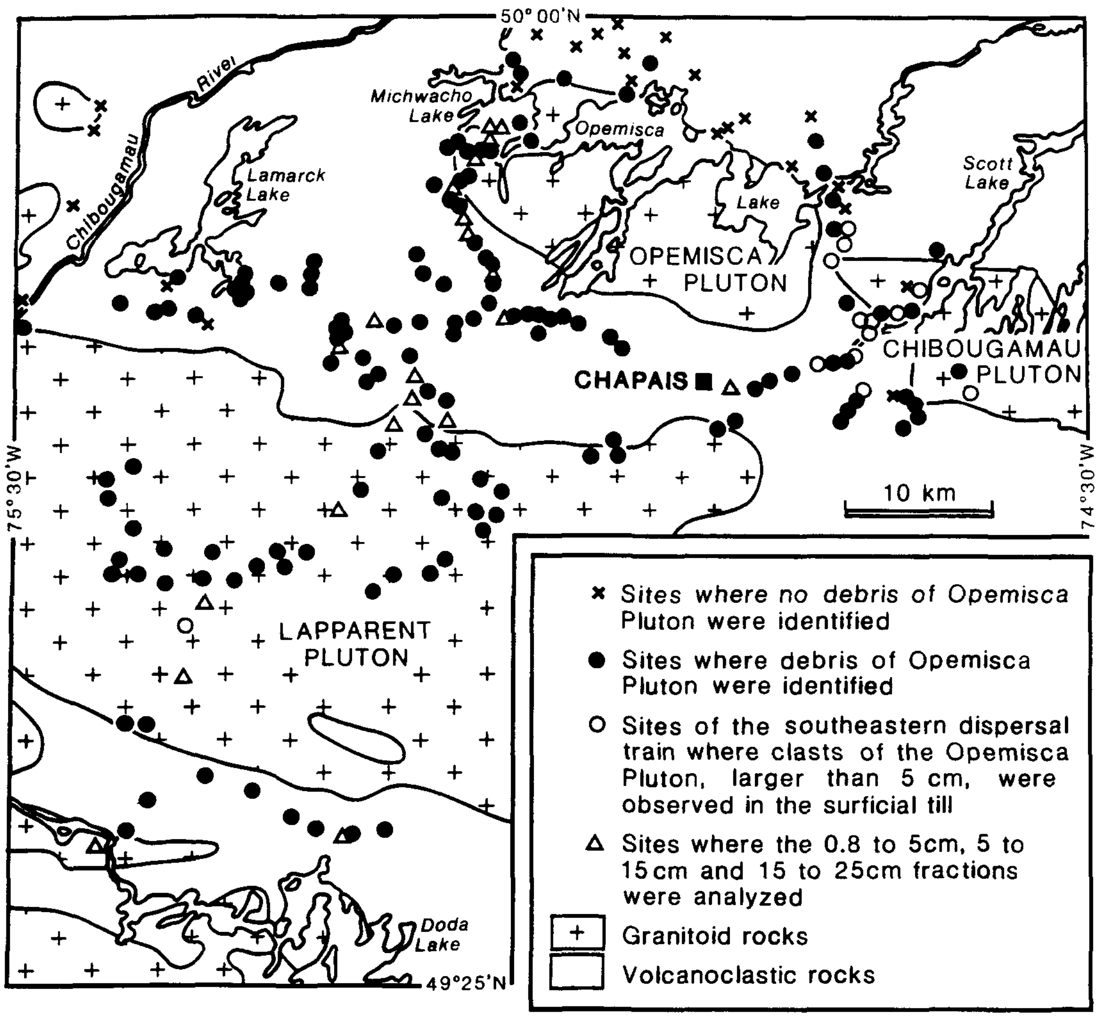

Fig.3.4 Location of sampling sites in the surface till of the Chapais area.

