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Calcareous Till Facies North of Lake Superior, Ontario: Implications for Laurentide Ice Streaming

Les faciès de till calcaire au nord du lac Supérieur, Ontario : les conséquences sur l'écoulement de l’Inlandsis laurentidien

Die Kalk-Till-Fazies im Norden von Lake Superior, Ontario: Auswirkungen auf das Fliessen des laurentischen lnlandeises

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Article abstract

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CALCAREOUS TILL FACIES NORTH OF LAKE SUPERIOR, ONTARIO: IMPLICATIONS FOR LAURENTIDE ICE STREAMING

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ABSTRACT In the Geraldton and Hemlo areas distantly-derived carbonate tills lie between slightly to non-calcareous tills and can be distinguished by textural, carbonate, and clast compositions. Their occurrence and uniform character over large areas of the Shield attest to high sediment flux by rapid movement of distal debris within the southern part of the Laurentide Ice Sheet. This is consistent with low surface profiles reconstructed for the Superior and Michigan lobes which were likely fed by ice north of Superior and probably affected by ice streaming. Till deposition in the Geraldton and Hemlo areas can be explained with one southwestward glacial advance. A broad ice stream probably issued out of James Bay and up the Albany conduit between zones of normal ice velocity within the Laurentide marginal area. It may have split to flow down the Drowning and Kenogami troughs. Eventually, zones of ice streaming reached the Geraldton and Hemlo areas where Shield uplands induced lee side extending flow, downward transport, and lodgment of calcareous englacial debris on local tills. Following the glacial maximum much of the distal englacial debris was laid down by subglacial meltout. However, a glacial reactivation occurred which moulded drumlins in the carbonate tills near Geraldton and deposited an upper calcareous lodgment till at Hemlo. Final Laurentide decay resulted in meltout of supraglacial debris that had been sheared up to or near the glacier surface from the stoss sides of the uplands.

RÉSUMÉ *Les faciès de till calcaire au nord du lac Supérieur, Ontario: les conséquences sur l'écoulement de l'Inlandsis laurentidien.* Dans les régions de Geraldton et de Hemlo, des tills carbonatés transportés sur de longues distances s'intercalent entre des couches de tills non calcaires ou très légèrement calcaires; ils se distinguent par leur texture, leur teneur en carbonate et la composition lithologique de la fraction grossière. Leur présence et leur uniformité sur de grandes étendues du Bouclier témoignent d'un important transport de sédiments grâce à un apport rapide de débris dans la partie méridionale de l'Inlandsis laurentidien. Cette hypothèse concorde avec la reconstitution de la faible pente de la surface des lobes glaciaires des lacs Supérieur et Michigan, vraisemblablement alimentés par des courants de glace en provenance du nord du lac Supérieur. La mise en place du till s'explique par une seule avancée glaciaire vers le sud-ouest. Un important courant de glace en provenance de la baie de James s'est écoulé le long du couloir d'Albany entre des zones de vitesse normale à l'intérieur des marges laurentidiennes. Le courant de glace s'est peut-être scindé pour s'écouler le long des fosses de Drowning et de Kénogami. Les zones de courants de glace ont ensuite atteint les régions de Geraldton et de Hemlo où la présence des hautes terres du Bouclier ont provoqué un écoulement extensif en aval, un transport vers les parties basses et la mise en place de débris calcaires intraglaciaires sur les tills locaux. Après l'extension maximale des glaciers, la plus grande partie des débris intraglaciaires a été déposée par fusion sous-glaciaire. Toutefois, une réactivation glaciaire a par la suite permis l'édification de drumlins dans les tills carbonatés près de Geraldton et la mise en place d'un till de fond supérieur calcaire à Hemlo. La fragmentation finale de l'Inlandsis laurentidien a provoqué la fonte des débris supraglaciaires qui avaient été cisaillés jusqu'en surface du glacier ou tout près, à partir du versant amont des hautes terres.

ZUSAMMENFASSUNG *Die Kalk-Till-Fazies im Norden von Lake Superior, Ontario: Auswirkungen auf das Fliessen des laurentischen Inlandeises.* In den Gebieten von Geraldton und Hemlo fügen sich Karbonat-Tills, die über weite Strecken transportiert wurden, zwischen leicht kalk-haltige bis nicht kalkhaltige Tills ein; sie unterscheiden sich durch ihre Textur, ihren Karbonatgehalt und ihre Gesteins-Zusammensetzung. Ihr Vorkommen und ihre Uniformität über grosse Gebiete des Schilds zeugen von einer bedeutenden Sedimentbewegung dank einer raschen Anschwemmung von Gesteinstrümmern im südlichen Teil der laurentischen Eisdecke. Diese Hypothese stimmt mit der Rekonstruktion der geringen Neigung der Oberflächenprofile der glazialen Lappen des Lake Superior und des Lake Michigan, welche wahrscheinlich durch vom Norden des Lake Superior kommende Eisströme genährt wurden, überein. Die Till-Ablagerung lässt sich durch einen einzigen südwestlichen glazialen Vorstoss erklären. Ein bedeutender, wahrscheinlich von der James-Bay kommender Eisstrom floss den Albany-Gang entlang zwischen den Zonen normaler Geschwindigkeit innerhalb der laurentischen Grenzen. Der Eisstrom hat sich vielleicht geteilt, um die Gräben von Drowning und Kénogami hinunterzufliessen. Schliesslich haben die Eisströmungszonen die Gebiete von Geraldton und Hemlo erreicht, wo die Hochebenen des Schilds ein extensives talabwärts Fliessen hervorgerufen haben, den Transport zu den tiefer gelegenen Teilen und die Ablagerung von kalkhaltigen intraglazialen Trümmern auf den östlichen Tills. Nach der maximalen Ausdehnung der Gletscher wurde der grösste Teil der intraglazialen Trümmer durch subglaziale Fusion abgelagert. Dennoch fand eine glaziale Reaktivierung statt, welche in den Karbonat-Tills bei Geraldton Drumlins bildete und bei Hemlo ein oberes kalkhaltiges Ablagerungs-Till. Die schliesslilche Fragmentierung der laurentischen Inland-Eisdecke führte zum Schmelzen der supraglazialen Trümmer.

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INTRODUCTION

The INQUA '87 symposium on the Laurentide Ice Sheet (Fulton and Andrews, 1987 published in this journal) made it clear that future advances in understanding the behaviour of the Ice Sheet would come from detailed field studies such as this report (Andrews, 1987). Such knowledge is important for modelling the behaviour of our polar ice sheets and associated global sea level changes, which is one of the pressing concerns for future human occupation of this planet (Andrews and Fulton, 1987; Fulton and Prest, 1987; Hughes, 1987).

Recent Quaternary geologic studies on the central Canadian Shield suggest that calcareous glacial drift is not uncommon there (Geddes, 1984; Geddes and Bajc, 1985a, 1985b; Geddes *et al.*, 1985; Geddes and Kristjansson, 1986; Kristjansson, 1986; Hicock, 1986, 1987a, 1987b, 1987c; Karrow and Geddes, 1987; Kristjansson and Thorleifson, 1987; Kristjansson *et al.*, in press; Thorleifson and Kristjansson, 1988). Two areas containing calcareous lodgment tills, near Hemlo and Geraldton, were recently studied by the author. The occurrence of these lodgment tills raises the question of how their particles could have been glacially transported hundreds of kilometres from their Paleozoic and Proterozoic sources in the James Bay Lowlands and eastern shore of Hudson Bay, respectively (Fig. 1 inset). This paper makes the assumption that the present distribution of bedrock areas was close to that encountered by the Laurentide Ice Sheet; that is, that the Laurentide did not simply erode (and totally remove) Paleozoic outliers just upglacier from Hemlo and Geraldton.

The purpose of this report is 1) to explain the entrainment, transport, and deposition of such abundant distantly-derived materials found in the tills, and 2) to propose how these processes relate to flow dynamics within the southern part of the Laurentide Ice Sheet. Occurrences of calcareous till in the gold-rich Hemlo area were explained by Hicock (1987b), where uplands affected glacier flow dynamics. This paper follows the format and style of its predecessor (Hicock, 1987b) in examining another Shield area of carbonate till, the gold-bearing Geraldton area, and relates it to the Hemlo area in order to infer Late Wisconsinan Laurentide flow behaviour north of Lake Superior.

