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Bedrock and surficial geology of the general area around Rouyn-Noranda, Quebec and Ontario

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Abstract: Rouyn-Noranda is located in the Abitibi Subprovince that contains the Abitibi Greenstone Belt, the largest granite-greenstone terrane in the world, comprised primarily of Archean sedimentary and volcanic sequences intruded by granitoids. About 70% of Canadian gold mines are located in this important mining camp. The region discussed herein lies within a radius of about 100 km from Rouyn-Noranda and covers the area of several smelter studies that are based on the sampling of glacial and lake-bottom sediments. Thick glacial, glaciofluvial, and glaciolacustrine deposits cover a large part of the Abitibi Greenstone Belt and regional studies have revealed a complex glacial history characterized by a sequence of shifting ice flows ending with convergent flows toward a major interlobate deglaciation landform, the Harricana Moraine. Glacial transport of materials from distant source areas is of special significance for the geochemical study of surficial deposits and lake-bottom sediments in the Abitibi–Témiscamingue region. The fine fraction of till and glaciolacustrine silt and clay in the western part of the region may contain calcareous rock flour 'imported' from the carbonate rocks of the Hudson Platform to the northwest; these deposits are devoid of carbonate material in the eastern part of the region. In examining the geochemistry of soils, lake sediments, and peat, the interpretation of element distribution patterns around the smelter at Rouyn-Noranda must consider not only the distribution of bedrock types, but also the effects of glacial transport on the geochemistry, carbonate content, and pH of glacially transported surficial materials.

Résumé : Rouyn-Noranda se trouve dans la sous-province de l'Abitibi, qui contient la ceinture de roches vertes de l'Abitibi. Cette dernière, qui constitue le plus grand terrane de granite et de roches vertes au monde, renferme principalement des séquences sédimentaires et volcaniques archéennes recoupées par des granitoïdes et compte environ 70 % des mines d'or canadiennes. La région dont on traite est située à quelque 100 km de Rouyn-Noranda; on y a exécuté plusieurs études fondées sur l'analyse d'échantillons de sédiments glaciaires et lacustres. La ceinture de roches vertes de l'Abitibi est en grande partie recouverte d'une épaisse couche de sédiments glaciaires, fluvioglaciaires et glaciolacustres. En outre, des études régionales ont révélé son histoire glaciaire complexe, qui se caractérise par une série d'écoulements glaciaires changeants laquelle s'est conclue par la convergence d'écoulements vers une importante entité topographique interlobaire de déglaciation, soit la Moraine d'Harricana. Le transport glaciaire de matériaux provenant de sources éloignées revêt une importance particulière lorsque l'on étudie la composition géochimique des dépôts de surface et des sédiments lacustres de la région de l'Abitibi-Témiscamingue. La fraction fine du till ainsi que le silt et l'argile glaciolacustres de l'ouest de la région peuvent contenir de la farine glaciaire calcaire issue de roches carbonatées de la plate-forme d'Hudson, située au nord-ouest. Dans l'est de la région, cette farine glaciaire est dépourvue de matériaux carbonatés. Pendant l'étude géochimique des sols, des sédiments lacustres et de la tourbe, l'interprétation de la répartition des éléments autour de la fonderie de Rouyn-Noranda doit non seulement tenir compte de la répartition des types de socle rocheux, mais également de l'incidence du transport glaciaire sur la géochimie, la teneur en carbonates et le pH des matériaux de surface charriés par les glaciers.

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INTRODUCTION

An overview of the bedrock geology, surficial geology, and glacial history of a large part of northwestern Quebec and northeastern Ontario (Fig. 1) is presented herein to provide a geological framework for the various studies carried out within the Rouyn-Noranda Metals in the Environment (MITE) smelter study described in Bonham-Carter (2005). The rich mineral resources of the Abitibi Subprovince, in which the Abitibi Greenstone Belt is located, have attracted geologists and prospectors for nearly a century. About 70% of gold mines in Canada are located in the Abitibi Greenstone Belt and more than 145 mines have produced precious and base metals over the years. From the very beginning, mining has been the main economic motor of the region. It is estimated that during the past 90 years, approximately 130 million ounces of gold worth $39 billion (at $300 US an ounce) have been mined from the Abitibi Greenstone Belt (M. Doggett, pers. comm., 1999, *in* McClenaghan, 2001).

The numerous mines located along the Cadillac-Larder Lake fault dictated the main concentrations of population; Val-d'Or and Rouyn-Noranda, the two largest cities of the region located along this fault, account for two thirds of the population within the Quebec portion of the Abitibi Greenstone Belt.

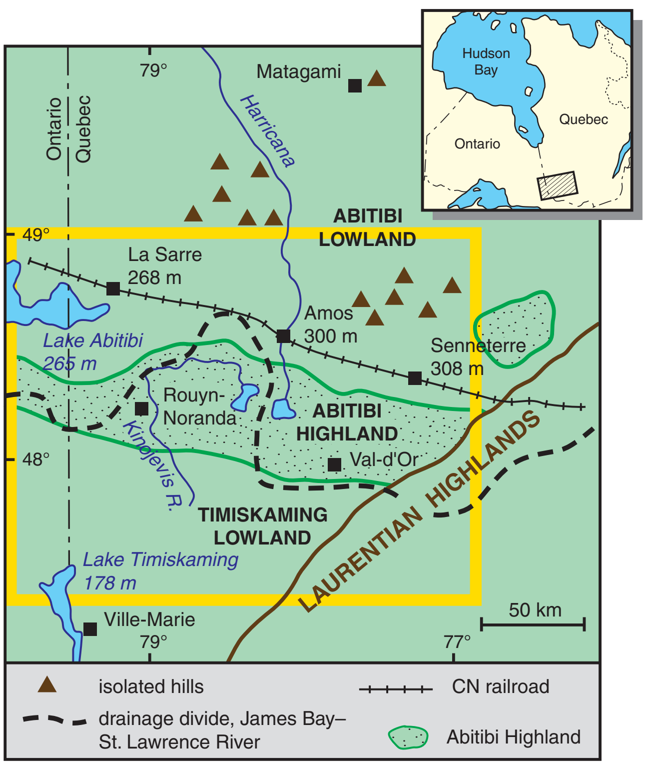

Figure 1. *Location and physiography of central Abitibi–Témiscamingue (*modified from *Bostock, 1970 and Vincent et al., 1995); the yellow box shows the area for which digital bedrock and surficial geology (Fig. 2) maps are provided. Elevations are in metres above sea level.*

The construction of the Canadian National Railway in 1910 through northern Quebec and northern Ontario acted as a catalyst for mineral exploration. Those were the days of the solitary prospector exploring mostly by canoe. The east-west railroad crossed the many rivers flowing toward James Bay, thus providing several access points to the region. Within a few years, several gold deposits had been discovered. In 1911, Ed Horne found a promising prospect in the Rouyn area, which he explored in detail between 1914 and 1917. In 1920, he claimed properties on the north shore of Lake Osisko (where the city of Rouyn-Noranda is now located), which started a staking rush in nearby townships. Despite these activities, investors remained hesitant and more interested in the large gold deposits of the Kirkland Lake and Porcupine areas in Ontario (Vincent et al., 1995)

The complex geology and the extent of the Abitibi Greenstone Belt were poorly understood. It was suggested in the annual report of the Ontario Department of Mines (1922) that the northern Ontario mineralized belt extended eastward into Quebec. The gold discovery of the Powell mine, close to claims owned by Horne, was then interpreted as a confirmation of this eastward extension, and started an unprecedented staking rush in the Rouyn area. Noranda Mines was formed to develop the Rouyn properties. In 1925, the company declared reserves of about 1 million tons containing gold, copper, and silver with an estimated value of about $20 million (Vincent et al., 1995). The construction of a mine, a copper smelter, and a town was undertaken. Rouyn (now Rouyn-Noranda) was born.

The study of the glacial history and surficial geology of the Abitibi–Témiscamingue area has long been overshadowed by the greater attention given to bedrock geology, the foundation of the region's strong and healthy mineral industry. In recent years, however, environmental concerns related to mining and forestry practices, the realization that glaciofluvial deposits contain large, high-quality groundwater reserves, and the growth of ecotourism have put Quaternary studies in the forefront. Glaciers of the last ice age left an extensive cover of thick glacial, glaciofluvial, and glaciolacustrine deposits that prevent direct access to bedrock over large areas of economic interest. This impediment makes areas of scarce outcrops such as the Casa Berardi area north of LaSarre, Quebec "...one of the most difficult exploration terrains in Canada..." (Northern Miner, June 13, 1988). Because of this, the gold exploration rush of the mid 1980s had to rely extensively on the use of prospecting methods applicable to glaciated terrain. Thousands of holes were drilled through glacial deposits down to bedrock. The mineral exploration industry gained a new appreciation of mineral exploration methods used in Quaternary geology while contributing to improve our knowledge of the stratigraphy of glacial deposits.

The studies described in Bonham-Carter (2005), several of which are based on the analysis of till and lake-bottom sediments, require a knowledge of the physical and geochemical properties of the Quaternary deposits over which is superimposed a large part of the drainage network. Shifting ice flows within continental ice sheets played a major role in determining the lithological and geochemical properties of the unconsolidated deposits of the region. Former ice flows have brought in rocks and minerals from distant source areas that mixed with local rocks, producing glacial sediments whose composition differs from that of the underlying bedrock at any given location. Consequently, the first prerequisite to a better understanding of the spatial distribution of trace metals is a physical and geochemical characterization of glacial sediments and a rigorous reconstruction of the sequence of events that produced them.