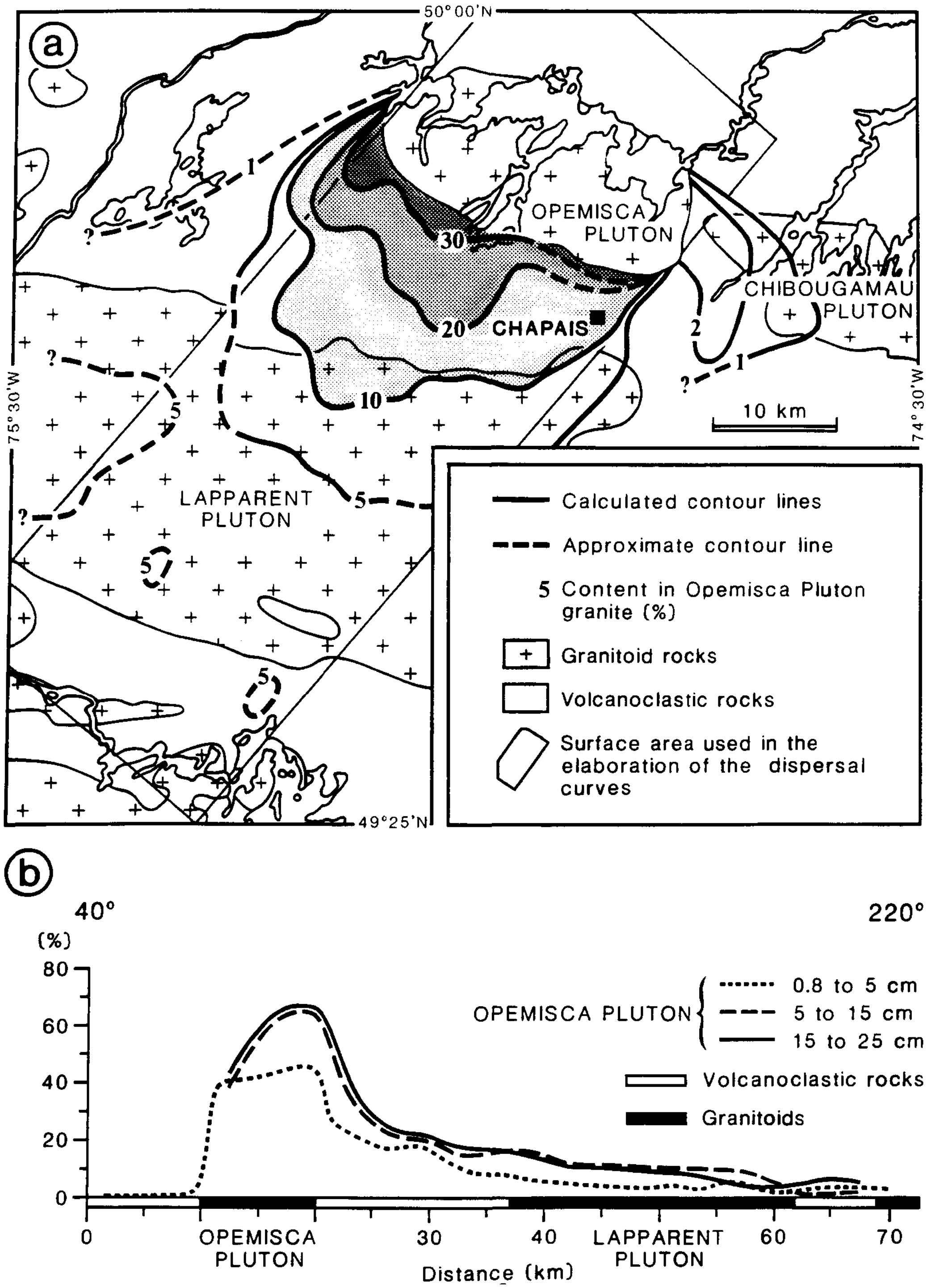

Fig.3.5 a. Distribution (in %) of the content of Opémisca Pluton clasts in the surface till. b. Dispersal curves of the Opémisca Pluton debris in the surface till.