Field work in the Geraldton area was done on old road cuts and an abandoned gravel pit in July, 1986. Eleven exposures were re-excavated with hand shovels, carefully cleaned with knives, and studied in detail for stratigraphic and structural relations of sediment units. Samples were collected for grain size, carbonate, pebble lithology, geochemical, and heavy mineral analyses in order to characterize the units and determine their modes of deposition and provenance. Granulometric analyses were performed by the hydrometer-sieve method of the American Society for Testing and Materials (1972), using 0.002 and 0.063 mm as the clay-silt and silt-sand boundaries, respectively; carbonate analyses after the method of Dreimanis (1962); and heavy mineral separations using liquid sodium polytungstate (specific gravity 2.90). Computer analyses of pebble long axis orientations (fabrics) were accomplished with the method of Mark (1973, 1974).

Till criteria and terminology used in this paper follow the system of the International Union for Quaternary Research's Commission on Lithology and Genesis of Glacial Deposits (Dreimanis, 1982; in press). In discussing stone provenance the word Archean is used in this paper to denote local to intermediate sources within the Precambrian Shield, south of its contact with Paleozoic rocks underlying the James Bay Lowlands. The term distal is used to describe transported glacial debris, or material in till, that were carried by glacier ice from sources north of that contact.

PHYSICAL SETTING AND PREVIOUS WORK

The Geraldton area abounds in glacially-aligned lakes and occupies a broad drumlinized trough with up to 100 m surface relief (Fig. 1). The trough contains calcareous drift up to 60 m thick (Kristjansson and Thorleifson, 1987) and is flanked by distinct uplands to the west, south, and east, as well as by a subtle upland north of Geraldton. The area is underlain by a structurally complex sequence of Archean lithologies including metavolcanic (mainly lavas, amphibolites, and pyroclastic rocks), metasedimentary (clastic and chemical rocks including banded iron formation), and granitoid plutonic (mainly tonalite to granodiorite) and gneissic rocks (presented later in Fig. 5b). Diabase dykes have intruded other lithologies ubiquitously and scattered patches of mafic to ultramafic rocks (gabbro, peridotite, serpentinite) can be found.

Quaternary studies north of Lake Superior have concentrated on surficial mapping and glacial lake studies (Farrand, 1962; Zoltai, 1965a, 1965b, 1967; Boissonneau, 1966; Grant, 1969); Zoltai and Boissonneau recognized the carbonate-rich till, as did Sado (1975). Coker and Shilts (1979) generally described the till in a lake geochemistry study, and Fortescue and Geddes (1983), Geddes (1984, 1986), Kristjansson (1984, 1986), Geddes and Bajc (1985a, 1985b), Geddes *et al.* (1985), Woods (1985), Geddes and Kristjansson (1986), White (1986), Hicock (1986, 1987b, 1987c), Kristjansson and Thorleifson (1987), Kristjansson *et al.* (in press), and Thorleifson and Kristjansson (1988) have described it in more detail. Gartner (1979a, 1979b, 1980) and Cooper (1983) provided engineering and terrain studies of the Geraldton area, and Karrow and Geddes (1987) summarized the implications of carbonate drift for radiocarbon dating, fossil shell preservation, acid precipitation buffering, and drift prospecting on the Canadian Shield. Finally, Shilts (1980, 1982, 1984, 1985), Dyke *et al.* (1982), Fisher *et al.* (1985), Boulton *et al.* (1985), Veillette (1986), Dyke and Prest (1987), and Dyke *et al.* (in press) documented and modelled regional glacier flow patterns beneath the central part of the Laurentide Ice Sheet.

Pleistocene sediments in the region appear to have been deposited during the Late Wisconsinan Substage. The oldest radiocarbon date is 9380 ± 150 years BP (GSC-287; Zoltai 1965a) from wood in late-glacial lake deposits.

CHARACTER AND STRATIGRAPHY OF GERALDTON DIAMICTONS

Four diamictons are recognized in the Geraldton area. Two are highly calcareous and are sandwiched between

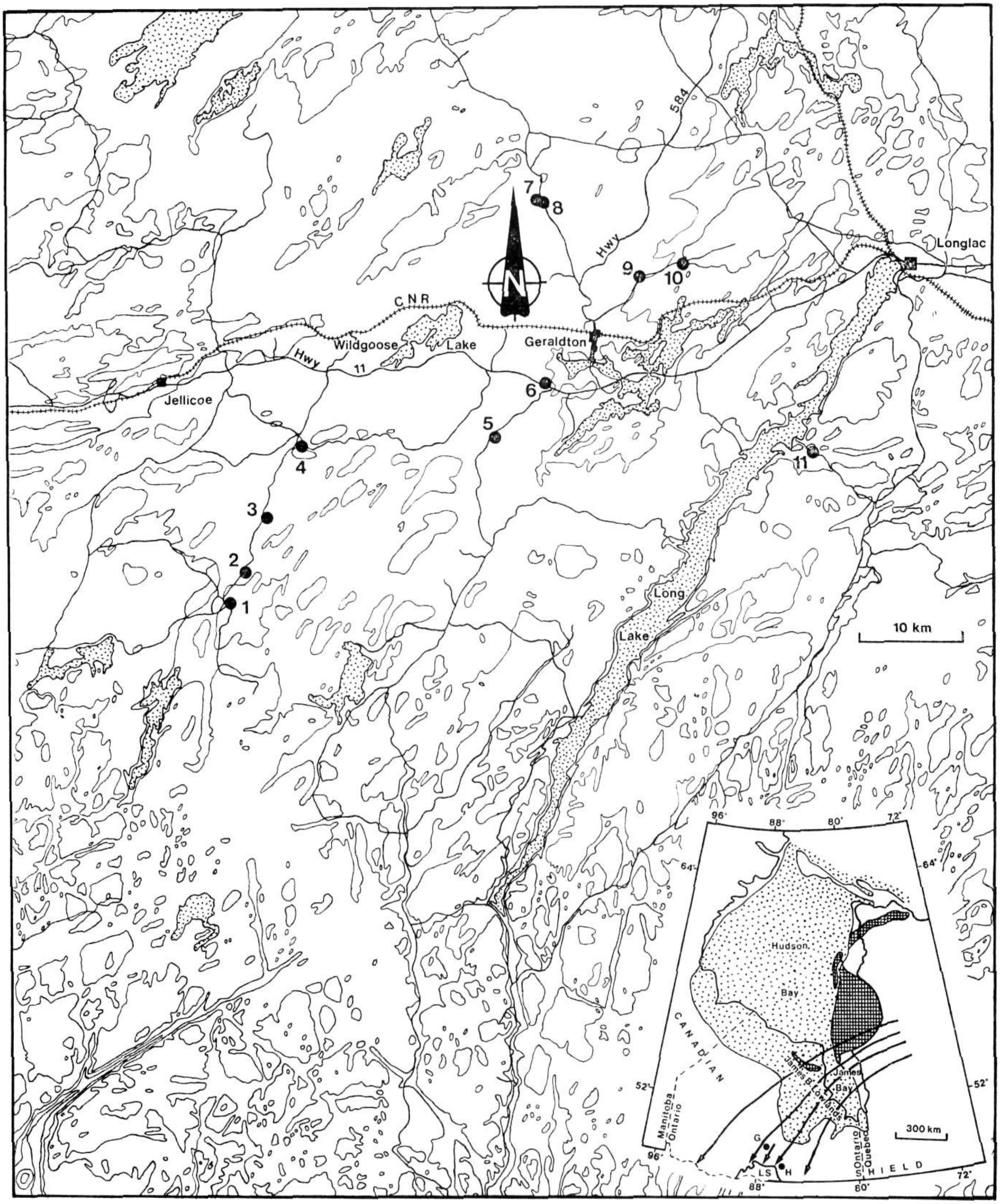

FIGURE 1. Topographic map of the Geraldton area with site localities, larger lakes (stippled) and roads (branching solid lines). Contour interval 60 m. Inset: regional ice flow paths, Paleozoic (stipples), and Proterozoic (cross-hatched) source rocks for Geraldton drift (modified after Shilts, 1980). LS = Lake Superior, G = Geraldton, H = Hemlo.

Carte topographique de la région de Geraldton ainsi que la localisation des sites, des principaux lacs (pointillés) et des routes (lignes pleines se recoupant). L'équidistance entre les courbes est de 60 m. Le carton montre le trajet de l'écoulement glaciaire régional, la source des roches paléozoïques (pointillé) et protérozoïques (quadrillé) du drift de Geraldton (modifié d'après Shilts, 1980). LS = lac Supérieur, G = Geraldton, H = Hemlo.

diamictons with lower carbonate content. The oldest sediment encountered in mine excavations and drillholes is a locally-derived gritty silty sand diamicton (Kristjansson 1984; 1986; Kristjansson and Thorleifson, 1987; Thorleifson and Kristjansson, 1988) which they identify as a lodgment till. It was not encountered in the sections studied by the author.