PHYSIOGRAPHY

The Abitibi Highland is the most prominent physiographic feature of the Abitibi–Témiscamingue area. It forms an east-west band up to 50 km wide, consisting of scattered, rounded bedrock hills that reach elevations of about 500 m above sea level (a.s.l.; all elevations referred to herein are above sea level). It extends from south of Lake Abitibi to the Laurentian Highlands to the east (Fig. 1). Since the clay plain left by Glacial Lake Barlow-Ojibway rarely exceeds 320 m in elevation, the Abitibi Highland shows up on a surficial geology map as clusters of bedrock knobs breaking through patches of fine-grained glaciolacustrine deposits of limited extent (see Fig. 2). The Laurentian Highlands, with elevations in the 400 to 600 m range, mark the level of a former peneplain, remnants of which form the Abitibi Highland (the Kekeko Hills near Rouyn-Noranda reach an elevation of 478 m). The divide between the James Bay and St. Lawrence River hydrographic basins is located in the Abitibi Highland. To the south, the Timiskaming Lowland slopes toward Lake Timiskaming (178 m) and to the north, the Abitibi Lowland slopes gradually northwestward toward James Bay from an elevation of about 300 m in the Amos area. Isolated hills north of Amos and Senneterre, some of which formed small islands in the vast expanse of Glacial Lake Ojibway, break the monotony of the clay plain. Most are less than 400 m in elevation, with rare exceptions such as Mount Plamondon northeast of LaSarre culminating at 543 m. Large breaches in the Abitibi Highland occur in the upper reaches of the Kinojevis and Harricana rivers, which acted as outlets for Glacial Lake Barlow-Ojibway.

BEDROCK LITHOLOGY

Rouyn-Noranda is located in the central part of the Abitibi Subprovince, the largest granite-greenstone terrane in the world (Fig. 3a). The Abitibi Greenstone Belt extends from the Timmins area in the southwest to the Lake Mistassini–Chibougamau area in the northeast; it is bounded by metasedimentary gneiss of the Quetico Subprovince to the north, by metamorphic rocks of the Grenville Province to the south, and by sedimentary rocks of the Cobalt Supergroup to the southwest. It consists primarily of Archean metamorphosed sedimentary and volcanic sequences intruded by granitoids. The east-west structural orientation, typical of the Superior Province, is truncated by the Grenville Front. Figure 3a shows the main source areas for far-travelled erratics commonly found in the northern parts of the Abitibi Greenstone Belt. These include carbonate rocks from the Hudson Platform in the James Bay Lowland and sedimentary Proterozoic rocks from southeastern Hudson Bay (Churchill Province) and from the Lake Mistassini basin to the northeast. Their distribution within the Abitibi Greenstone Belt will be discussed later.

The location and types of active mines in the Abitibi Subprovince and the location of kimberlite pipes discovered in recent years are shown in Figure 3b.

The bedrock lithology of a large (35 000 km²) area centred roughly on Rouyn-Noranda is shown on the bedrock lithology map (*see* /Data directory on this CD) adapted from the MERQ–OGS (1984) lithostratigraphic map of the Abitibi Greenstone Belt. Rock units on this map are grouped solely on the basis of lithology. Most studies included in Bonham-Carter (2005) are located entirely or partly within this area. Some specific studies such as the dispersal of dust in snow (Kliza et al., 2005) extend beyond this area. Most rocks within a radius of about 100 km from Rouyn-Noranda are Archean, but some Proterozoic and Paleozoic rocks occur as well.

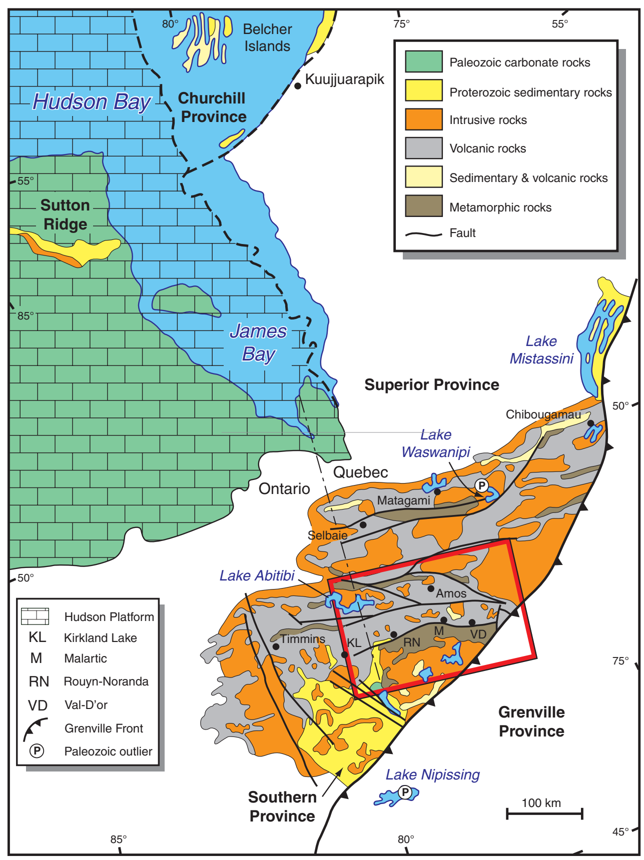

Figure 3. a) *Map showing the extent of the Abitibi Subprovince in Quebec and Ontario, carbonate rocks of the Hudson Platform in the James Bay Lowland, and Proterozoic rocks from southeastern Hudson Bay (Churchill Province) and from the Lake Mistassini basin to the northeast* (modified from *Minerals and Metals Sector and National Energy Board, 2001, and MERQ–OGS, 1984).*

The oldest rocks of the region are the Archean metasedimentary rocks (greywacke, slate, argillite) of the Pontiac Group (MERQ–OGS, 1984) that form the large east-west band just south of the Cadillac-Larder Lake Fault, east-west bands north of the fault, and large areas in the vicinity of Lake Simard (Fig. 3b). Along with the younger clastic Proterozoic rocks of the Cobalt Supergroup (glaciogenic sedimentary rock (tillite), argillite (lithified varves), sandstone, and quartzite), which are widespread in Ontario west of Lake Timiskaming and extend almost to Rouyn-Noranda, the Archean rocks of the Pontiac Group form the siliciclastic sedimentary unit on the bedrock lithology map (*see* /Data directory on this CD). Rocks of the Pontiac Group also include minor mafic and ultramafic flows around Lake Simard. Volcanic rocks occur mostly north of the Cadillac-Larder Lake fault. Mafic volcanic rocks are widespread. The Blake River syncline around RouynNoranda consists predominantly of basalt and rhyolite with minor synvolcanic intrusives (gabbro, monzonite, granodiorite). A large band of mixed volcanic rocks extends from Lake Abitibi to the Amos area.

The most extensive rocks of the area are late Archean acidic intrusives. The largest continuous area of granitoids, mostly syenite and monzonite, is centred on Lake Simard. North of the Cadillac-Larder Lake Fault, semicircular gneissic and granitic intrusives occur along elongated metabasalt bodies, gabbro sills, and narrow bands of metasedimentary rocks.

Proterozoic diabase intrusives occur as dykes (not shown on Fig. 3) and on all sides of the Paleozoic outlier (Nipissing diabase) in upper Lake Timiskaming.

Rocks of the Grenville Province (Fig. 3b) occupy the extreme southeastern portion of the area shown on the bedrock lithology map(*see* /Data directory on this CD). The complexity of structural deformations and the moderate to high degree of regional metamorphism indicate that the Grenville rocks were formed at great depth. Pronounced uplift and extensive erosion removed the upper rock layers right down to the katazone. Gneiss, paragneiss, migmatite, and associated granite are the dominant rock types of the Grenville Province.

The youngest rocks of the region are the Paleozoic carbonate rocks of Lake Timiskaming, which form the 400 km² Paleozoic outlier of Lake Timiskaming. Although these rocks are of limited extent, they are important from the point of view of glacial transport and their impact on soil geochemistry, as the high pH values associated with soils derived from them affect ion mobility in soils.

SURFICIAL GEOLOGY

Glacial history is the key to understanding the surficial geology of the region. It refers here to the succession of glacial (and nonglacial) events that left older deposits buried at depth below those of the last glaciation and shaped the modern landscape of the region. Events are described from oldest to youngest, using examples from the region.