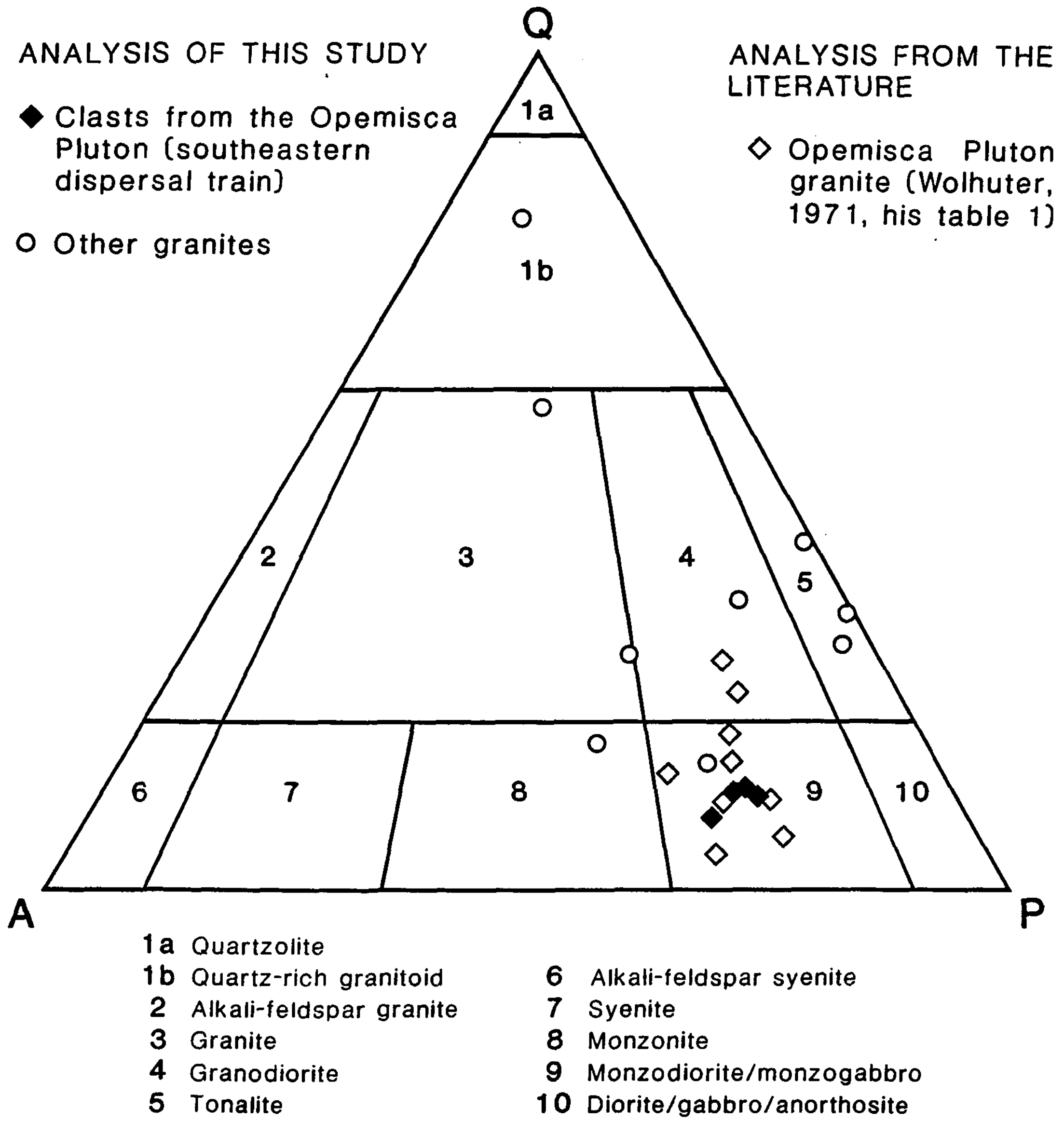

Fig.3.6 Streckeisen diagram for granitoid rocks. The other granite located inside the cluster formed by the samples from the Opémisca Pluton is from an area of the Lapparent Pluton where the granite is similar to the tracer. The other granites are clasts coming from till.