The overlying unit occurs in seven of the eleven sections studied, which are presented diagrammatically in Figure 2 and pictorially in Figure 3. It comprises dark grey, compacted, calcareous diamicton which is at least 2.5 m thick at site 4. The diamicton is fissile, stony, and contains striated, facetted, and bullet-nosed stones, as well as rare pockets of sand at site 11. Diamicton matrix (– 2.00 mm) comprises about 35% sand, 55% silt, 10% clay (Fig. 4a), and 30-40% total carbonates (calcite and dolomite; Fig. 4b). Stones are generally subrounded to subangular and dominated by Paleozoic and Proterozoic lithologies, indicating glacial transport from distant sources (Fig. 4c). Parallel and transverse alignment of stones in the diamicton, as well as displaced striated bedrock blocks in contact with the till west of site 6 (Fig. 3a), extension fractures (Fig. 3b), striated stoss and lee boulders in pavements at site 4 (Fig. 3c), and a sand-filled shear plane at site 5, are consistently oriented with striae on the stones (Fig. 2). The above characteristics indicate that this compact diamicton was deposited under moving ice by lodgment as defined by Dreimanis (1976, 1982, in press) and Shaw (1985). The diamicton is therefore called lodgment till. At sites 6 and 10 crumbly, dark grey, massive sandy silt diamicton directly overlies the lodgment unit (Fig. 3d) and is interpreted as having formed from it as a debris flow. That is, the lodgment till was remobilized to form the overlying debris flow. Grain size, carbonate, and stone contents are indistinguishable between the two diamictons.

At site 6 lodgment till is underlain by bedded and faulted sand in the lee of a bedrock knob. The equal area, lower hemisphere, stereographic projection of bedding and fault planes, as well as of axial planes of mud flow lobes within the sand (Fig. 2), indicate that the structures are unrelated to ice movement data at or near the site. The sand probably formed as an advance proglacial or subglacial outwash fan in the lee of the knob which was penecontemporaneously overriden by the glacier. The faults likely reflect dewatering and gravity settling of the sand. Between the sand and till are interbedded current-bedded sand and diamicton layers mm to cm thick. These probably represent proglacial or subglacial debris flows down the sand surface prior to ice grounding and lodgment of the overlying till. In fact, the attitude of the sand/diamicton contact is similar to that of the sand bedding

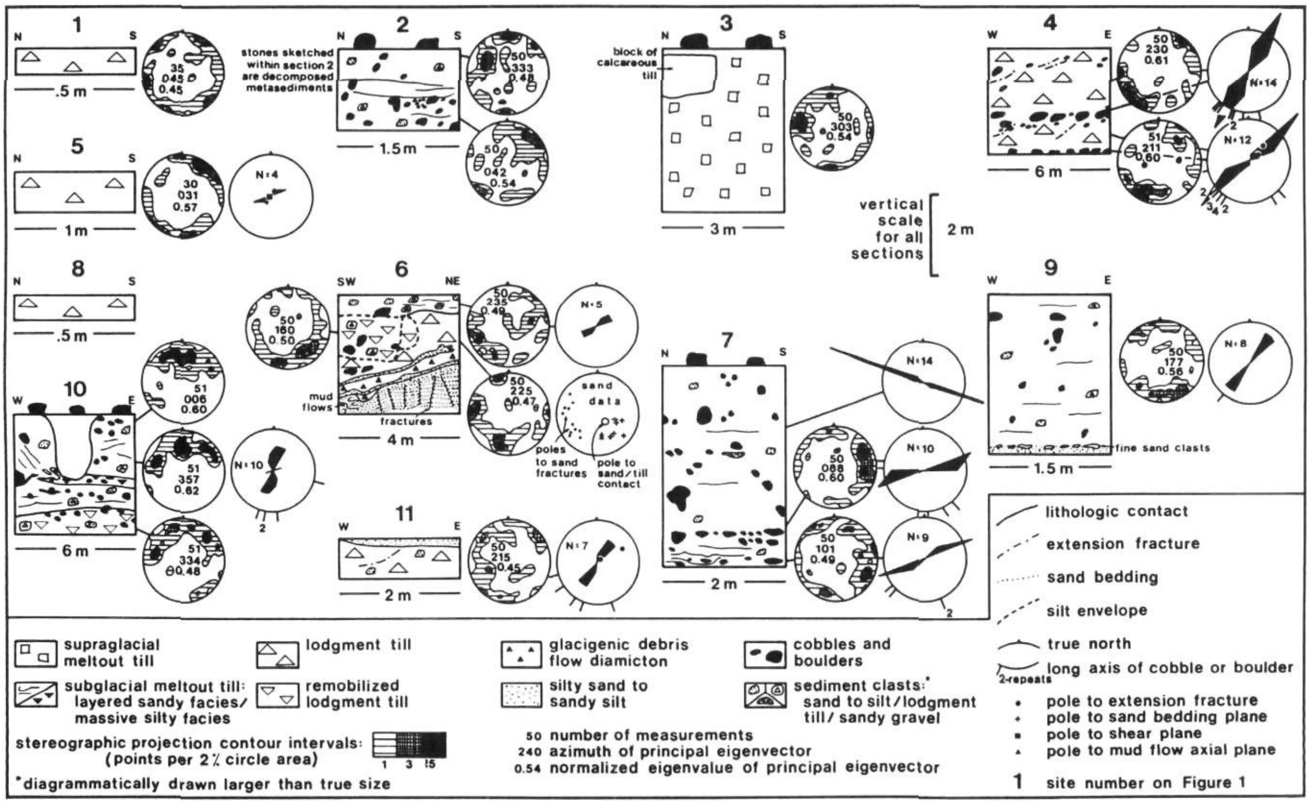

FIGURE 2. Diagrammatic lithostratigraphic sections with contoured equal area, lower hemisphere, stereographic projections of pebbles long (a) axes. Mirror image, two-dimensional rose diagrams of striae on top surfaces of cobbles and boulders presented beside the stereograms at approximative level of their measurement in section.

Diagrammes des coupes lithostratigraphiques et zones cotées correspondantes, hémisphère inférieur, projection stéréographique des axes longs (a) des galets. Diagrammes circulaires bi-dimensionnels à image inversée des stries à la surface des petits et des gros blocs, présentés à la droite des stéréogrammes, à peu près au même niveau que dans la coupe.

(Fig. 2) suggesting flow down the fan. This glacial sequence formed a crag and tail feature whose long axis is parallel to drumlins and bedrock striae in the area.

The compact calcareous till is overlain by a light grey, noncompacted, generally coarser-textured diamicton complex. This calcareous diamicton was found at five sites and is at least 5 m thick at site 7 (Fig. 2). At site 6 the contact appears to be transitional. At some sites the unit extends to the ground surface where it has been heavily oxidized and leached of carbonate by soil development. This unit is commonly massive but at some sites it contains interlayered and lenticular silt, sand, gravel, and massive silty diamictic strata. Bedding is commonly truncated by or draped over stones (Fig. 3e). Striated and facetted stones, as well as clasts of sorted sediment and compact till, are abundant. The occurrence of delicate sediment clasts, many of them angular (Fig. 3f), precludes basal transport involving subglacial shearing (Shaw, 1982, 1985). Diamicton matrices contain 60-70% sand, 20-30% silt, under 5% clay (Fig. 4a), and 25-35% carbonate (Fig. 4b). Stones are generally subrounded to subangular and the distal content varies in pebble samples but is in more equal proportion to the Archean content than in the lodgment till (Fig. 4c). Alignment of stones is generally parallel or transverse to striae on stones within the diamicton (Fig. 2).

These data indicate that this unit was formed (in the meaning of Shaw, 1982, p. 1548) passively under and within inactive ice, mainly by meltout as defined by Dreimanis (1976, 1982, in press), Shaw (1979, 1982, 1985), and Haldorsen and Shaw (1982), but with subglacial to englacial streams and debris flows forming some of the sorted and diamictic strata, respectively. Pressure melting and lodgment probably also contributed to the formation of part of the unit, prior to final deposition (in the meaning of Shaw, 1982, p. 1548), since boulder pavements were found within it at site 7 (Figs. 2, 3g). A model of their formation is presented later. Section 7 may represent a transition from lodgment to subglacial meltout processes as internal movement within the basal zone of the glacier gradually ceased, perhaps in a stick-slip fashion.

At site 3 noncompacted, slightly calcareous, coarse-textured diamicton (Fig. 4a, b) is dominated by subangular Archean clasts (many of them rotted metasediments; Figs. 3h, 4c) and contains a large block of calcareous till (Figs. 2, 3h). The section occurs in a mound covered by large subangular Quetico metasedimentary boulders derived from the underlying bedrock formation. Other boulder-covered mounds occur near the site and Quetico blocks commonly mantle the ground surface at other sites. Stone alignment at site 3 is bimodal but appears to be mainly a transverse fabric, implying compressive glacial flow and erosion of the local bedrock.