Past environments are generally difficult to reconstruct from the succession of deposits alone, especially where sections showing extended sequences of unconsolidated sediments are rare or non-existent. The Abitibi–Témiscamingue area illustrates this well, as years of field investigations along lake and river banks have failed to reveal natural exposures showing deposits older than those of the last glacial cycle, which includes, from bottom to top, till, glaciofluvial, and glaciolacustrine deposits. These deposits represent only the retreat of the last ice sheet and the submergence of the region by proglacial Lake Barlow-Ojibway. Holes drilled to bedrock through glacial deposits, however, locally encounter pockets of much older glacial sediments and organic matter covered by deposits of the last glacial cycle (Fig. 4). Rare occurrences of older glacial sediments (pre-Matheson Till) have also been reported in some anthropogenic excavations (*see* Veillette et al., 1989, for details). Events older than the deposition of the Matheson Till are mentioned only briefly herein, because they are less relevant to

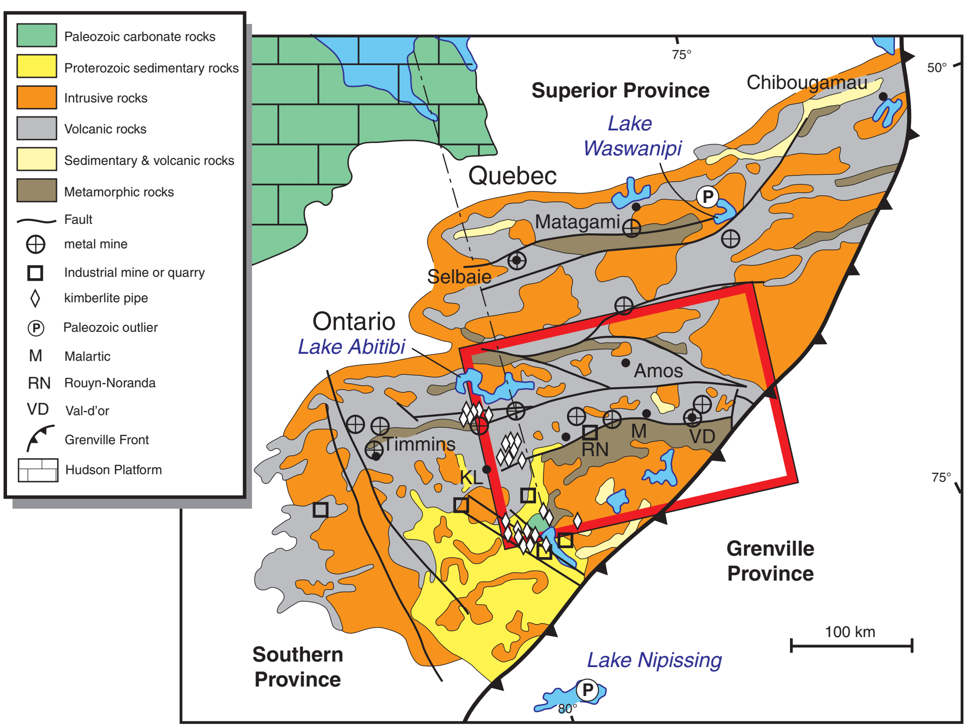

Figure 3. b) Location of active metal and industrial mineral mines and kimberlite pipes in and near the Abitibi Greenstone Belt (location of kimberlite pipes from McClenaghan et al., 2001, and M.B. McClenaghan, pers. comm., 2002).

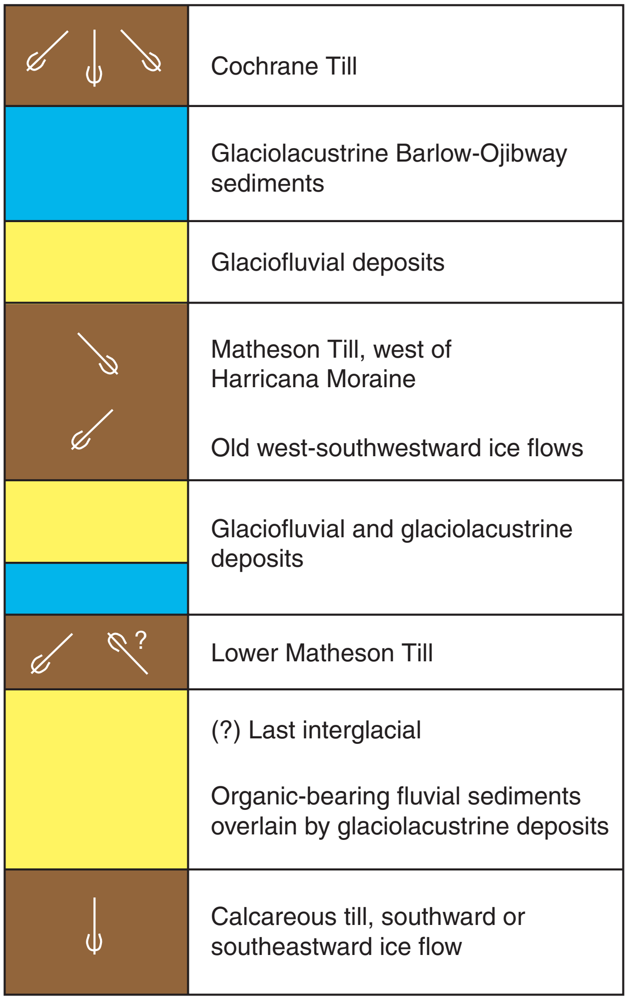

Figure 4. *Generalized stratigraphy of glacial deposits in northwestern Quebec and part of eastern Ontario* (modified from *Veillette and McClenaghan, 1996).*

the MITE smelter studies. Of greater importance to the MITE work is the provenance of transported materials in the till and clay. The lack of direct observation of older sediments severely limits the use of stratigraphy as a tool for reconstructing former glacial events in the region. Nonetheless, the abundant drillhole data gathered over the years (Chauvin and LaSalle, 1978; Averill, 1978; DiLabio et al., 1988; Veillette et al., 1989; provincial assessment files for the numerous reverse circulation programs carried out in recent years), compared with earlier work on natural sections (Skinner, 1973) in the lower reaches of rivers flowing into James Bay, led to the basic stratigraphic framework shown in Figure 4.

Surficial geology map of the Rouyn-Noranda area

Figure 2 shows the simplified surficial geology at a scale of 1:250 000 of a selected area around Rouyn-Noranda. It is a compilation of published (Veillette, 1986a, 1987a, b, 1989, 1996, 2004; Baker, 2000a, b; Vagners and Courtney, 2000) and unpublished (S.J. Paradis, work in progress, 2004; P. Thibaudeau and J.J. Veillette, work in progress, 2004) work from Quebec and Ontario. Symbols commonly used on surficial geology maps have been omitted as the main objective of this compilation was to show the distribution of surficial materials in order to assist in the interpretation of geochemical data collected within the MITE smelter studies.

Bedrock and till

Rock outcrops (Fig. 2, unit R) and till (Fig. 2, units 1a, 1b) are widespread in the southeastern part of the area south of Val-d'Or, east and north of Lake Simard, around the Rouyn-Noranda area, in the large Abijevis Hills south of Taschereau, between Engelhart and Lake Abitibi in Ontario, and northeast of Lake Timiskaming. These surficial deposits are located predominantly within the Abitibi Highland (Fig. 1). Bedrock areas with little or no soil cover are found on steep slopes where deposition of unconsolidated sediments did not occur or, more commonly, where the deposits were eroded by Glacial Lake Barlow-Ojibway waters, as observed around the Decelles reservoir.

The till cover is most extensive in areas located above the maximum level reached by Glacial Lake Barlow-Ojibway (a few high hills of limited extent) and in the area east and south of the Decelles reservoir, which lies beyond the extent of Glacial Lake Barlow-Ojibway.

Outcrops of carbonate Paleozoic rocks and the till derived predominantly from these rocks occur in upper Lake Timiskaming (Fig. 2, units R, 1c, 1d).

Moraines and eskers

All moraines (Fig. 2, unit 2a) and eskers (Fig. 2, unit 2b), except for some rare esker segments located outside the Glacial Lake Barlow-Ojibway basin, were formed by glacial meltwater in contact with deep proglacial water. The moraines consist entirely of sorted sediments, sand, and gravel. The largest and most prominent is the Harricana Moraine, interpreted as an interlobate feature that was deposited between ice lobes retreating to the northeast and northwest (Hardy, 1976; Veillette, 1996). It extends northeastward from the Lake Simard area to Val-d'Or where it shifts northward. It is the largest body of granular material in northern Quebec and Ontario.

The Roulier Moraine is a 70 km ridge of sand and gravel located some 20 km north of Lake Timiskaming. It marks an ice-frontal position of the northwestward-retreating glacier. It is associated with two large esker deltas (Fig. 2, unit 3c) located along major structural depressions. Other moraines of limited extent are found in the upper Lake Timiskaming area.

The eskers are important components of the Abitibi physiography. They were formed by meltwater flowing under hydrostatic pressure in subglacial conduits that opened up in the glacial lake. This abrupt change in flow regime led to the formation of large subaqueous fans of sand and silt that cover an inner core of coarse gravel and cobbles. This mode of deposition, coupled with reworking of the sediments by wave action due to regression of the glacial lake, and postglacial processes such as wind action and paludification, produced the broad and poorly defined outlines typical of the Abitibi eskers surrounded by the clay plain. These contrast with the more classical, well defined, sharp-crested eskers typical of interfluves outside the Glacial Lake Barlow-Ojibway basin.

Eskers have a strong impact on the local economy. An east-west transect across the surficial geology map in Figure 2 intercepts a major esker on average every 15 km. Joining all the eskers together to form a single line would produce a continuous ribbon of sand and gravel about 1400 km long. Because of their many uses, eskers are at the heart of serious land-use conflicts. They serve as bases for the primary, secondary, and forestry road networks and as borrow pits for aggregates and construction material. They are used for recreation purposes mainly because of the pristine kettle lakes and open jack pine forests they support, as aquifers supplying large wells for municipal requirements of clean water, and as sources of commercial bottled water and water for fish farming. To these varied uses must be added municipal dumps in depleted gravel and sand pits, which add to the difficulty of managing the resource. Water flows easily through the porous sand and gravel of eskers, which makes these eskers groundwater recharge points. The fragility of the features and their susceptibility to contamination are at the heart of major hydrogeological programs being planned to understand the internal architecture and properties of eskers as groundwater reservoirs.

