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See table of contents

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Article abstract

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ALLOCHTHONOUS SEDIMENT IN TILL NEAR A LITHOLOGICAL BOUNDARY IN CENTRAL ONTARIO

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ABSTRACT Clast counts, and measurements of carbonate abundance in the sand fraction, show that little of the till covering a portion of central Ontario was carried across the boundary between Precambrian rocks (up-ice) and Palaeozoic limestone (down-ice). Seven eighths of the pebble fraction is local, from within ~2-5 km of the site of deposition. The distantly-derived component becomes gradually less abundant down-ice from the lithological boundary, with an exponential distance scale of about 30 km. We ascribe this gradual loss to a combination of comminution and depletion by deposition. However it is not possible to map variations in the abundance of erratics; the pattern is spatially homogeneous and random. The same is true of the abundance of insoluble sand which, moreover, is highly variable. The role of transport of allochthonous sand from the Shield cannot be separated from those of comminution, erosion of local bedrock, postglacial alteration and inheritance of pre-glacial material. The till is best understood as an intimate mixture of “frictional gouge”, still more or less *in situ*, and englacially-transported sediment. Thus it is neither lodgement till nor meltout till; it may be a deformation till, but if so the episode of deformation can have lasted only a few hundred years.

RÉSUMÉ *Sédiments allochtones dans un till près d'une limite lithologique, en Ontario central.* Les comptages de cailloux et les données sur l'abondance des carbonates dans la fraction sableuse démontrent que bien peu d'éléments du till qui recouvre une partie du centre de l'Ontario a été transporté par l'inlandsis au-delà de la limite lithologique entre les roches précambriennes (amont glaciaire) et les roches calcaires paléozoîques (aval glaciaire). Les sept huitièmes de la fraction caillouteuse sont d'origine locale et proviennent de 2 à 5 km du site de dépôt. La composante d'origine plus lointaine diminue graduellement en aval de la limite lithologique, le paramètre exponentiel de distance étant d'environ 30 km. Nous attribuons cette diminution graduelle à la désagrégation survenue au cours du transport et aux pertes dues à la sédimentation. On ne peut cependant pas cartographier les variations de l'abondance des erratiques car son organisation spatiale est homogène et aléatoire. Cela vaut aussi pour les teneurs en sable insoluble qui sont, de plus, hautement variables. On ne peut pas différencier le rôle du transport des matières allochtones précambriennes de ceux de la désagrégration, de l'érosion du substratum rocheux local, de l'altération postglaciaire ou de la présence de résidus d'altérites préglaciaires. Le till semble donc correspondre à un mélange étroit de brèches de friction, demeurées à peu près *in situ* , et de sédiments qui ont subi un transport intraglaciaire. Ce n'est donc ni un till de fond ni un till de fonte. Il s'agit peut-être d'un till d'entraînement ou de déformation (au sens de Boulton) ; dans ce dernier cas, l'épisode de déformation n'aurait pu durer que quelques centaines d'années.

ZUSAMMENFASSUNG *Allochthone Sedimente in einem Till nahe der lithologischen Grenze in Zentral-Ontario.* Die Zählung der Kiesel und Messungen des Karbonate-Reichtums in der Sand-Fraktion zeigen, daß nur ein geringer Teil des Tills, das einen Teil von Zentral-Ontario bedeckte, über die Grenzlinie zwischen präkambrischem Gestein (Eis-aufwärts) und paläozoischem Kalkstein (Eis-abwärts) transportiert wurde. Sieben Achtel der Kiesel-Fraktion sind lokalen Ursprungs und stammen aus einer Entfernung von ~2 - 5 km des Ablagerungsplatzes. Der von weiterher stammende Bestandteil nimmt zum unteren Teil der lithologischen Grenze hin allmählich ab, wobei der Exponential-Entfernungsparameter etwa 30 km beträgt. Diesen graduellen Verlust führen wir auf eine Kombination von Zersplitterung und Verminderung durch den Transport zurück. Jedoch ist es nicht möglich, die Variationen in der Fülle des erratischen Materials zu kartographieren; das Muster ist räumlich homogen und willkürlich. Dasselbe kann man von dem Gehalt an unauflösbarem Sand sagen, der außerdem sehr variabel ist. Die Rolle des Transports von allochthonem Sand von dem Schuld kann nicht von der Rolle der Zersplitterung, der Erosion örtlichen anstehenden Gesteins, der post-glazialen Zersetzung und der Übernahme präglazialen Materials getrennt werden. Man versteht das Till am besten als eine enge Mischung von Zerreibungsbreschen, mehr oder weniger *in situ,* und Sediment, das intra-glazial transportiert wurde. Also ist es weder ein Grundtill noch ein Schmelztill; es könnte ein Verformungstill sein, doch in diesem Fall kann die Episode der Verformung nur einige Jahrehunderte gedauert haben.