Some of the mounds are kames and the diamicton and boulder mantles are most likely supraglacial drift formed by the lowering of debris by supraglacial meltout from or near the ice surface. The striated, subrounded distal clasts at site 3 were probably sheared up to or near the supraglacial position of the transporting glacier prior to lowering its debris cover to ground level during deposition of the supraglacial meltout till. Younger glaciofluvial and glaciolacustrine sediments were studied by Kristjansson (1986), Kristjansson and Thorleifson (1987), Kristjansson *et al.* (in press) and are not dealt with here.

In summary, the till units can be differentiated by their matrix textural compositions and generally by their carbonate contents, and clast lithologies (Fig. 4). The lodgment till is characterized by a finer and more calcareous matrix with calcite/dolomite (c/d) ratios commonly between 0.7 and 1, and it generally contains over 70% distal clasts. The subglacial meltout till complex tends to be sandier, less calcareous with c/d ratios commonly less than 0.7, and more equal proportions of distal and Archean stones. At site 3 supraglacial till is coarse, like the meltout facies, but is slightly calcareous with mainly subangular Archean clasts.

GLACIER FLOW DIRECTION

Accurate determination of glacier movement directions in the area is essential to development of a depositional model for the tills and locating till source areas. A summary of ice flow directions is presented in a kineto-stratigraphic diagram (Fig. 5a). Ice flow was generally towards the southwest, in agreement with ice movement data on the map which was compiled from Zoltai (1967), Sado (1975), Gartner (1979, 1980), and Kristjansson *et al.* (in press), and is also consistent with the elongation of lakes in Figure 1. However, Zoltai (1967), Kristjansson (1986), Kristjansson and Thorleifson (1987), and Thorleifson and Kristjansson (1988) also found older, southward, striae on bedrock in the Geraldton area which was caused by an earlier glacial advance whose only remaining evidence appears to be the striae.

In the lodgment till, orientations of pebble long (a) axes are generally well developed, commonly display both parallel and transverse clast alignment (Fig. 2), and indicate that general glacier flow was towards the southwest. At sites 6 and 11 low eigenvalues reflect computer averaging of bimodal fabrics and thus do not accurately represent the degree of fabric development (Woodcock, 1977; Dowdeswell *et al.*, 1985; Dowdeswell and Sharp, 1986). Sand-filled extension fractures within the unit at site 4 (formed penecontemporaneously with till deposition; Fig. 3b) dip downglacier (Broster *et al.*, 1979; Hicock and Dreimanis, 1985), a sand-filled shear plane at site 5 rises downglacier (Hicock and Dreimanis, 1985), and striated bedrock slabs west of site 6 along Highway 11 are slightly displaced downglacier and intervening spaces filled with lodgment till (Fig. 3a). These data support the southwest trend, as do striae on the top surfaces of stones within the till and long axes of cobbles and boulders.

At site 6 the pebble fabric is oriented almost north-south (Fig. 2) and probably reflects locally convergent glacier flow into the lee of the rock knob (the crag of the crag and tail feature). At site 4 a few of the boulder long axes are transverse to the others in the lower pavement, which is consistent with the strongly oriented bimodal pebble fabric data. Fabrics of remobilized lodgment till at sites 6 (Fig. 3d) and 10 are interpreted as girdles reflecting flowage of the diamicton from its parent lodgment till. At site 11 the fabric is nearly random

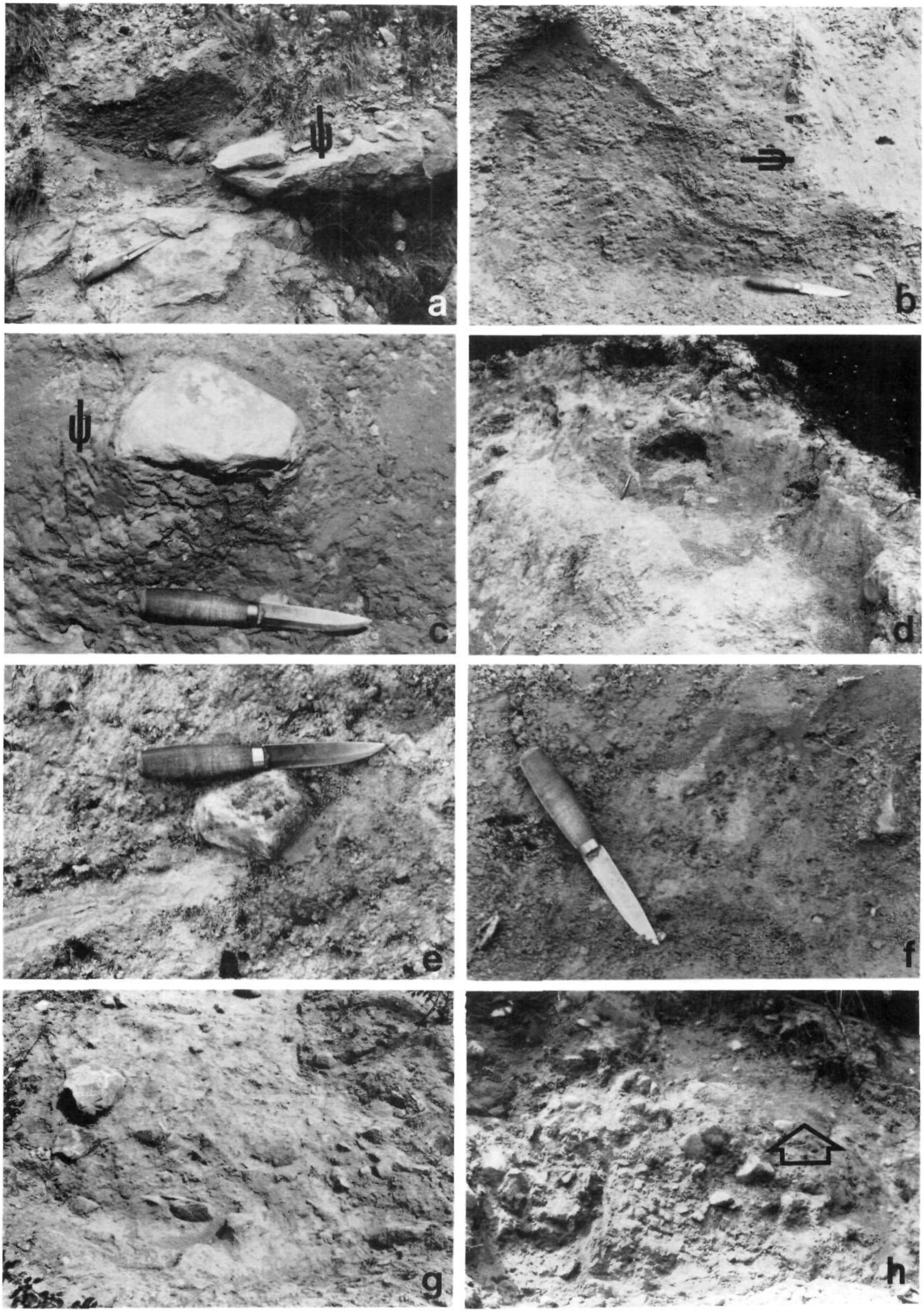
a
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FIGURE 3. Geraldton till facies and representative structures. Striae symbols indicate approximate ice advance direction in the photo. Knife 20 cm long.: (a) Fractured, striated, and displaced bedrock slabs west of site 6 on Highway 11 with calcareous lodgment till infilling spaces between slabs (*e.g.* at knife point). Fractured bedrock overlain by fissile lodgment till (left centre). Ice advance toward the reader.; (b) Fissile lodgment till containing a sand-filled curved extension fracture (above knife handle) at site 4. Fracture probably formed by glacial drag penecontemporaneously with till deposition.; (c) Fissile lodgment till containing a striated bullet-nosed boulder (part of pavement) at site 4. Ice advance toward the reader.; (d) Section through silt-enveloped flow lobes (darker shade) of remobilized lodgment till overlying undisturbed lodgment till (lighter shade) at site 6. Direction of flow is unknown. Knife lies between silt envelopes; (e) Stone truncating bedding within subglacial meltout till at site 10; (f) Delicate angular sand clasts (centre) within subglacial meltout till at site 9. Decomposed plutonic stone to left of knife handle; (g) Boulder pavements within subglacial meltout till at site 7. Buckled fine sand bed above knife, between two pavements. Ice advance away from reader, during formation of the pavements; (h) Supraglacial meltout till with abundant subangular Archean clasts at site 3. Arrow points to base of calcareous till block with fewer, smaller, stones (upper right quadrant). Shovel handle 12 cm wide (bottom right corner).