Glaciolacustrine deposits

Glaciolacustrine deposits include 1) deltaic deposits (Fig. 2, unit 3c) found where meltwater from eskers entered the deep parts of the glacial lake, for example the two deltas associated with the Roulier Moraine and a third delta northwest of Lake Simard, as well as outwash-type deposits found in very shallow water (with some subaerial areas), such as occur in the long bedrock valleys in the extreme southeastern portion of the area shown in Figure 2; 2) shallow-water deposits (Fig. 2, unit 3b), predominantly sand and gravel, reworked by wave action from eskers and moraines during lake regression; and 3) deep-water deposits (Fig. 2, unit 3a) consisting of clay and silt.

The extensive clay plain, typical of the Abitibi landscape, rarely exceeds 320 m in elevation and consists predominantly of varves. In general, varves are couplets of silt and clay layers deposited in summer (silt), when meltwater activity was maximal, and in winter (clay) in calm waters below the seasonal ice cover. Varved clay is the most widespread surficial deposit in the Abitibi region north of the drainage divide. These fine-grained sediments (Fig. 5) are found where water depths reached about 40 m or more in the former lake basin. Varves result from turbidity currents produced by sediment-laden meltwater at the ice front, and show lateral continuity over several kilometres, even tens of kilometres (Antevs, 1925; Banerjee, 1973). This characteristic explains why the calcareous rock flour from the Hudson Platform contained in varves, mostly in the silt layer, was dispersed toward the southeast in western Abitibi, well beyond the area of calcareous rock flour contained in the matrix of the Matheson Till, as will be seen later.

Postglacial deposits

Postglacial deposits accumulated after the ice and the glacial lake disappeared. Alluvial deposits (Fig. 2, unit 4) form narrow bands along streams and correspond in most cases to modern floodplain deposits, although some are related to paleofloodplains. Such is the case for the largest surface of alluvial deposits in the area shown in Figure 2, which is formed by the paleofloodplain of the Blanche River north of Lake Timiskaming. Organic deposits (Fig. 2, unit 5) consist predominantly of peat and muck and are found mostly on poorly drained, fine-grained glaciolacustrine deposits.

Erosional record

The chronological order of ice flows was established primarily on the basis of crosscutting striated surfaces. These are found on outcrops that bear erosional marks (striations, grooves) from two or more ice movements of different ages and directions. Former (old) striated surfaces are found on parts of outcrops that have been sheltered from the erosive action of younger ice flows (Fig. 6). Unweathered surfaces of

Figure 5*. Section through varves in the Amos area. Note the ice-rafted boulder to the right and sun glasses as scale. GSC 205009-I*

Figure 6. *Example of a multifaceted striated outcrop used to reconstruct the sequence of ice flows. GSC 2003-291*

the hard volcanic rocks of the Abitibi Greenstone Belt exposed by natural or anthropogenic processes, compared with gneissic and granitic rock surfaces that are readily eroded, preserve an excellent record of erosional marks left by the shifting ice flows of the last ice sheet. In Figure 7, overlapping arrows show the sequence of ice flows derived from the compilation of over 3000 striated rock facets in Quebec and Ontario (Veillette and McClenaghan, 1996).

Flow I, toward the northwest (290°–315°), is the oldest regional ice flow mapped from striations in the James Bay basin. No evidence for this flow was found south of latitude 49°N in northern Abitibi. It is probably related to the early phase of the last ice sheet, which expanded from the Quebec Highlands toward Hudson Bay (Veillette, 1995; Veillette et al., 1999).

Flows II and III, toward the west (260°–270°) and southwest (230°–250°), record a counterclockwise shift in ice flow from flow I. Striations from flows II and III are best preserved west of the Harricana Moraine on the lee side of outcrops moulded by flow V.

Flow IV, toward the south and southwest (190°–220°), probably started with early deglaciation in response to the opening of the ice sheet in the southern Timiskaming area. This flow was an important carrier of glacial debris over long distances.

Flow V results from the deglaciation of Abitibi–Témiscamingue, which lasted about 2000 years. It consists of two main ice-flow directions converging toward a roughly north-south central axis, the Harricana Moraine (*see* Fig. 7). Ice flowed southeastward west of the Harricana Moraine and southwestward east of the moraine. Although of short duration, flow V shaped the modern glacial landscape, which determines our perception of the events of the last glaciation. It did not transport glacier debris over long distances.

The orientation of the youngest striations (erosional record) in a given area matches the orientation of landforms indicative of ice retreat, such as drumlins and frontal moraines (depositional record). The direction and orientation of ice flows older than the last regional flow must be derived without the benefit of the striations and landforms association, as landforms formed by older flows generally have been obliterated by younger flows. Old striations are survivors from former glacier movements. Since no adequate stratigraphic information exists to correlate with older striations over large areas, the reconstruction of glacial events must rely on a combination of lithological indicators of glacial transport and analysis of striations. This method was used to propose the sequence of events displayed in Figure 7.

Depositional record

Because ice associated with each flow described in the preceding section transported glacial debris, this complex sequence of ice flows should ideally be matched by a comparable distribution of lithological indicators of glacial transport. In fact, moving glaciers did mix rock types in the area, but this is difficult to detect in many parts of the Abitibi Greenstone Belt. This is due in part to the east-west structural trends in the bedrock of the Abitibi Subprovince (Fig. 3a). The alternating bands of granitic, volcanic, and metasedimentary rocks are aligned roughly at right angles or at a high angle to the main directions of ice flow, i.e. from the northwest and

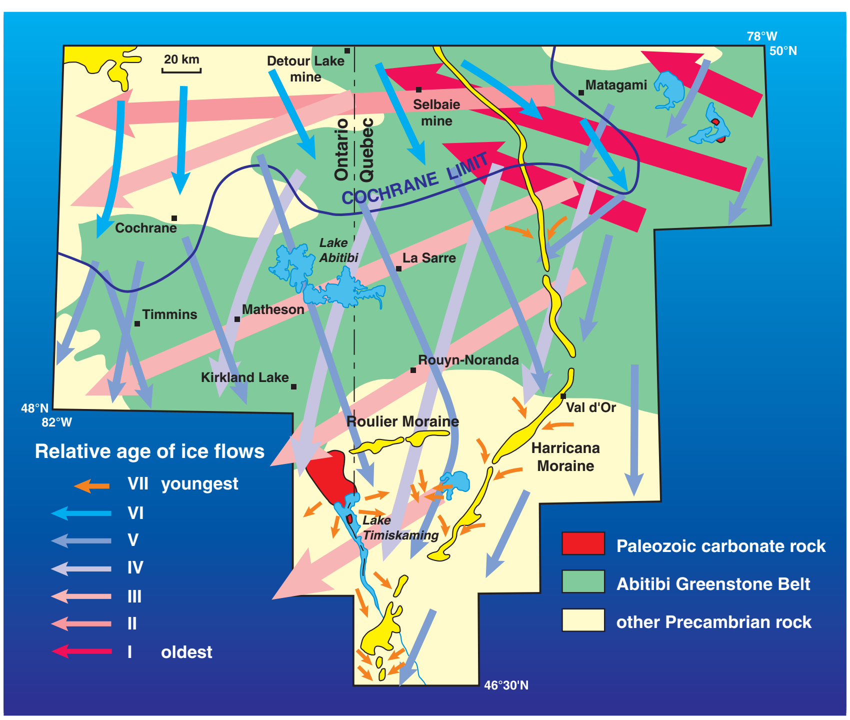

Figure 7.

Sequence of ice flows for northeastern Ontario and northwestern Quebec. The overlapping arrows represent the relative age of ice movements of regional significance; the interpretation is derived from over 3000 measurements of striated facets (modified from *Veillette and McClenaghan, 1996).*

northeast. Ice flows across this repetitive sequence have produced a mélange of rock types that may occur in similar proportions in samples from vastly different locations. This severely limits the use of pebble lithology (subdividing the pebbles of a till sample into lithological classes that are then compared to the lithological composition of bedrock) as an indicator of glacial transport directions on a regional scale.

Matching directions of glacial transport with striations can, however, be achieved using distinctive erratics (usually boulders and cobbles) from remote source areas and, on a local scale, by tracing mineralogical or geochemical indicators (kimberlite indicator minerals, gold grains, and trace elements) from mineralized sources.