INTRODUCTION

In central Ontario the Northern or Simcoe Lobe of the Laurentide Ice Sheet flowed roughly normal to the strike of a prominent lithological boundary — the contact between basement rocks of the Canadian Shield and overlying Ordovician limestone. The ice carried sediment from the Shield onto the limestone, and erratic Precambrian clasts are readily recognizable in the resulting mantle of till. In this paper we discuss measurements of this erratic or allochthonous fraction of the till near Peterborough, Ontario, concentrating on the gravel and sand size classes. ("Allochthonous" is a synonym of "erratic" in its adjectival use.) We aim to determine typical distances of sediment transport, and thus to infer mechanisms of transport and perhaps also of comminution of the mobile sediment.

For 150 years erratics have been valuable sources for glacial history, allowing the reconstruction of ice dispersal patterns, flow directions and transport distances. Two recent compilations of work on these subjects are by DiLabio and Coker (1989) and Kujansuu and Saarnisto (1990).

As regards distances of transport, results are mixed. Prest (1990) demonstrated that distinctive clasts from the middle of Hudson Bay have been carried by the Laurentide ice across distances not less than 2300 km in a sector at least 100 degrees of arc wide, although multiple glacial advances and some postglacial reworking were probably involved. Klassen (1995) has documented transport of resistant clasts from beneath the Keewatin ice divide over distances of tens to hundreds of kilometres. Anderson (1957) found that pebbles in Erie-lobe till in Indiana comprised 36 % Ordovician limestone, presumably from eastern Lake Ontario 600-700 km away, and 24 % Precambrian clasts from even farther away. Harrison (1960) argued that nine tenths of a till, also in Indiana, was derived from distant sources, and that the till reflected equal erosion rates per unit bed area throughout the length of a flow path originating in Labrador. Harrison found only 7 % Precambrian clasts, significantly less than Anderson's . Anderson sampled end moraines while Harrison sampled ground moraine, perhaps thus furnishing evidence for the concentration of erratics in ice-marginal deposits.

On a smaller scale, Levasseur and Prichonnet (1995) observed decreases in the abundance of marker erratics over tens of kilometres in the Chibougamau area. Gravenor and Bayrock (1961) reported on the basis of heavy-mineral abundances that till in central Alberta was about four fifths local. Clark and Karrow (1983) showed that pebble lithology in till in northern New York changes rapidly across bedrock lithological boundaries, and is mainly a function of whatever bedrock the till overlies. Hicock (1986) found that clast dispersal distances were short (20 km or less) in an alpine setting on Vancouver Island. Hicock and Kristjansson (1989) found similarly short dispersal distances in northern Ontario; here it was possible to distinguish local from non-local till, although the distinction was apparently partly stratigraphic, unlike the intimate mixture of components to be documented below. Holmes (1952) found that over 95 % of pebbles in till in west-central New York had travelled less than 80 km. He documented the disappearance of pebbles of black shale within 6.5 km, in contrast to the survival of resistant sandstone clasts over tens of kilometres. Holmes measured an average abundance of Precambrian clasts of 1.8 %, 100-200 km down-ice from the nearest sources. This is also consistent with results documented below.

Clark (1987) compiled dispersal data from the literature, and estimated the decrease in abundance of erratics with distance from source. He found length scales (*i.e. e*-folding distances) from less than 1 km up to 80 km. He argued that the range arose from variations in topographic control of ice flow and in basal sliding velocity.

We do not seek to explain this observed range of variation, but rather to contribute further observations. Ours are at finer spatial resolution than most, and we have devoted considerable effort to controlling uncertainties. We have measured the proportion of Precambrian clasts, and the abundance of carbonate in the sand fraction, in till from both sides of the Shield boundary. Down-ice from the contact, we expect these measurements to indicate how much of the till has been transported from the far side of the contact.