Le faciès du till de Geraldton et les structures représentatives. Le symbole de stries sur la photo donne la direction approximative de l'avancée glaciaire. Le canif mesure 20 cm. a) Dalles fracturées du substratum rocheux, striés et déplacés, à l'ouest du site n° 6 sur la route 11; le till de fond remplit les espaces entre les dalles (à la pointe du canif). Le substratum fracturé recouvert par un till de fond fissile (centre gauche). La direction de l'avancée glaciaire donne vers l'extérieur; b) Au site n° 4, le till de fond fissile renferme une fracture courbe remplie de sable (au-dessus du manche du canif). La fracture s'est probablement formée par frottement glaciaire pénécontemporain à la mise en place du till; c) Au site n° 4, till de fond renfermant un bloc strié en forme d'ogive. La direction de l'avancée glaciaire donne vers l'extérieur; d) Au site n° 6, coupe dans le till de fond remobilisé recouvrant un till de fond demeuré intact (teinte claire) à travers des lobes d'écoulement enveloppés de silt (teinte foncée). La direction de l'écoulement n'est pas connue. Le canif repose entre les enveloppes de silt; e) Au site n° 10, pierre tronquant le litage dans le till de fond; f) Au site n° 9, fragments de sable anguleux dans le till de fusion sous-glaciaire (au centre). À gauche du manche du canif, roche plutonique altérée; g) Au site n° 7, dallage de blocs dans le till de fusion sous-glaciaire. Lit de sable fin ondulé au-dessus du canif, entre deux dallages. La direction de l'avancée glaciaire, pendant la formation du dallage donne vers l'arrière de la photo; h) Au site n° 3, till de fusion supraglaciaire avec de nombreux fragments subanguleux archéens. La flèche pointe vers la base d'un bloc de till calcaire accompagné de quelques pierres plus petites (coin supérieur droit). Le manche de la pelle mesure 12 cm de large (coin inférieur droit).

and may reflect cryoturbation as the analysis was performed near the ground surface.

Pebble fabrics in the meltout till also display parallel-transverse combinations and suggest that glacier flow was to the southwest, with some local variations. This is supported by striae on stones as well as cobble and boulder long axes in the unit (Fig. 2), At site 7 a westward shift in glacier flow direction between boulder pavements (Fig. 3g) is indicated. Pavement boulder long axes at that site are transverse to boulder striae and bimodal pebble fabrics. This implies transport of the boulders in englacial ice under compressive flow just prior to their lodgment and subsequent deposition by meltout. At site 10 fabrics are interpreted as girdles representing flowage of the silty facies of the meltout unit and winter frost activity where the upper analysis was conducted near the ground surface.

Finally, the pebble fabric in supraglacial meltout till at site 3 appears to be a southward transverse fabric implying compressive glacier flow and shearing up of local subangular Quetico metasedimentary rocks to or near the glacier surface. This would have occurred after glacier ice passed over uplands north of Geraldton (Fig. 1) and was subsequently pressed into softer metasedimentary terrain in their lee sides during downward glacial flow.

TILL PROVENANCE

In addition to ice movement indicators (Fig. 5a), determination of source areas of the till materials is valuable for checking flow directions, as well as interpreting modes of glacial transport and deposition. It is obvious that the Paleozoic carbonate clasts and Proterozoic dark wackes must have been derived from the James Bay Lowlands and eastern shore of Hudson Bay, respectively (Fig. 1 inset), and that ice flow was southwestward to Geraldton from those source areas (Zoltai, 1967; Sado, 1975; Shilts, 1980, 1982, 1984, 1985; Kristjansson, 1984, 1986; Hicock, 1987a, 1987c; Kristjansson and Thorleifson, 1987; Thorleifson and Kristjansson, 1988). However, in addition to the obvious distant provenance, a study of the Archean lithologies in the till samples may help to refine the interpretation of ice movements in the Geraldton area and supplement the glaciotectonic data presented above.

Pebble lithologic data for the Geraldton area is presented as pie diagrams arranged stratigraphically in Figure 5b. Stones ranging from 1 to 10 cm diameter were collected. This is the most common size range and likely to be most representative of bedrock lithologies occurring upglacier. Many stones were thin sectioned and identified under transmitted polarized light until sufficient confidence was gained to identify the remainder under a binocular microscope. Clasts were then subdivided into seven categories reflecting the bedrock lithologies around the study area: Archean granitoid (mainly tonalite and granodiorite); metavolcanic (metabasalt, amphibolite, pyroclastics); metasedimentary (intermediate-grade schists, pelites, and iron formation); diabase dyke rock; mafic to ultramafic (gabbro, peridotite, and serpentinite); Paleozoic sedimentary rocks (limestone, dolostone, chert, siltstone, and sandstone); and Proterozoic dark wackes. There are no reliable Archean indicator lithologies. Mafic to ultramafic rocks are most abundant in an east-west belt south of Geraldton, but other smaller patches occur, especially near Jellicoe (Fig. 5b). Similarly, iron formation, although commonest near Geraldton, is scattered throughout the area in thin ribbons (Stott, 1984).

Lodgment till pebble assemblages are clearly dominated by distal clasts and imply only minor erosion and entrainment of Archean rocks of local to intermediate provenance. The Archean pebble component suggests that ice movement was across rather than along lithologic contacts, assuming that some Archean bedrock erosion occurred. For example, at site 1 (on granitoid bedrock) Archean stones comprise roughly equal amounts of granitoid, metavolcanic, and metasedimentary clasts, indicating debris transport from the northwest,

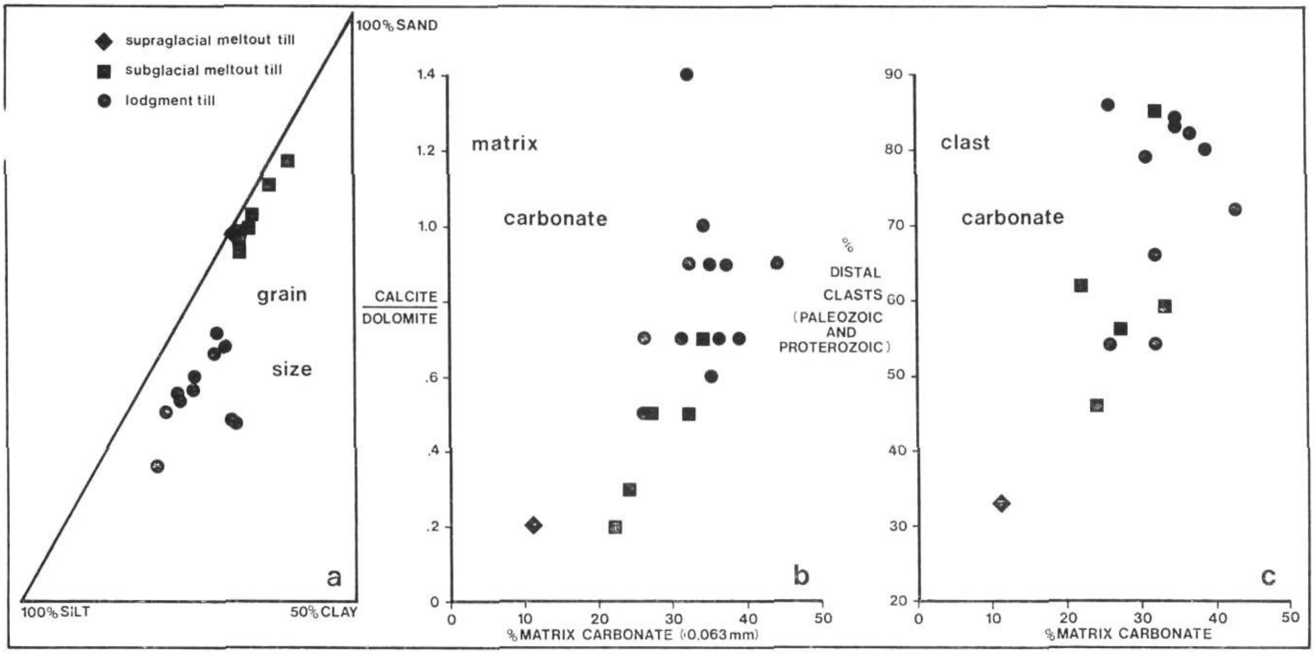

FIGURE 4. Laboratory data summary: a) textural ternary; b) matrix carbonate; and c) clast carbonate.