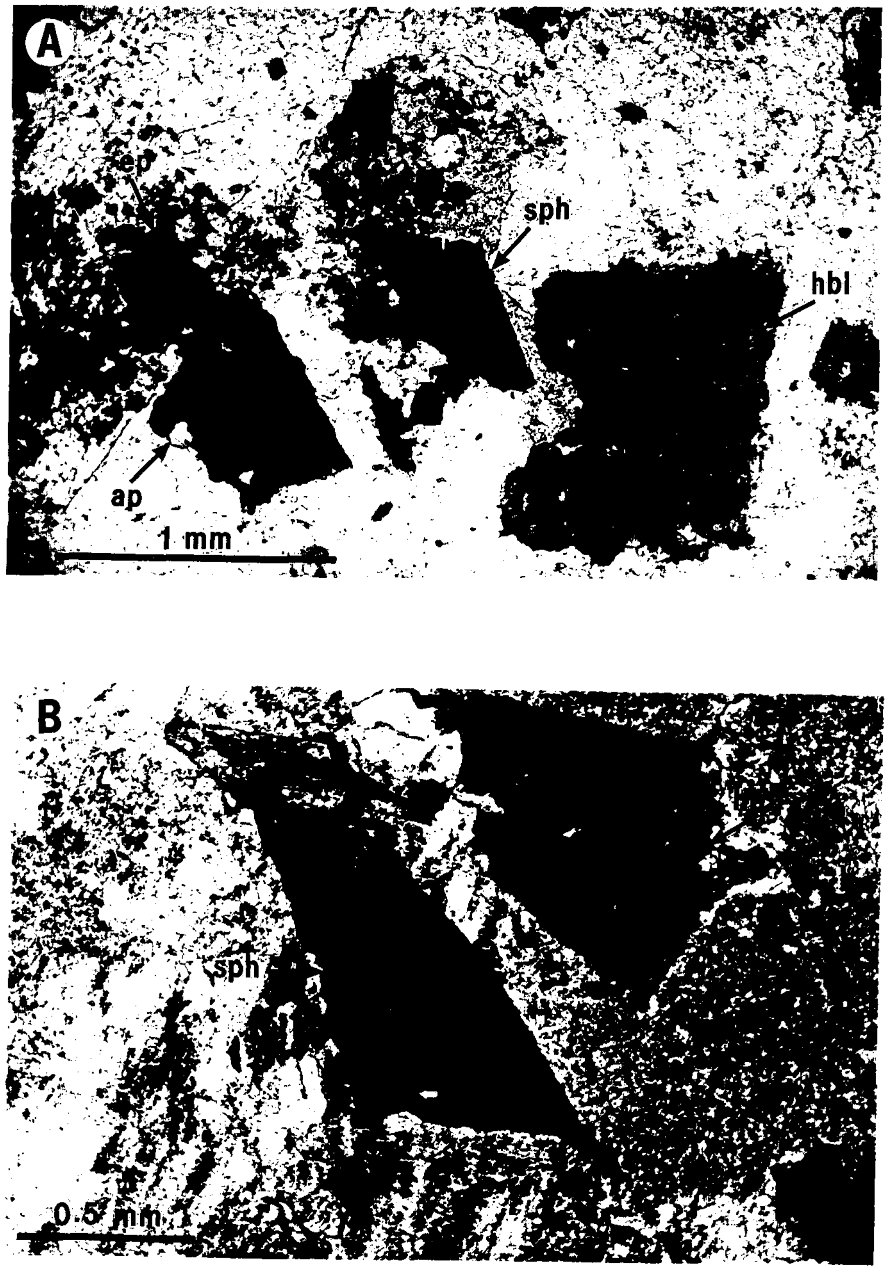

Fig.3.7 Thin sections from the granite of the Opémisca Pluton. A. Sample from the bedrock, south of Lake Michwacho. B. Sample of a clast sampled in the surface till, southeast of the pluton. Abbreviations: hbl, hornblende; sph, sphene; ap, apatite; ep, epidote.

CONCLUSIONS GÉNÉRALES

Les travaux réalisés dans le cadre de cette thèse ont pour objectif d'améliorer la connaissance des moraines de De Geer et de la dispersion glaciaire clastique. Les régions de Chapais et de Radisson sont intéressantes à cause de l'importance des champs de moraines et de l'abondante couverture de till.

Moraines de De Geer

L'étude des moraines de De Geer des régions de Chapais et de Radisson porte sur quelques aspects de leur géomorphologie tels que leur distribution spatiale, le tracé des segments morainiques et leur relation avec d'autres formes d'accumulation glaciaires. Mais les travaux concernent également l'étude de leurs faciès, soit les structures sédimentaires primaires, les structures de déformation, les fabriques de till et la composition lithologique des sédiments. Les observations recueillies et l'analyse de nombreuses mesures in situ ont servi à l'élaboration d'un modèle de mise en place.

Géomorphologie

Quelques conclusions importantes ressortent de l'étude géomorphologique. (1) L'espacement entre les moraines paraît plus irrégulier que ce qui est généralement présenté dans la documentation scientifique. Cecui-ci varie entre 15 et 900 m, et les valeurs moyennes (180 à 190 m) dénotent une distribution asymétrique centrée sur les espacements les plus faibles. (2) La géométrie en plan des segments morainiques est très variable, mais la plupart forment un tracé en chevrons. L'observation de moraines constituées d'un segment principal et d'un ou plusieurs appendices à angle droit ou oblique est également fréquente. Des moraines formant un réseau angulaire en grille ont également été identifiées.