Long-distance transport

Erratics from the Proterozoic rocks of the Lake Mistassini basin, from the Churchill Province of southeastern Hudson Bay as far as 800 km away, and from the Paleozoic rocks of the Hudson Platform all occur within the northern portion of the Abitibi Greenstone Belt, as clasts within till and glaciofluvial deposits, as dropstones left by drifting ice, or as rock flour in till and glaciolacustrine clay. Figure 8 shows the areal distribution of each type of erratic from its source area. At times, the mode of transport was complex. For example, erratics of the Churchill Province of southeastern Hudson Bay (Prest, 1990; Prest et al., 2000) and from the Hudson Platform were first carried by glaciers in the northern part of

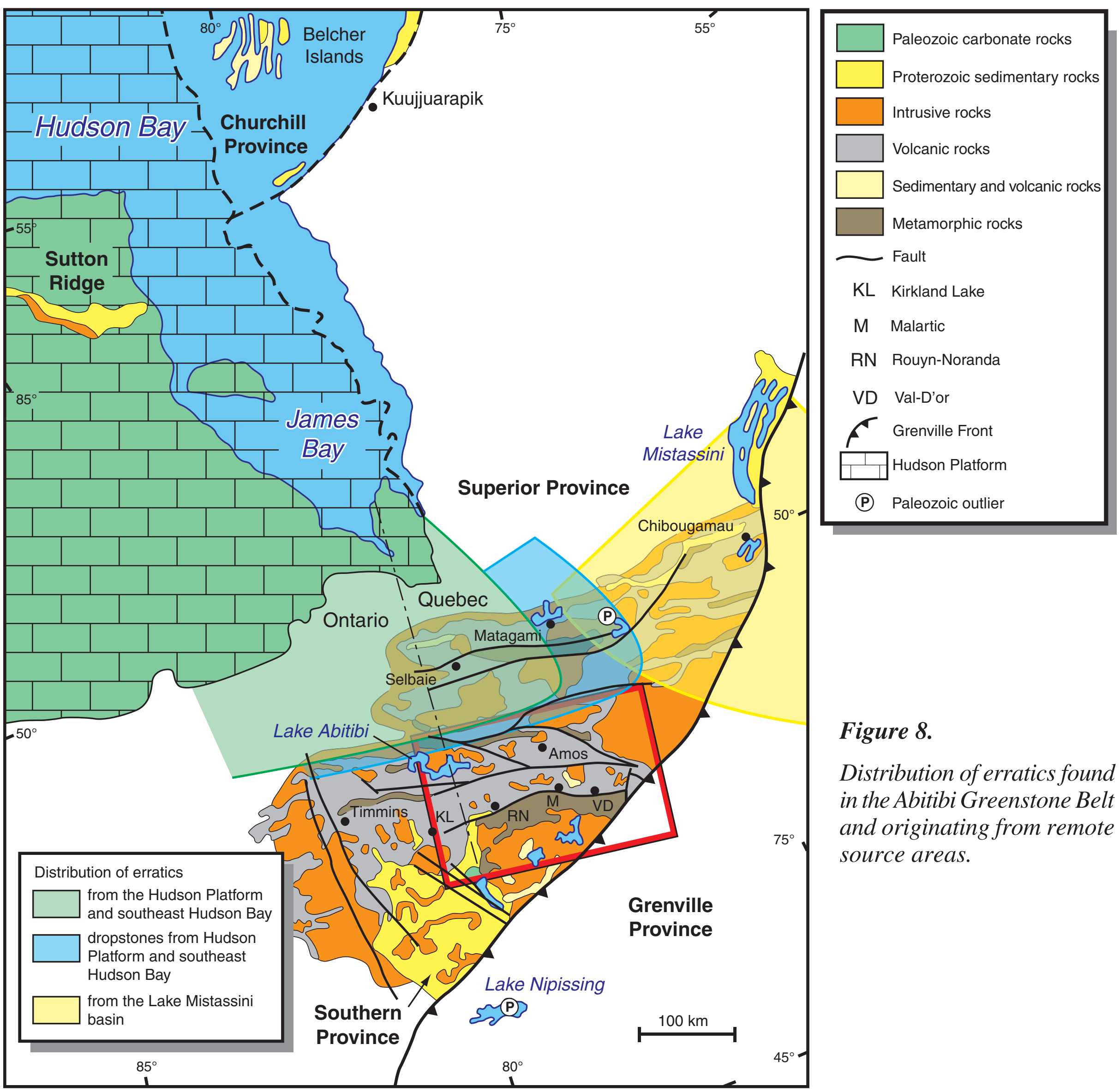

Figure 8.

Distribution of erratics found in the Abitibi Greenstone Belt and originating from remote source areas.

the Abitibi Greenstone Belt, then dispersed in a general eastward direction by wind-driven icebergs and ice rafts and released as dropstones (Fig. 9) at the soil surface (Veillette et al., 1991; Veillette and Paradis, 1996). Erratics from Lake Mistassini were found almost exclusively in till and glaciofluvial deposits, which suggests a mode of deposition in which floating ice played a minor role. The deposition of rock flour in Glacial Lake Ojibway was predominantly by density currents and will be discussed in a later section.

Short-distance transport

Dispersal trains containing elevated levels of pathfinder elements such as arsenic, or gold grains and kimberlite indicator minerals in minute amounts in glacial deposits, are generally easier to map over short distances (hundreds of metres) from their source. The reconstruction of dispersal trains from borehole samples has been used extensively in Abitibi in recent years and has assisted in locating buried orebodies in areas of thick overburden (Sauerbrai et al., 1987; *see* Veillette et al., 1989). Kimberlite indicator minerals, given their unique characteristics and the small dimensions of the orebodies, are somewhat exceptional and in some cases have been traced over long distances (*see* McClenaghan et al., 2001).

The Cadillac project (Kish et al., 1979), initiated by the Quebec Department of Natural Resources in 1971 to stimulate mineral exploration in central Abitibi, is a good example of short-distance tracing. The project was based on the assumptions that 1) glacial transport is minimal at the till–bedrock interface; 2) a single till sheet deposited by southeastward-flowing ice existed in the area; and 3) drillholes could reach the base of the till. Basal till was thus considered to be the most reliable material to sample for detecting dispersal trains from mineralized sources. Using lightweight equipment (Gleeson and Cormier, 1971), thousands of holes were drilled and 8000 samples were analyzed for various elements. The first reports in the mid 1970s generated little interest among prospectors. As gold prospecting intensified in the mid 1980s, samples were reanalyzed for Au, As, W, and Sb by neutron activation (LaSalle and Henry, 1987). Investigators were surprised to find that basal till samples at several locations revealed transport toward the southwest rather than the southeast, as suggested by the orientation of landforms, roches moutonnées, and the most obvious striations in the general area. Figure 10 shows the distribution of As in the central portion of the Abitibi Greenstone Belt between Val-d'Or and Rouyn-Noranda. The arc-shaped Cadillac-Larder Lake fault is clearly delineated between Rouyn-Noranda, Cadillac, Malartic, and Val-d'Or (the extent of the fault system is shown in Fig. 3b). South of Rouyn-Noranda, As values show dispersal plumes toward the southwest, along the earliest southwestward flow (Fig. 7, flow 3). LaSalle and Henry (1987) estimated transport distances to be relatively short (less than 600 m). Beaumier et al. (1994) showed that the distribution of staurolite and other heavy minerals (derived from the metasedimentary rocks of the Pontiac Group) in till of the Rouyn-Noranda area is similar to that of arsenic in basal till samples.

Figure 9. *Proterozoic ice-rafted greywacke (omar) erratic from southeastern Hudson Bay found in the Lake Waswanipi area, Quebec. GSC 2003-292*

Major shift in ice-flow direction within the Matheson Till

The difference in the direction of flow between the base and the top of the till sheet as described in the Cadillac project and reported elsewhere in western Abitibi by a number of exploration companies could not be adequately explained at the time, mainly because previous investigations had not mapped the 'old' striated surfaces. Chauvin (1977), J.H. Richard (pers. comm., 1985), and P.P. David (pers. comm., 1984, 1985) reported isolated observations of cross-striated surfaces and speculated on their significance. The first indication that widespread westward and southwestward ice flows preceded the southeastward flow in western Abitibi came from a systematic reconnaissance survey of striated outcrops bearing marks of two or more striated facets showing well defined crosscutting relationships (Veillette, 1986b). It was not known at the time whether the southwestward and southeastward directions of flow were associated with distinct glacial events, as no intertill deposits separating the basal and upper portions of the till had ever been identified in areas where both transport directions had been recorded. To complicate matters, Quaternary stratigraphers usually assign a unique direction of flow to a till sheet of apparent homogenous structure and composition.

The first reliable evidence of a major shift in ice-flow direction within the Matheson Till sheet was found in the large open pit of the Selbaie mine in 1988 (Fig. 11a). The pit is a unique window on the stratigraphy and glacial history of the area. By reverse circulation drilling, W.E. Brereton (unpub. rept., 1975) outlined a dispersal train oriented 225° from the Selbaie mine site, which suggested that earlier ice flows occurred toward the southwest and not the southeast as indicated by the orientation of landforms and the most obvious surface striations. Overburden thickness, as seen along the perimeter of the pit in 1988, varied from about 6 m to 60 m. This uneven bedrock topography revealed a striking 'stratigraphy' of erosional surfaces. The bedrock floor of the excavation is everywhere polished and striated and shows well developed stoss-and-lee topography, indicating ice movement