Sommaire des données de laboratoire: a) diagramme triangulaire des textures; b) carbonate dans la matrice; c) fragments de carbonates.

north, or northeast. Westerly sources would have resulted in more metasedimentary clasts, and southerly or easterly ones would have yielded more granitoid clasts at site 1. Minor local erosion is indicated by the relative paucity of metasedimentary clasts. Again, assuming erosion occurred, these should be more abundant since ice movement data (Figs. 2, 5a) indicate that ice traversed some 30 km of metasedimentary terrain before reaching site 1. Perhaps an abundance of meltwater inhibited freeze-on and entrainment of bedrock to the glacier sole and, if rapid flow is invoked, perhaps there was not enough time. Alternatively, ice may have been separated from the bedrock by older drift, but if it was the local sand till then reworking would have resulted in less matrix carbonate and more local materials.

Similar arguments apply to sites 5 and 6 where Archean clasts are much less abundant, although metavolcanics are in higher proportion than at site 1 because a large belt of metavolcanic bedrock occurs north of Geraldton. Site 8 epitomizes the case for rapid flow and reduced local erosion prior to lodgment. It lies at the southern edge of a large granitoid complex yet contains few granitoid pebbles and is clearly dominated by distal lithologies (86% in Fig. 5b). This may be explained by its location on the lee side of the upland itself; in an area of extending glacier flow and lower ice pressure. Peridotite at site 4 indicates that ice came from a northerly, as opposed to southerly source. Site 11 implies ice advance from the northeast since other directions would have yielded higher amounts of granitoid or metasedimentary stones.

Pebble assemblages in the meltout till are also commonly dominated by distal clasts but contain a wider range of stones of Archean to distal provenance than does lodgment till. The Archean clasts were probably derived from shearing up of basal debris when the glacier was still active prior to meltout deposition. Site 7 exemplifies this and contains abundant subangular granitoid rocks (on which it rests) indicating erosion of a granitoid upland just north of site 7 prior to meltout deposition. This is consistent with local glacial entrainment and the meltout of lodged slabs of basal ice at site 7, as mentioned earlier. Site 6 may also reflect some local glacial shearing up, or perhaps reworking of older drift, as it is almost devoid of granitoid clasts, but contains minor amounts of metasediments and metavolcanics which subcrop just north of the site.

The clast proportions in the meltout unit also suggest that glacier advance was across lithologic contacts, assuming that there was some erosion of Archean bedrock in the area and subsequent subglacial meltout deposition of its materials. For example at site 2 Archean lithologies are roughly in equal proportion (although many metasedimentary clasts were decomposed (Fig. 2), could not be collected, and may be underrepresented in Fig. 5b) implying that ice advanced from the northwest, north, or northeast. As argued for lodgment till at nearby site 1, westward provenance would have resulted in more metasedimentary clasts and southerly or easterly sources would have yielded more granitoid pebbles. Similar arguments can be made for sites 6, 9, and 10 where ice flow along lithologic units would have produced more metasedimentary and metavolcanic clasts. The upper meltout assemblages at sites 2 and 10 are from the weathering zone where many of the Paleozoic carbonate clasts had probably been dissolved and are thus underrepresented in Figure 5b.

Finally, at site 3 the supraglacial till is dominated by subangular Archean clasts (67% in Fig. 5b; Fig. 3h) with granitic clasts clearly dominating, although many decomposed me-

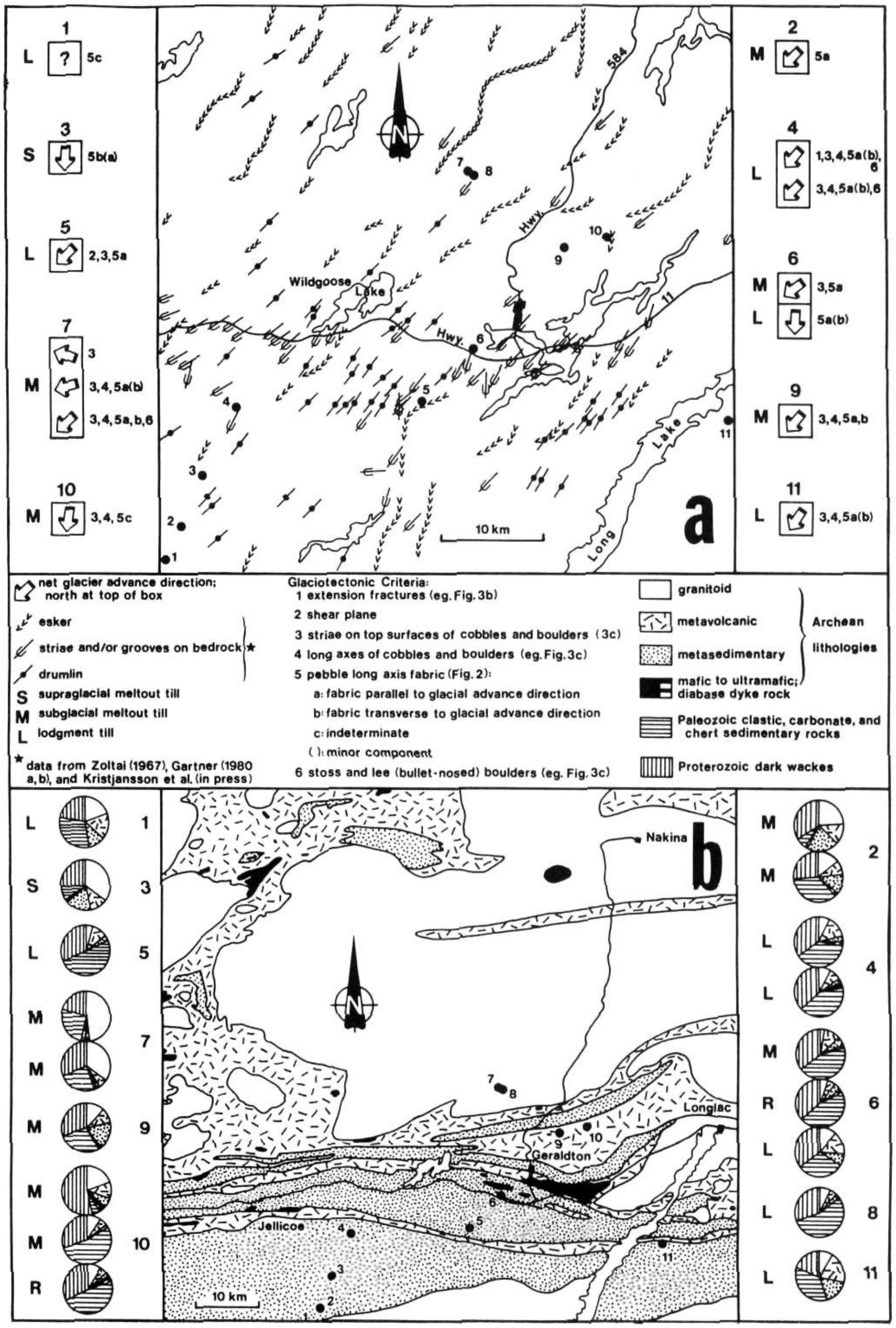

FIGURE 5. Summary of glacial movement directional data: a) kineto-stratigraphic diagram of ice advance directions, and b) stone provenance diagram relating stratigraphically arranged pie charts to bedrock lithologies at sites 1-11, R = remobilized logment till. Bedrock map simplified after Scott (1984).

Sommaire des données sur les directions du transport glaciaire: a) diagramme kinéto-stratigraphique des directions des avancées glaciaires, et b) diagramme de la provenance des roches reliant les diagrammes en pointes de tarte aux lithologies du substratum des sites nos 1 à 11. R = till de fond remobilisé. La carte du substratum a été modifiée d'après Scott (1984).

tasedimentary clasts could not be collected and the lithology may be underrepresented in Figure 5b. Such an assemblage implies that erosion of the granitoid upland to the northeast of site 3, and shearing up of local basal debris, occurred when the glacier was active prior to final supraglacial meltout deposition. Glacial debris transport must have been from a northerly source since metasediments are less abundant in the till.

Heavy minerals (0.125-0.250 mm fraction) from till matrices were also examined in epoxy-mounted grain mounts (ground to optical thickness) under transmitted polarized light. The size chosen is the most representative of silicate particles formed by glacial comminution far from their source (Dreimanis and Vagners, 1971; Gwyn and Dreimanis, 1979; Haldorsen, 1981). Horneblende, pyroxene, garnet, epidote, opaques, tremolite-actinolite, and biotite are the most abundant heavies but each occurs in multiple bedrock types in the study area (Stott, 1984), rendering provenance interpretation extremely difficult. Glacial reworking and mixing of mineral grains might also have obscured distinctive 'signatures' of source areas. A northerly provenance for sites 1 to 4 is at least implied, since significant areas of amphibole- and pyroxene-bearing rocks do not occur south of them. Light minerals are mainly quartz, plagioclase, and microcline. Microcline occurs mainly in the northern granitoid terrain (*ibid.*; Fig. 5b), and probably indicates a northerly source for most sites. Opaque minerals were studied in polished grain mounts under reflected light and include hematite, pyrrhotite, sphalerite, magnetite (some rimmed by hematite), and traces of pyrite. Gold inclusions were found in an epidotized augite grain from calcareous subglacial meltout till at site 9, whose source is unknown. Many active and inactive minesites are scattered throughout the area which could be the sources for these metallic minerals; hematite, magnetite, and pyrite are typical of the regional crystalline terrain. The opaques, therefore, appear to be useless as glacial transport indicators in this case.