Relations spatiales avec d'autres formes d'accumulation glaciaires

La relation spatiale, à l'échelle régionale, entre les moraines de De Geer et d'autres formes d'accumulation glaciaires est documentée. (1) L'observation majeure est la mise en évidence de la diminution de la densité des drumlins vers l'intérieur des champs de moraines de De Geer. Dans le détail, les moraines recoupent souvent des formes qui ont un profil drumlinoïde sans en posséder toutes les caractéristiques. Des drumlins tronqués directement à l'amont de moraines de De Geer ont été identifiés. Ceci suggère que les sédiments composant ces moraines proviennent d'une déformation du drumlin sous-jacent. (2) La relation spatiale entre les moraines de De Geer et les eskers montre bien que les moraines sont incurvées vers l'amont glaciaire à proximité de ces accumulations fluvioglaciaires. Ceci confirme d'autres exemples cités dans la littérature. Un esker qui semble être constitué de moraines de De Geer coalescentes a été identifié. Ceci suggère un lien possible entre les moraines de De Geer formées de sédiments triés et certains eskers. (3) Une relation est observée entre les moraines de De Geer et les moraines de Rogen dans la région de Chapais: à l'intérieur du bassin glaciolacustre, les moraines de De Geer possèdent toutes les caractéristiques morphologiques connues, à savoir des segments minces et allongés dont la crête est pointue et le profil symétrique ou asymétrique; par contre, vers la bordure du bassin glaciolacustre, les formes deviennent plus ténues et plus larges, et passent latéralement à des moraines de Rogen. Dans la région de Chapais, une forme de transition entre les moraines de De Geer et des moraines de Rogen a été décrite pour la première fois. Les trois types de moraines mineures occupent le bassin du lac Caopatina. Les moraines de De Geer sont localisées du côté amont du bassin, les moraines de Rogen du côté aval et les moraines de transition occupent le centre de la dépression. Les moraines de transition sont constituées de deux ou trois crêtes accolées les unes aux autres. Leur morphologie et leur position entre les moraines de De Geer et les moraines de Rogen suggèrent qu'il pourrait s'agir de moraines de De Geer accolées les unes aux autres lors du passage d'un régime d'extension à un régime de compression.

Étude des faciès

Trois faciès ont été reconnus dans l'étude de douze coupes, dont huit furent taillées en séries dans des moraines successives.

(1) Des séries de moraines (jusqu'à 15 segments successifs et parallèles entre eux) sont constituées de sédiments triés. Des moraines plus isolées mais présentant ce faciès sont également observées. Les séries pourraient être associées à des accumulations majeures de sédiments fluvioglaciaires. Les sédiments triés représentent 25 à 100% de la surface des coupes étudiées. Ils forment des lits obliques inclinés vers l'aval glaciaire, perpendiculairement à l'axe de la moraine. Du diamicton et du till drapent parfois la surface du versant proximal ou forment des lentilles injectées dans les sédiments triés. Des structures de déformation telles des plis déversés à couchés et des failles inverses ont été identifiées du côté proximal et sous la crête. Les plans axiaux des plis et les plans de failles sont inclinés vers l'amont glaciaire. Les déplacements des lits obliques le long des plans de failles traduisent des compressions mineures et sans doute répétitives en direction de l'aval glaciaire.

(2) Beaucoup de moraines sont composées de till peu compact et non fissile. Ce till peut contenir des lentilles de sédiments triés et recouvre des sédiments stratifiés. Des mesures sur les lits obliques des sédiments stratifiés permettent de conclure que les eaux de fonte s'écoulaient vers l'aval glaciaire, perpendiculairement à l'axe de la forme. Les fabriques de till ne montrent pas d'orientation préférentielle

du grand axe des galets. Mais les lentilles de sédiments triés incorporées dans le till et les structures sédimentaires des sédiments stratifiés sont déformées. Les structures de déformation consistent en des plis déversés à couchés, des failles inverses, des structures d'entraînement et des figures de charge. Les plans axiaux des plis et les plans de cisaillement sont tous inclinés vers l'amont glaciaire. Le déplacement le long des plans de failles et les structures d'entraînement traduisent un mouvement dans le sens de l'écoulement glaciaire. Donc, les observations et les mesures suggèrent des poussées mineures par une glace active.