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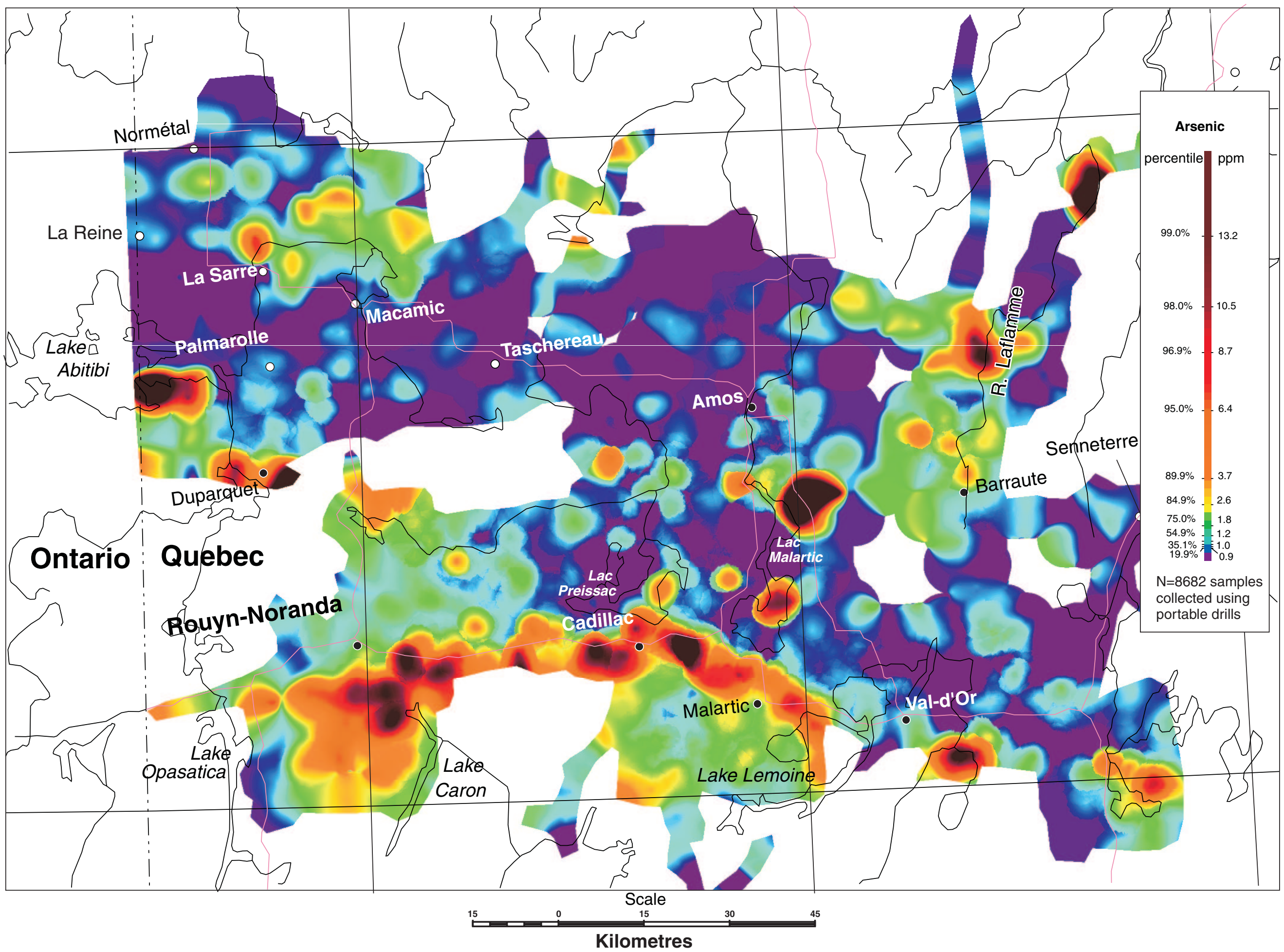

Figure 10. Distribution of As in samples (n = 8682) of basal till (<177 µm) in the Rouyn-Noranda–Val-d'Or area. Note the high As values along the Cadillac-Larder Lake fault and the southwest dispersal trains from the fault in the Rouyn-Noranda area (modified from *LaSalle and Henry (1987) and P. LaSalle (unpubl. data, 2003) by M. Beaumier, Quebec Ministry of Natural Resources).*

Figure 11. a) *Aerial view of Selbaie mine open pit in 1988 showing the thick sequence of glacial and glaciolacustrine sediments (uppermost sloping surface) masking the uneven bedrock topography (far right). GSC 2003-293*

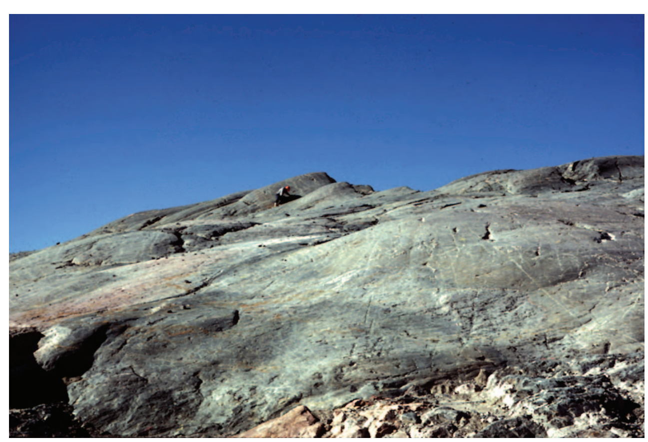

Figure 11. b) *Stoss-and-lee topography on bedrock floor of the Selbaie mine open pit showing ice movement toward 260° to 270°(toward the right of photograph). GSC 2003-294*

toward the west-southwest (260°–270°) below a depth of 3 to 6 m below the surface (Fig. 11b). In the upper 3 to 6 m below the surface, the bedrock surface is striated toward the southeast, with rare striated facets indicative of southwestward ice flow preserved in places. This late shift in ice movement is supported by numerous similar measurements in the vicinity of the pit and elsewhere in the general area (Veillette et al., 1989). These observations were interpreted as indicative of shifting ice flows occurring within a till sheet of apparent similar lithological composition. To verify the shifting ice-flow hypothesis, a 17 m section of sandy Matheson Till resting on bedrock striated toward the west in the Selbaie open pit was examined in detail (Fig. 11c). Till fabrics at 9 m and 15 m below the surface record a shift from southeastward (top) to southwestward (bottom) flows, matched by a gradual decrease in the carbonate content of the till matrix from about 10% in the upper part of the till to less than 2% at the till–bedrock interface (a similar trend was observed for carbonate pebbles). Paleozoic carbonate rocks from the Hudson Platform, located about 100 km northwest of Selbaie, are the most probable source for the calcareous material. The shift was gradual and no obvious characteristics such as colour change were observed that would indicate a different provenance. The Paleozoic carbonate rocks present in the till at the base of the section in contact with bedrock striated toward the west-southwest are attributed to the oldest ice flow so far recorded in the James Bay Lowland. At one location in the deepest part of the pit, a megagroove several metres long, about 1 m wide, and indicating ice flowing toward 175° to 180°, has been preserved in the lee side of roches moutonnées shaped by the westward flow (*see* Veillette et al., 1989, for details). Pockets of carbonate-rich till (up to 15%, *see* Fig. 11c) were found in depressions on the bedrock floor of the pit. These pockets have survived the erosive action of the westward flow and are considered to be relict deposits from the former southward flow associated with the megagroove. S.A. Averill (unpub. rept., 1986) suggested a Hudson Platform origin for old, weathered, carbonate-rich glacial deposits overlain by non-calcareous till that have been encountered at the base of a few deep boreholes in northwestern Quebec.

The examples described above illustrate the influence that two or more ice flows from source areas with different rock types can have on the lithological composition and geochemical properties of till. Paleozoic carbonate material mixed with predominantly acidic rocks, as is the case in western Abitibi (and in upper Lake Timiskaming), offer optimum conditions for differentiating source areas.

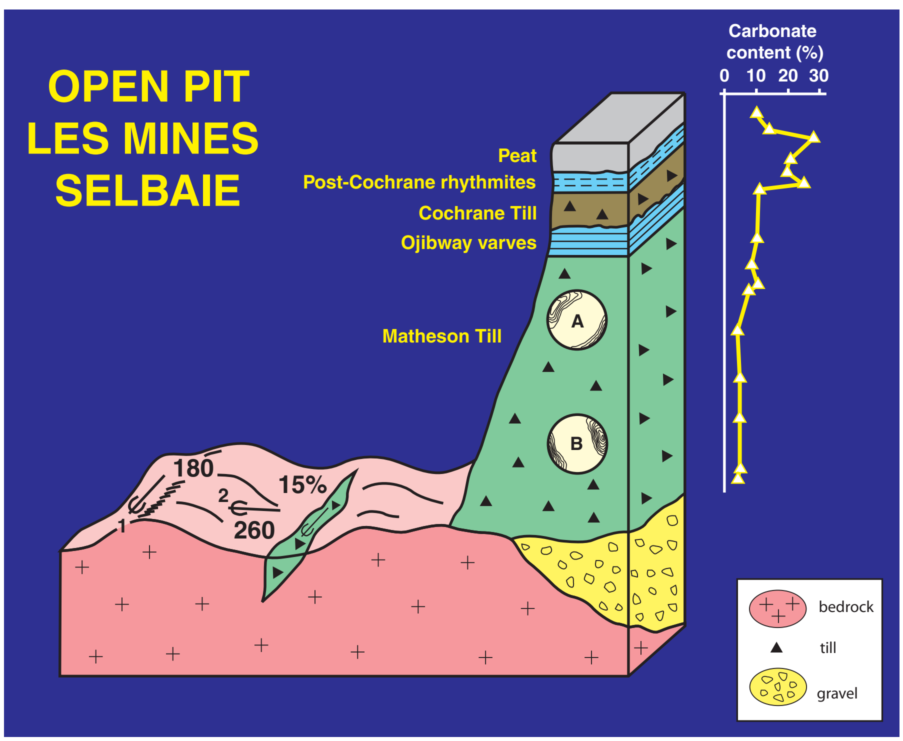

Figure 11. c) *Schematic view of the stratigraphy in the Selbaie pit. The bedrock floor at depth bears striations and ice-flow features indicating a widespread westward flow with rare marks of an older flow toward the south preserved in sheltered hollows. The bedrock in the uppermost parts of the excavation, near the surface, is striated toward the southeast. Till fabrics (A and B) show a shift from southwest flow near the base of the 17 m till column to southeast flow near the top, whereas carbonate content decreases gradually with depth (*see *text for interpretation).*

Ice retreat and Glacial Lake Barlow-Ojibway

Extensive clay deposits laid down by Glacial Lake Barlow-Ojibway cover most parts of the Abitibi Greenstone Belt that lie below or at about 300 m in elevation. The presence of these deposits has always been a major impediment to mineral exploration. However, as will be seen later, the geochemical properties of glaciolacustrine deposits can supply useful information about deglaciation style and sediment provenance.