ICE STREAMING AND TILL DEPOSITIONAL HISTORY NORTH OF LAKE SUPERIOR

Ice movement indicators and stone provenance support southwestward glacial flow of the Laurentide Ice Sheet over the Geraldton area, as determined by Zoltai (1967), Sado (1975), Gartner (1979, 1980), and Kristjansson *et al.* (in press). In the Hemlo area to the south, where tills are also rich in carbonate, ice movement was also southwestward (Geddes and Bajc, 1985a, 1985b; Geddes *et al.*, 1985; Geddes and Kristjansson, 1986; Hicock, 1986, 1987b). Calcareous lodgment tills in both areas are remarkably similar in texture and matrix/clast carbonate, as are the calcareous meltout tills. This lithologic consistency suggests that the formation of tills in the two areas is somehow related. In order to deposit areas of thick calcareous till (which are elongated parallel to regional ice flow) on the Canadian Shield (Geddes *et al.*, 1985; Geddes, 1986; Geddes and Kristjansson, 1986; Kristjansson, 1986; Karrow and Geddes, 1987; Hicock, 1986, 1987a, 1987b, 1987c; Kristjansson and Thorleifson, 1987; Thorleifson and Kristjansson, 1988), comprising distal materials carried hundreds of kilometres downglacier from their sources, a high sediment flux by glacial transport must be invoked. In Arctic Canada, along the northern margin of the Laurentide Ice Sheet, Dyke *et al.* (1982, 1988) and Dyke (1984) found similar wide bands of calcareous drift separated by zones of noncalcareous drift. They attributed them to ice streams issuing eastward from the M'Clintock ice divide, separated by ice travelling at normal velocities. A similar scenario may also apply north of Lake Superior where the Hemlo and Geraldton belts of thick calcareous till are flanked by zones of slightly to non-calcareous thin till and bedrock (Geddes *et al.*, 1985; Geddes and Bajc, 1985a, 1985b; Kristjansson and Thorleifson, 1987; Sado and Carswell, 1987; Kristjansson *et al.*, in press).

The concept of ice streaming and/or surging of parts of the Laurentide Ice Sheet is not new (*e.g.* Wright, 1969; Prest, 1969), but only recently has supporting geological evidence been found, especially in belts of highly calcareous till on the Canadian Shield. Furthermore, Wright (1973) and Begét (1986) have demonstrated that the Late Wisconsinan Superior and Michigan lobes of the southern margin of the Laurentide Ice Sheet had surface profiles much lower than those of modern ice sheets. Their work was based on till rheology and profiles of lateral moraines and in Michigan and Minnesota, respectively. This indicates that ice lobes were thin and possibly moving more rapidly than normal, as was also found by several authors, including Mathews (1974), Clayton *et al.* (1985), and Begét (1987), for the margin of the western part of the Laurentide sheet. In fact it is now thought that the Laurentide sheet profile was asymmetric from north to south and east to west (Fisher *et al.*, 1985; Begét, 1986, 1987). Late Wisconsinan glacial flow north of Lake Superior must have fed the Superior and Michigan lobes (Mickelson *et al.*, 1983; Prest, 1984) and so, by extension, rapid flow could be implied for the study area. If the Late Wisconsinan spreading centres of the Laurentide Ice Sheet were long lived (Shilts, 1980, 1984; Fisher *et al.*, 1985; Boulton *et al.*, 1985; Veillette, 1986; Dyke and Prest, 1987), then rapid flow was probably sustained over thousands of years and is here called ice streaming rather than surging, as in Clayton *et al.* (1985). This is important for using the history of Laurentide marginal flow dynamics to model modern ice sheet behaviour (and global sea level changes) since about 90% of their volumes are drained to the oceans by ice streams (Hughes, 1987, p. 90).

Both modern and ancient ice streams were found to occupy broad bedrock troughs or areas of low relief (Hughes, 1981, 1987; McIntyre, 1985; Begét, 1987; with a notable exception documented by Dyke, 1984) and some similarites may be noted with the region north of Superior. The Albany valley is one of the most prominent in the James Bay Lowland and could have served as a major ice stream conduit (see Prest, 1969) leading to the Geraldton and Hemlo areas. The well-studied Ice Stream B of Antarctica spills over a bedrock step at the head of a large bedrock trough which enhances stream velocity (McIntyre, 1985; Vornberger and Whillans, 1986).

In the Hemlo area bedrock uplands affected glacial dynamics and induced the deposition of calcareous lodgment till (Hicock, 1986; 1987a, 1987b, 1987c). North of Geraldton a small upland occurs upglacier of the belt of thick calcareous till (Fig. 1; Kristjansson, 1986; Hicock, 1987c). Both uplands could have served as steps enhancing ice flow as under Antarctic Ice Stream B. Also similar in Ice Stream B is the splayed flow pattern near its margin. Striated and grooved bedrock, drumlins, and eskers reveal splayed flow patterns from southward to westward in both the Geraldton and Hemlo areas (Zoltai, 1967; Geddes and Bajc, 1985a, 1985b; Kristjansson and Thorleifson, 1987; Sado and Carswell, 1987; Kristjansson *et al.*, in press).

A wet-based ice stream could have travelled up the Albany valley, perhaps due to flow convergence of Laurentide ice downglacier from the junction of the Hudson and Mistassini ice divides (Dyke and Prest, 1987). The stream may have split to continue down the drowning and Kenogami valleys, eroding and entraining soft Paleozoic sedimentary rocks and transporting glacial debris in englacial positions, especially near the Paleozoic/Precambrian boundary (Fig. 6). Within the ice sheet marginal zone, ice streams may have been separated by zones of slower flow, and continued past Nakina and westward to Geraldton, and eastward to Hemlo (Fig. 6; compare with the plumes of thick till around Hemlo and Geraldton in Sado and Carswell, 1987). The actual mechanism of ice streaming is addressed by Hicock *et al.* (in prep.) who invoke a combination of bed characteristics including deformable glacial substrata (Boulton and Jones, 1979; Boulton *et al.*, 1985; Alley *et al.*, 1986; Begét, 1986; Boulton, 1987) and subglacial drainage (Clayton *et al.*, 1985; Kamb *et al.*, 1985).

Uplands in both areas affected glacial flow, transport, and deposition. Hicock (1986, 1987a, 1987b, 1987c) presented a model of this for the Hemlo area but it applies equally well to Geraldton. Therefore, the upland model is briefly summarized below but in the context of ice streaming in the region north of Lake Superior. In this paper it also includes a new model of boulder pavement deposition by subglacial meltout. Encountering uplands, ice probably initially flowed around them, eroding local bedrock and depositing Kristjansson's (1984, 1986; Kristjansson and Thorleifson, 1987) local gritty, silty sand till near Geraldton, and Geddes' local subglacial till near Hemlo (Geddes, 1984; Geddes and Bajc, 1985a, 1985b; Geddes *et al.*, 1985; Geddes and Kristjansson, 1986). Eventually its increasing thickness allowed it to flow over the uplands (Hicock, 1986; 1987a, 1987b, 1987c), which induced compressive flow and some stoss side upshearing, enhanced ice streaming, and lee side extending flow. Combined basal melting and downward ice flow brought englacial debris to the basal zone. The position of the stoss side shear zone probably remained stationary over the upland with ice continuously passing through the zone with abundant distal debris and a small amount of locally eroded material. Most of the minor local material was probably sheared up into the ice and transported downglacier, beyond the study area. Penecontemporaneous lee side extending flow into the structural trough south of Wildgoose Lake (Fig. 1), together with basal melting, resulted in lodgment deposition of distantly-derived englacial debris on the local tills. Once deposited, the silty lodgment till had low permeability and probably held water which enhanced ice streaming over it.

After the glacier reached its maximum extent it probably ceased internal flowage north of Superior, when much of the englacial debris was laid down mainly by subglacial meltout. However, subglacial stream and debris flow activity was intimately associated with meltout, as evidenced by lenses of gravel and massive silty diamicton within the meltout unit. A model of subglacial meltout deposition north of Superior is schematically presented in Figure 7. It is based on Shaw's (1979, 1985) model but incorporates information gained from the Geraldton and Hemlo studies.