(3) D'autres moraines sont constituées d'un till compact et fissile. Ce till est surconsolidé et il ne contient généralement pas de laminations de sédiments triés, mais il peut être observé recouvrant une unité de sédiments stratifiés ou le till de fond. Des structures de déformation ont été identifiées dans les sédiments stratifiés et dans le till. Il s'agit de plis déversés à couchés. Leurs plans axiaux sont inclinés vers l'amont glaciaire. Une fabrique de till mesurée dans une moraine montre que les grands axes sont inclinés vers l'amont glaciaire. Donc, les caractéristiques du till et ces mesures suggèrent que les sédiments ont été déposés à la base d'un glacier actif.

(4) Les trois faciès documentés semblent être reliés spatialement. Un continuum a été identifié depuis les séries de moraines constituées de sédiments triés

jusqu'aux moraines composées d'un till compact et fissile. Cette relation spatiale suggère que l'influence des eaux de fonte, dans le dépôt des sédiments formant les trois faciès, aurait varié latéralement.

(5) La composition lithologique des sédiments morainiques et du till de fond montre que celles-ci sont semblables. Dans certains secteurs, la composition lithologique du till de fond diffère dans des sites d'échantillonnage séparés par quelques centaines de mètres. Ces sites sont localisés quelques mètres en amont de moraines de De Geer dont la composition lithologique a été analysée. Dans tous les cas, la composition lithologique des sédiments morainiques est la même que celle du till de fond situé directement en amont. Ces observations suggèrent que les sédiments constituant les moraines proviennent des environs immédiats de la construction. Toutefois, certaines moraines contiennent plus d'éléments du substratum rocheux local que le till de fond situé à l'amont. Ceci pourrait signifier que des éléments du substratum rocheux auraient été délogés et incorporés au till pendant le dépôt des sédiments morainiques. Ces caractéristiques leur confère une certaine valeur pour des études de la dispersion glaciaire clastique.

Mode de mise en place

Les caractéristiques identifiées ont permis de proposer leur mise en place dans des crevasses basales, par un glacier actif. Le glacier étant en contact avec un plan d'eau (le lac glaciaire Ojibway ou la Mer de Tyrrell), la marge du glacier avait tendance à se soulever. Ce soulèvement de la glace devait entraîner une augmentation des tensions le long de la ligne d'ancrage du glacier. Ceci devait favoriser l'ouverture des crevasses basales. Les eaux de fonte, chenalisées dans certains secteurs, triaient et déposaient les sédiments en lits obliques dans les crevasses. Le glacier était toujours actif pendant cette phase de sédimentation puisque les structures sédimentaires primaires ont été déformées. Le till a été déposé du côté proximal, sous forme d'une mince couverture superficielle ou de lentilles injectées dans les sédiments triés. Latéralement aux zones de circulation plus intense des eaux de fonte, la diminution des écoulements ne permettait qu'un faible dépôt de sédiments fins triés. La présence de grands lambeaux de till peu compact et non fissile qui recouvrent ces sédiments fins triés, les structures de déformation et leur composition lithologique permettent de conclure à une activité tardive du glacier. Pendant cette activité, des lambeaux de till provenant de la partie superficielle de la nappe de till de fond ont été remobilisés et déformés, et ensuite déplacés vers des crevasses basales localisées en aval pour former des moraines. En s'éloignant d'avantage des zones de circulation d'eaux de fonte, le till était déposé par accrétion à la base du glacier. Les modalités de mise en place présentées ici témoignent donc en faveur d'une marge glaciaire très active et d'une abondance des eaux de fonte.

Contributions aux connaissances scientifiques

L'étude des moraines de De Geer des régions de Chapais et de Radisson contribue à l'avancement des connaissances scientifiques de plusieurs façons.