STUDY AREA

The region over which this study extends (Fig. 1) lies between the Oak Ridges Interlobate Moraine (Chapman and Putnam, 1984; Barnett, 1992) in the south and an arbitrary line drawn a few kilometres north of the Shield boundary. The Oak Ridges Moraine was a contact zone between lobes of the retreating Laurentide Ice Sheet, and consists largely of fluvioglacial and kame (proglacial) sediment with intercalated till (Duckworth, 1979). Its exposed width varies from near 0 km to 15 km. We exclude the Oak Ridges Moraine itself from our study because we wish to be confident that our till samples are the product of Northern-Lobe ice. Within the study area, we excluded water bodies, glacial spillways, eskers and other fluvioglacial features, areas mantled by glaciolacustrine sediments, and areas of alluvial and colluvial fill in inter-drumlin lowlands.

The basement rocks of the Grenville Province, in the north of the study area, are highly diverse (Department of Mines, 1957) but are dominated by granite and related rocks, metasediments and metavolcanics in the schist and amphibolite facies, and overlying Precambrian crystalline limestone which is only mildly altered. To the south the Shield is covered by shallow-water limestone of the middle Ordovician Black River and lower Trenton Groups. Except for thin basal sandstones, and occasional thin calcareous shales, the sediment column consists of grey, blue-grey or brownish-grey micrites and biomicrites, abundantly fossiliferous in places (Winder, 1954; Carson, 1980).

Traces survive only of the most recent of several to many advances of the Laurentide Ice Sheet into the area, dating from the final stages of glaciation between 12,500 and 12,000 years ago. Gravenor (1957) argued, for example from glaciolacustrine sediment preserved above Oak Ridges

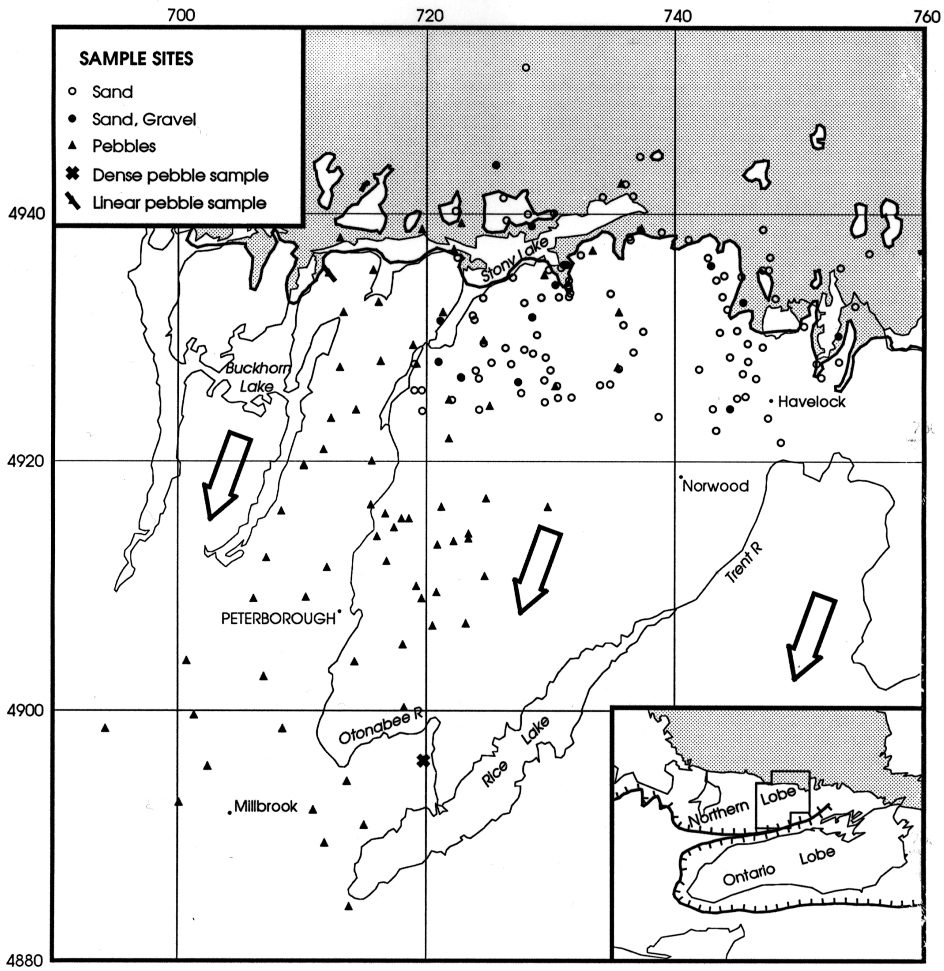

FIGURE 1. The study area. The shaded portion is the Canadian Shield. Arrows, at an azimuth of 200°, represent average ice-flow direction as inferred from drumlin orientations. Grid lines are labelled with UTM Zone 17 coordinates (km). Inset: Central southern Ontario, showing the margin of the Laurentide ice (pecked line, after Chapman and Putnam 1984) at about 12.5 ka, just before final deglaciation of the study area (indented rectangle). The long re-entrant in the ice margin marks the site of the interlobate Oak Ridges Moraine.