Stage 1 (Fig. 7a) depicts a stationary slab of debris-rich basal ice resting on lodgment till, with active ice lodging boulders onto the slab surface, and represents a transition from lodgment to subglacial meltout. This process has been postulated by Shaw (1985, p. 38) and Dreimanis *et al.* (1987, p. 83, 85). In stage 2 (Fig. 7b) the slab has started to melt out and now contains a boulder pavement formed (in the meaning of Shaw, 1982, p. 1548) by lodgment but being deposited (*ibid.*) by meltout. More boulders are being lodged by active ice overriding the slab and large clasts are starting to settle into the melting ice and ice-rich sediment layers. Glaciofluvial activity and debris flows occur in englacial cavities where water escapes from expanded ice sutures and conduits (Haldorsen and Shaw,

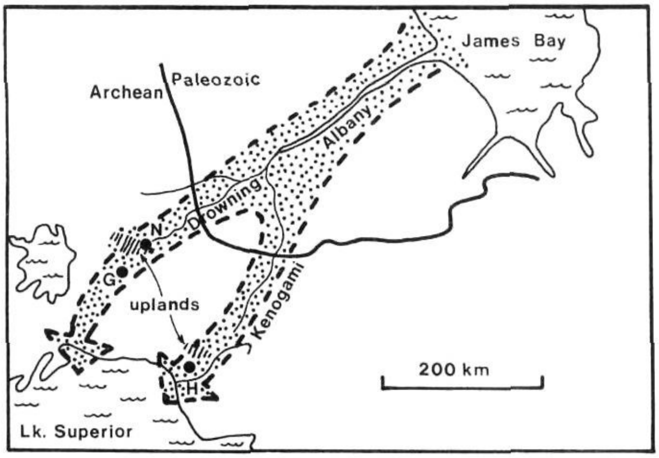

FIGURE 6. Hypothetical location of two zones of rapid ice flow (streaming = stipples) north of Lake Superior, within marginal area of Late Wisconsinan Laurentide Ice Sheet. G = Geraldton; H = Hemlo.

Localisation hypothétique de deux zones de courants glaciaires rapides (pointillé), au nord du lac Supérieur, à la marge de l'Inlandsis laurentidien au Wisconsinien supérieur. G = Geraldton; H = Hemlo.

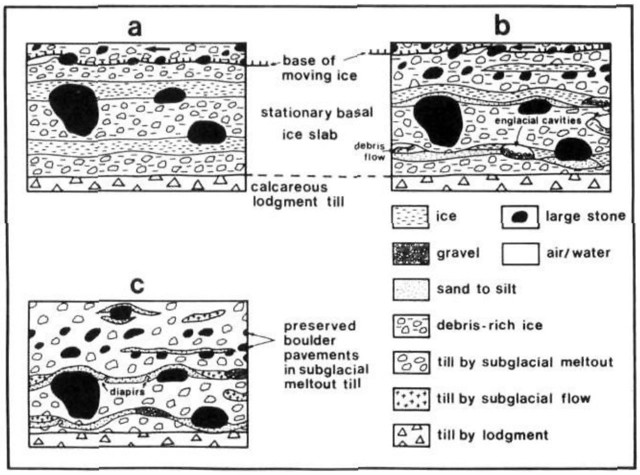

FIGURE 7. Schematic sequence of subglacial meltout deposition including boulder pavements formed by lodgment. a) Lodgment on a stationary basal ice slab; b) lodgment on stationary basal ice slabs melting out; and c) resultant meltout till package with boulder pavements. The lodgment-meltout contact could be gradational. Not drawn to scale.

Séquence schématisée de la mise en place du till de fusion sous-glaciaire incluant les dallages de blocs plaqués. a) Placage sur une lame de glace stationnaire; b) placage sur une lame de glace stationnaire en voie de fonte; et c) moraine de fusion consécutive avec ses dallages de blocs. Le contact entre le till de fond et le till de fusion pourrait être gradué. Le dessin n'est pas à l'échelle.

1982; Shaw, 1985). Ice layers and their melted out sediment settle over large clasts. After glacier flow has ceased, and meltout completed, the resultant till sequence might resemble stage 3 (Fig. 7c). Sediment layers drape over large clasts which commonly depress layers beneath. Subglacial flow till and outwash lenses are intimately associated with subglacial meltout till, and underconsolidated till diapirs have intruded sandy units in places. Finally, consistently striated boulder pavements (Fig. 2 site 7, and Hicock, 1987b, Fig. 2 site 4) formed by lodgment have been deposited by subglacial meltout and preserved within parts of the subglacial meltout till unit.

For some reason the southern margin of the Laurentide Ice Sheet was reactiviated. Carbonate tills were eroded, forming drumlins in the Geraldton area (composed entirely of calcareous till and surrounded by noncalcareous drift in places; Zoltai, 1967; Kristjansson, 1984; Kristjansson and Thorleifson, 1987; Kristjansson *et al.*, in press), but depositing an upper calcareous lodgment till at Hemlo (Hicock, 1986, 1987b). This event may correlate with the Nipigon phase of Zoltai (1965a) or the Cochrane readvance of Boissonneau (1966) and Shilts (1980). In both areas vigorous stoss side erosion of uplands sheared up more local materials to or near the ice surface. During final ice disintegration the upsheared, angular, supraglacial debris was lowered to the surface of the underlying subglacial meltout till by supraglacial meltout.

The entire till sequence in both the Hemlo and Geraldton areas can be viewed as the product of one glacial advance. This is supported by the lack of paleosols, weathering zones and rinds on clasts (although rotted granitoid and metasedimentary clasts are common at some sites), or organic layers within the drift sequence which might suggest interstadial intervals. Whether the tills were deposited entirely during general deglaciation of the area, or in part by ice flow during the Late Wisconsinan maximum, is very difficult to discern.

CONCLUSIONS

In the Geraldton area four tills can be recognized, two of which were distantly derived from at least 120 km upglacier in the James Bay Lowlands. Ice movement indicators and pebble provenance demonstrate that ice flow was southwestward over a small upland area about 20 km upglacier from Geraldton and Wildgoose Lake, across bedrock lithologic contacts. The deposition of all four tills can be explained by a single glacial advance involving penecontemporaneous stoss side upshearing and lee side downward transport of calcareous englacial debris for lodgment deposition, as modelled by Hicock (1986, 1987b) for the Hemlo area. Eventually, internal ice flow ceased and glacier downwasting formed subglacial, then supraglacial meltout tills, with an intervening glacial reactivation that carved drumlins into calcareous tills near Geraldton but deposited an upper calcareous lodgment till at Hemlo (*ibid.*).

The occurrence of thick belts of distal carbonate tills in both areas, with remarkable lithologic similarity, implies the existence of related zones of high sediment flux by rapid ice movement within the southern part of the Laurentide Ice Sheet. This accords with reconstructions of low surface profiles for the Superior and Michigan lobes (Wright, 1973; Begét, 1986) which ice over this study area must have fed (Mickelson *et al.*, 1983; Prest, 1984). If Laurentide spreading centres were long-lived then this rapid flow was likely in the form of ice streaming rather than surging. Such an ice stream may have travelled out of James Bay up the broad Albany valley, between zones of normal ice velocities, and perhaps split down the Drowning and Kenogami troughs to the Geraldton and Hemlo areas, respectively. Zones of ice streaming would have traversed, eroded, and transported soft Paleozoic rocks of the James Bay Lowlands in englacial positions, especially near the Paleozoic/Precambrian boundary. Englacial ice streaming of this carbonate debris over bedrock steps in the Geraldton and Hemlo areas resulted in the deposition of calcareous silty lodgment till with low permeability. It probably held water and enhanced wet-based glacier flow over it, in effect exerting a positive feedback on ice streaming.

On a practical note, drift prospecting would be hindered by the presence of the carbonate tills because they are mainly distantly-derived and any ore dispersal trains in them would be too diffuse to trace back to their sources (Geddes, 1984; Kristjansson, 1986; Hicock, 1986; 1987b, 1987c; Geddes and Kristjansson, 1986; Karrow and Geddes, 1987; Kristjansson and Thorleifson, 1987; Thorleifson and Kristjansson, 1988). The supraglacial till comprises local materials, is richest in metals (including gold) of the tills studied in this report, and would be most likely to contain well-defined dispersal trains (Hicock, 1986, 1987c). Kristjansson's local gritty, silty sand till (which is enriched in gold in several places; F. J. Kristjansson, oral communication, 1987) and Geddes' local subglacial till would also be candidates for applying drift prospecting techniques. The carbonate tills, however, would serve as effective buffers against acid precipitation, as well as cores in dams constructed to confine acidic mine tailings.

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