Cette thèse accorde une plus grande importance aux faciès. Si les faciès décrits avaient été reconnus déjà, c'est la première fois que leur agencement et la variation de leur pourcentage sont détaillés dans des moraines de De Geer. Larsen et al. (1991) ont bien présenté brièvement certains faciès semblables à ceux décrits ici et Smith (1982) a décrit des moraines constituées de sédiments stratifiés et déformés, mais la plupart des études antérieures n'ont pas attaché la même importance aux sédiments triés, ni décrit les structures de déformation. Et Zilliacus (1987b, fig.26) qui signale la présence de sédiments fins triés sous le till formant une moraine n'a pas accordé d'importance à une telle disposition des faciès. Il nous paraît important d'avoir montré en particulier la relation spatiale entre les trois faciès décrits. Celle-ci suggère que plusieurs segments morainiques successifs pouvaient se construire simultanément à la base du glacier. Ceci constitue un argument de taille contre les hypothèses voulant que les moraines de De Geer soient utilisées comme marqueurs chronologiques. La méthodologie de terrain, basée sur une description détaillée et un relevé des structures primaires et secondaires permet une meilleure compréhension des processus dynamiques au front du glacier. Ainsi, le glacier semblait être actif pendant la construction des moraines. Cette activité était responsable de l'écoulement des eaux de fonte. Lorsque les eaux se concentraient dans de grands tunnels, le résultat était la mise en place de très longs eskers. Lorsque les eaux s'échappaient par des circuits plus petits et anastomosés, le matériel trié remplissait les crevasses frontales.

Une attention particulière a aussi été accordée à la composition lithologique des sédiments morainiques et à certains aspects de leur géomorphologie. Zilliacus (1987b) a suggéré que les sédiments morainiques avaient une provenance plus distale que le till de fond adjacent. Nos analyses montrent plutôt que ces sédiments ont une composition lithologique comparable et que, dans certains cas, des débris du substratum rocheux sous-jacent semblent avoir été incorporés dans le matériel morainique, lui conférant une origine plus locale que le till de fond adjacent. Cette observation a un impact évident au niveau de l'exploration minérale puisque l'utilisation du matériel morainique s'avère utile pour la recherche de minéraux économiques, du moins pour les fractions granulométriques de 0.8 à 25 cm. Sur le plan de la géomorphologie, la contribution porte sur quatre aspects: (a) l'analyse du tracé des segments morainiques. On a pu observer que ceux-ci sont souvent en forme de chevrons. Prichonnet et al. (1984) avaient d'ailleurs remarqué cette caractéristique des moraines de De Geer à l'est de Chapais; (b) l'analyse de la relation entre les moraines de De Geer et les drumlins. Hardy (1976) avait déjà souligné divers degrés de développement de ces deux formes lorsqu'elles sont associées l'une à l'autre. Ici, il a été démontré que la densité des drumlins diminue vers l'intérieur des champs de moraines de De Geer; (c) l'identification d'une forme de transition entre les moraines de De Geer et les moraines de Rogen. Cette forme est probablement décrite pour la première fois; (d) la proposition d'un modèle incluant les moraines de De Geer dans la succession des formes glaciaires (Fig.2.13). Dans ce modèle, les moraines de De Geer sont corrélées avec les quatre derniers membres du modèle de Sugden and John (1976). Les moraines de De Geer ont été mises en place puisque la nappe d'eau frontale a modifié la dynamique de la marge glaciaire.

Dispersion glaciaire clastique

L'étude de la dispersion glaciaire clastique dans la région de Chapais porte sur le contenu en débris du pluton d'Opémisca dans la nappe de till de fond régionale, couvrant une superficie de 3 700 km^2. Les débris de trois fractions granulométriques sont analysés (0.8 à 5 cm; 5 à 15 cm; 15 à 25). L'objectif est de vérifier l'influence des quatre écoulements glaciaires identifiés dans cette région sur la dispersion des débris délogés du substratum rocheux.

Cette étude a permis l'identification d'un transport de débris du pluton d'Opémisca dans deux directions orthogonales. (1) Une traînée de dispersion majeure est dirigée vers le sud-ouest. Elle est parallèle au dernier écoulement glaciaire régional mis en évidence par des marques d'érosion à la surface d'affleurements rocheux. (2) Une traînée de dispersion résiduelle en direction du sud-est est également identifiée. Elle est parallèle à l'écoulement glaciaire régional le plus ancien sur la moitié de son extension. Puis la terminaison de cette traînée résiduelle est déviée vers le sud-sud-ouest. Ceci pourrait suggérer une reprise en charge du till de fond par l'écoulement sud-ouest. L'influence de cet ancien écoulement glaciaire, bien que suspectée par d'autres (Bisson, 1987; De Corta, 1988), semble devoir être considérée avec plus d'attention à l'avenir puisque l'allure de ces traînées de dispersion semble confirmer la chronologie des écoulements glaciaires proposée pour la région de Chapais; l'écoulement vers le sud-est a précédé l'écoulement vers le sud-ouest. Ces résultats pourront être utiles à ceux utilisant le contenu minéral des dépôts d'origine glaciaire pour la recherche de minéraux économiques. Les données documentées ici s'ajoutent à celles présentées par d'autres auteurs qui ont proposé des modèles concernant la configuration de l'inlandsis laurentidien. L'analyse des présentes données suggère qu'au moment où le train de dispersion de direction sud-est a été mis en place, il y avait probablement une ligne de partage des glaces ou un dôme centré au sud-ouest de la baie d'Hudson.