The name 'Barlow' refers to the body of water found south of the drainage divide and the name 'Ojibway', to the body of water north of it. At one time, a single body of water covered the drainage divide, hence the name 'Barlow-Ojibway'. This was an ice-contact glacial lake, i.e. parts of its margin were in contact with the retreating glacier. The lake's evolution was reconstructed by mapping raised shorelines and washing limits and from the distribution of biological indicators of lacustrine submergence (Dadswell, 1974; Vincent and Hardy, 1979; Veillette, 1994). The chronology of deglaciation was established on the basis of radiocarbon dates obtained from cores of basal gyttja collected in small lakes and ponds (Veillette, 1988) and a regional pollen zonation was established for Timiskaming (Richard et al., 1989; Richard and Larouche, 1989). The chronological record is less detailed north of the drainage divide because of the rarity of lake basins located at or above the highest levels reached by Glacial Lake Ojibway. However, the date of the drainage of Glacial Lake Ojibway into the Tyrrell Sea (now Hudson Bay) at about 7600 BP (Barber et al., 1999), when compared with the chronology developed for Timiskaming, indicates that it took about 1000 years for the glacier to retreat from Val-d'Or to James Bay. The glacial landscape of Abitibi was formed during this relatively short period.

A few hundred years before the collapse of the ice sheet, the glacier readvanced into Glacial Lake Ojibway. These late-glacial fluctuations of the ice margin, known as the 'Cochrane surges' (Hughes, 1955; Hardy, 1976), released large volumes of icebergs at the calving front in the northern part of the Abitibi Greenstone Belt (Veillette et al., 1991; Veillette and Paradis, 1996). The glacier sliding over Glacial Lake Ojibway clay left a thin (1–2 m) layer of pebbly clay containing large amounts of carbonate erratics from the Hudson Platform and Proterozoic rocks from southeastern Hudson Bay.

Dispersal of Paleozoic carbonate clasts and rock flour in the surficial deposits of northeastern Ontario and northwestern Quebec

Ice flows III and IV (*see* Fig. 7) moved southwestward in western Abitibi. This general direction is reflected in the southwest-northeast orientation of the 10% limit of carbonate dispersal in the Matheson Till (Fig. 12a). West of Lake Abitibi, Paleozoic calcareous rock flour and clasts occur in till sheets of all ages, since former ice flows, whether directed southward, southwestward, or southeastward, had source areas over the rocks of the Hudson Platform. During deglaciation, convergent southeastward and southwestward flows (flow V) developed in the direction of the Harricana Moraine. The absence of carbonate erratics in the till in the large triangular area between Joutel, Kirkland Lake, and Val-d'Or, despite the presence of well developed striations and landforms indicative of southeastward-directed flow, suggests a rapid northwestward deglaciation and short transport distances in this area. The slight southeastward bulge in the 10% and 0% carbonate isopleths for till, between Lake Abitibi and the Selbaie mine, is the only evidence for southeastward glacial transport during deglaciation.

On the other hand, calcareous silt and clay extend well beyond the calcareous facies of the Matheson Till (Fig. 12b). The carbonate content of varves decreases steadily toward the southeast, i.e. at right angle to the retreating ice front, from 20 to 25% in the Lake Abitibi area to less than 2% east of a line joining Rouyn-Noranda and Matagami. This distribution is entirely due to glacial and glaciolacustrine processes and is in no way related to the composition of the underlying Precambrian bedrock. This southeastward (eastward north of Matagami) extension is attributed to turbidity currents generated at the retreating ice front toward the northwest and explains why the carbonate content of varves differs greatly in western and eastern Abitibi.

The last major event to have an impact on the distribution of calcareous rock flour is related to the Cochrane surges. The glacier readvanced into Glacial Lake Ojibway, bringing in more calcareous debris from the Hudson Platform in the James Bay Lowland (Fig. 12c), and deposited a thin layer of calcareous, stone-poor, clay-rich till.

Transition zone between calcareous and noncalcareous surficial deposits

A more exact limit of calcareous Matheson Till in the Quebec portion of northwestern Abitibi, which includes the study area, is shown in Figure 13a. South of a line joining LaSarre and Matagami, the till matrix is devoid of calcareous rock flour and no carbonate clasts have been observed in the till. The highest carbonate values were recorded within a few kilometres of the interprovincial boundary. The only other occurrence of calcareous rock flour and Paleozoic carbonate clasts in till is in the Lake Waswanipi area, down ice from a small outlier of Paleozoic limestone (*see* Fig. 3a, b).

On the other hand, the carbonate content of Glacial Lake Ojibway clay reveals a pronounced southeastward incursion of underflow meltwater currents carrying calcareous rock flour from the Hudson Platform (Fig. 13b). The distribution, however, shows the same general northeast-southwest orientation as observed in the Matheson Till.

CONCLUSIONS

The Rouyn-Noranda general area is located in the central part of the Abitibi Greenstone Belt and at the junction of two major ice-flow systems that had a strong impact on the lithological and geochemical composition of the region's Quaternary sediments. The Harricana interlobate moraine is the demarcation line between the two systems, with the last ice

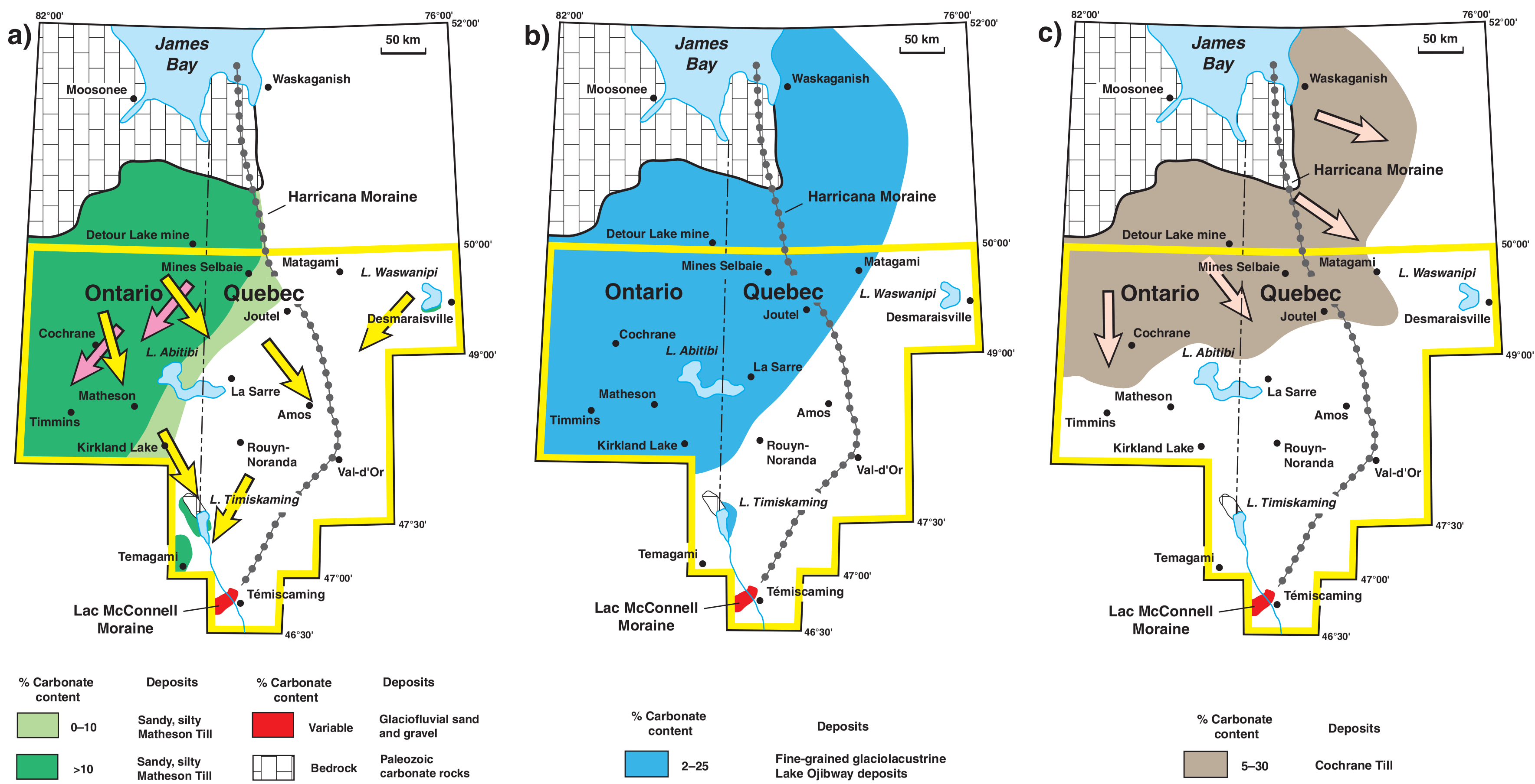

Figure 12. *Dispersal of Paleozoic carbonate clasts and rock flour from the Hudson Platform in surficial sediments of northeastern Ontario and northwestern Quebec (arrows represent ice-flow direction, pink arrows representing the oldest flow) in* ***a)*** *Matheson Till;* ***b)*** *Glacial Lake Ojibway clay;* ***c)*** *Cochrane Till. The carbonate content of rock flour was measured on the <63 μm fraction using the Chittick (Dreimanis, 1962) and Leco (Foscolos and Barefoot, 1970) methods.*