Études futures

Des éléments nouveaux sont identifiés dans cette thèse, mais tous les aspects reliés aux problématiques développées n'ont pu être couverts et mériteraient d'être approfondis.

L'analyse détaillée des faciès semble favoriser une meilleure compréhension des processus responsables de la mise en place des moraines de De Geer. D'autres études régionales permettraient de vérifier si les faits observés ici se répètent ailleurs. Une attention particulière devrait être accordée à la présence de sédiments triés, de structures de déformations glaciotectoniques et à la relation spatiale entre les faciès. Ces travaux pourraient contribuer à améliorer nos connaissances sur la dynamique glaciaire pendant une déglaciation, en particulier pour déterminer les conditions hydrauliques à la base du glacier et le degré d'activité de la glace. Il est probable que de telles observations permettraient de mieux comprendre la signification des moraines mineures dans la suite des événements qui marquent une déglaciation, et en particulier de relativiser le rôle de marqueur chronologique des moraines de De Geer.

Certains aspects de la géomorphologie de ce type de moraines mineures mériteraient d'être développés. (1) L'analyse du tracé des segments morainiques pourrait permettre de préciser l'hypothèse d'un dépôt dans des crevasses sous-glaciaires. (2) La relation stratigraphique entre les drumlins et les moraines de De Geer devrait être détaillée. Les processus de déformation et de remobilisation des sédiments composant les drumlins seraient sans doute mieux compris. (3) L'étude de la relation entre les moraines de De Geer et les autres formes d'accumulation glaciaires devrait permettre de préciser la place de ce type de moraines mineures dans le modèle de succession des formes glaciaires. (4) L'étude du phénomène de transition entre les moraines de De Geer et les moraines de Rögen pourrait permettre d'acquérir de nouvelles données sur la genèse des moraines mineures, et de mieux comprendre les raisons du confinement des moraines de De Geer aux bassins glaciolacustres et glaciomarins. (5) La mise en évidence de relations entre les moraines de De Geer et certaines moraines de Rogen ainsi que les nombreuses hypothèses proposées à ce jour relativement à leur mode de mise en place permettent de poser la question suivante: cette relation devrait-elle nous ramener vers la nomenclature proposée par Elson (1968), où les moraines du type De Geer sont décrites comme faisant partie d'un ensemble de moraines mineures?

L'étude de dispersion glaciaire clastique a été réalisée uniquement à partir d'échantillons prélevés dans la partie superficielle de la nappe de till. Mais le substratum rocheux de la région de Chapais est recouvert d'une épaisseur de dépôts meubles dépassant parfois 50 m, dont plus de 30 m de till. Le traçage de minéraux économiques à partir du contenu minéral des sédiments diamictiques pourrait devenir une méthode plus appliquée dans les régions minières. Mais d'autres études portant sur les variations verticales de la composition lithologique de la nappe de till devraient être réalisées. Les effets de la topographie du substratum rocheux sur l'écoulement de la glace et l'influence de l'ancien écoulement glaciaire vers le sud-est à l'interface roc/till seraient probablement mieux compris. La collaboration entre les entreprises minières et les chercheurs serait des plus profitable. Ces études permettraient d'améliorer les méthodes de prospection minière dans des régions couvertes par de grandes épaisseurs de mort-terrain et d'améliorer nos connaissances sur la stratigraphie régionale. En effet, jusqu'à ce jour, peu de données permettent de reconstituer l'évolution de la géométrie du Glacier du Nouveau-Québec pendant le Wisconsinien. Seules des marques d'érosion glaciaires sont utilisées à cette fin. Leur étude mériterait d'être étendue depuis Chapais vers la baie James afin de préciser la position des dômes ou des lignes de partage des glaces.

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