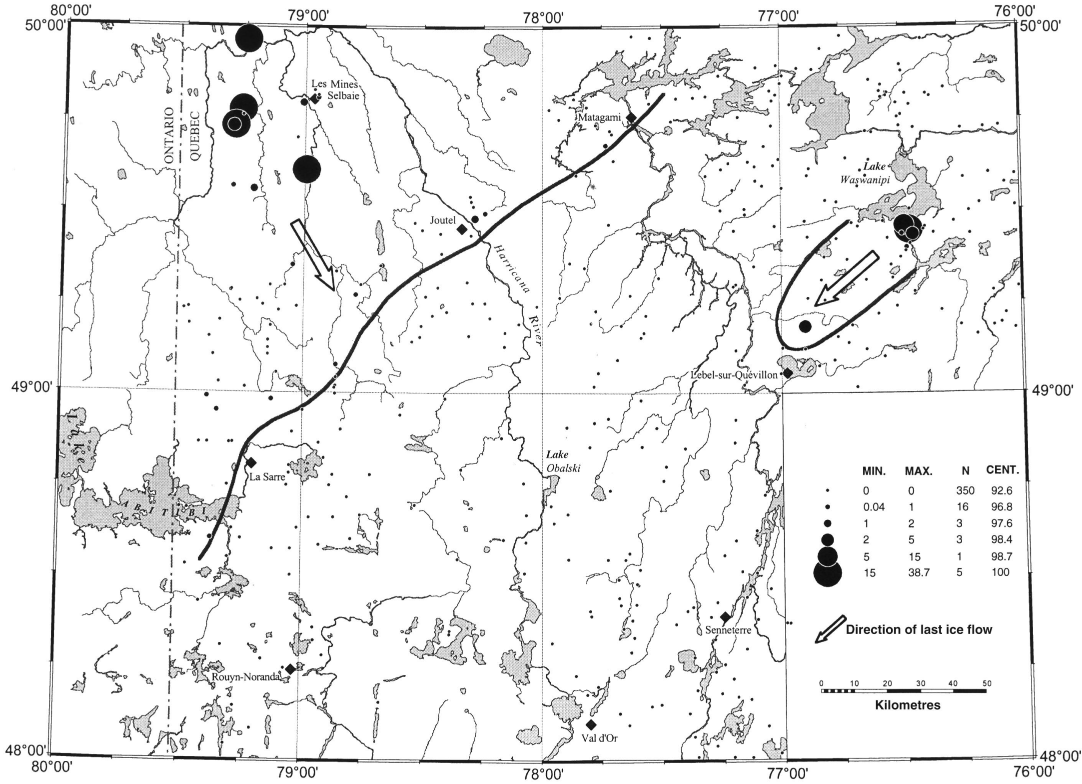

Figure 13a) *Content (%) of Paleozoic carbonate granules (5.6–2 mm) from the Hudson Platform in Matheson Till in northwestern Quebec.*

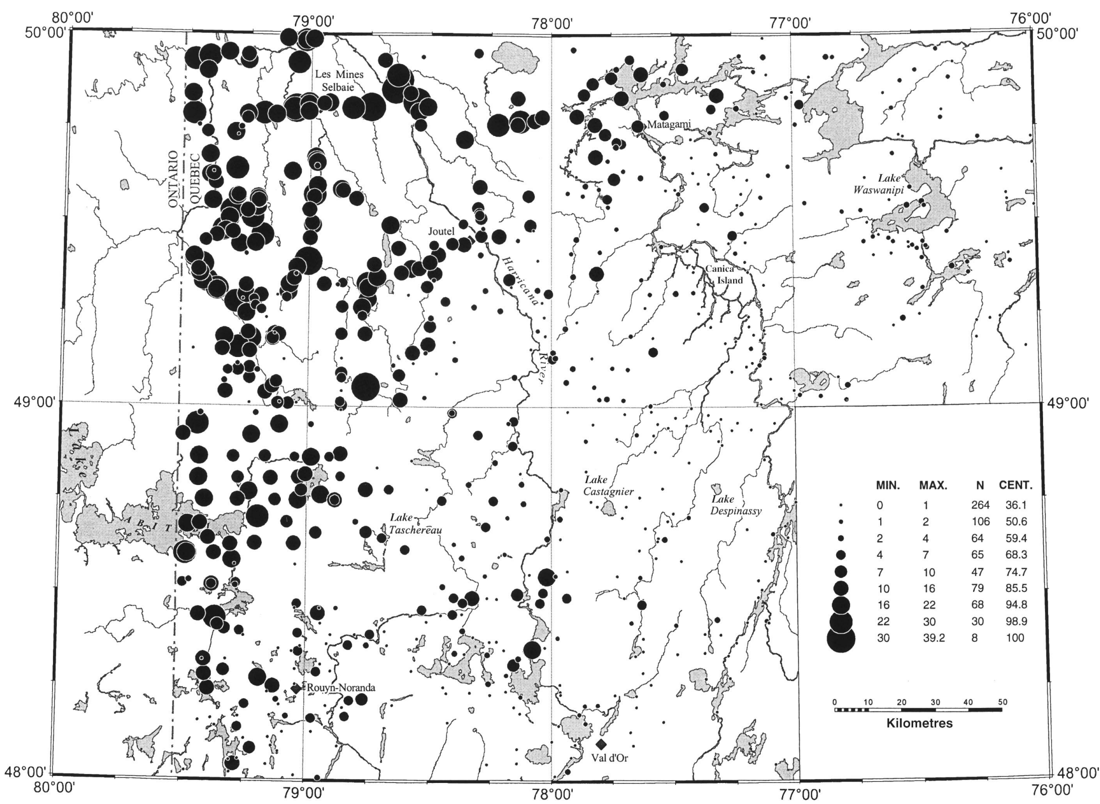

Figure 13b) *Carbonate content (%) of Glacial Lake Ojibway clay (<63 μm) in northwestern Quebec.*

sheet retreating northwestward west of the moraine and northeastward east of it. Prior to deglaciation, ice flows were predominantly from the east and northeast.

The two main factors related to Quaternary geology that affect MITE studies are sediment composition and distribution resulting from glacial transport. In interpreting the results of smelter studies based on the sampling of till, glaciolacustrine clay, and lake-bottom sediments, the complex ice-flow history of the region must be taken into account. The bedrock of northern Ontario and northwestern Quebec is predominantly acidic, but most northern Ontario glacial sediments are calcareous because they are located down ice from the Hudson Platform. Moving eastward from Ontario into northwestern Quebec, this composition changes over a few tens of kilometres. The transition zone between calcareous and noncalcareous glaciolacustrine sediments is located in the study area. Because soil pH affects ion mobility, it is important to know the exact distribution of calcareous rock flour in soils. Geochemical properties of sediments of the same type may show large variations over relatively short distances as a result of sediment provenance related to glacial transport, as shown by the dispersal of Paleozoic carbonate rocks in till. On the other hand, calcareous rock flour derived from Paleozoic carbonate rocks found in glaciolacustrine fine-grained sediments decreases more gradually away from the ice margin and covers a much larger area than the calcareous till. This difference is due to the different style of sedimentation: ice-contact processes for the till and underflow currents in Glacial Lake Ojibway for the clay. The clay plain of the area west of the Harricana Moraine, which is associated with northwestward ice retreat, shows a gradual increase in carbonate content toward the northwest, whereas the clay is devoid of calcareous rock flour east of the moraine (except in the vicinity of the Lake Waswanipi Paleozoic outlier) because the northwestward-retreating lobe did not override a calcareous substrate.

These differences in the distribution of calcareous material are especially relevant for lake-bottom sediment studies. An important part of the drainage network of the region is cut off from bedrock and glacial sediments by a thick clay blanket. Several stream beds, river beds, and lake basins below 300 m elevation have been cut entirely in Glacial Lake Ojibway clay. A lake basin in the calcareous clay plain of western Abitibi may have geochemical properties that are drastically different from those of a nearby lake basin located in an esker, only a few metres higher in elevation. The esker does not contain Paleozoic carbonate rocks and consists predominantly of bedrock clasts, gravel, and sand from the local acidic Precambrian bedrock. Not only does the clay plain differ from the esker by its grain size, but it also contains calcareous rock flour and other material derived from source areas more than 150 km to the northwest.

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