Localisation de la région à l'étude. La partie tramée correspond au Bouclier canadien. Les flèches, à 200° d'azimut, indiquent la direction de l'écoulement glaciaire moyen donnée par l'orientation des drumlins. Les lignes du quadrillage correspondent à la zone 17 de la projection MTU . En carton, le centre sud de l'Ontario et la position de la marge glaciaire laurentidienne (ligne hachurée, selon Chapman et Putnam, 1984) vers 12,5 ka, juste avant la déglaciation finale de la région à l'étude (rectangle irrégulier). La longue échancrure correspond au site de la Moraine interlobée d'Oak Ridges.

kame material and below ground moraine, that at least one sequence of retreat and readvance of the ice is preserved in the sedimentary record. The last readvance of the Northern Lobe overrode the Oak Ridges Moraine so that its contact with the Ontario Lobe lay farther south, near the shoreline of Lake Ontario.

The till is typically several metres thick, although bedrock is exposed sporadically. Most of the till is ground moraine, and much of it is drumlinized. No stratigraphic differentiation can be recognized within the till. It is grey to buff-grey, massive, and poorly-sorted; texturally it is a gravelly sand with 0-20% clay, 10-30% silt and frequent cobbles and boulders (Gravenor, 1957, and our unpublished data). The till is easy to distinguish by eye from the better-sorted and commonly lenticular fluvioglacial sediment which is widespread in the area. Just down-ice from the Shield boundary is the Dummer Moraine, characterized as a recessional moraine by Gravenor (1957). This is a region of hummocky and discontinuous till about 5-10 km wide in the direction of ice flow. It is interpreted as marking a slowdown in the retreat of the ice margin, although Brennand and Shaw (1994) favour a subglacial origin contemporaneous with the till sheet to the south.

METHODS

DISTANCES

The distance of each sample site from the Shield boundary was measured on a map, along an azimuth of 200°, close to the average ice-flow direction across the study area inferred from the orientation of drumlins (Fig. 1). Sites up-ice from the Shield boundary have negative distances, and sites within limestone outliers on the Shield are given distances reckoned from the up-ice edge of the outlier. These distances have uncertainties of about ±0.1 km, except where the Shield boundary is poorly located beneath lakes and the uncertainty may reach ±0.3 km. More significantly, it is not clear how relevant they are to actual distances of sediment transport, because we do not know how tortuous the actual transport paths of erratic clasts might have been.

CLAST COUNTING

Sampling sites were chosen from accessible, unvegetated exposures of till without signs of soil profile development. Where possible, three subsamples were taken at each site within 5 m of each other. A surface layer of depth ~5 cm was removed, and a substantial quantity of till was hand-sieved for 2 min through a nest of sieves. (The aim, not always met, was to count at least 100 clasts.) Clasts were counted in each of the 8-16 mm ("small pebble") and 16-32 mm ("large pebble") fractions.

Within each size class the clasts are allotted to one of two lithological classes: "limestone" and "Precambrian". This is quick and easy, because the grey and blue-grey limestone clasts are in striking visual contrast to the Precambrian clasts which are either pink ("granite"), black ("amphibolite") or "mixed". The latter term covers a variety of lithologies, commonly veined and/or gneissic, which are clearly not Ordovician limestone.

Sampling was denser at some selected sites (Fig. 1). At one, ten sets of triplicate samples were taken over an exposed area of ~400 m^2 to allow us to examine lithological variability over the 10-m scale, in contrast to the ~1-m scale sampled by the regular collection of replicate samples. At another, near to the Shield boundary, a line of 10 sites spaced about 100 m apart was sampled.

CARBONATE ABUNDANCE IN THE SAND-SIZED SEDIMENT

Samples of the sand class were gathered in the field as described above. Three subsamples were collected at each site, within 1-2 m of each other. The sand (0.063-2.0 mm) was separated from coarser classes in the field, and from finer sediment in the laboratory after drying. The carbonate abundance was measured with an insoluble-residue test (Cogley and Aikman, 1997) which offers better control of uncertainties, and more rapid throughput, than the standard method of Dreimanis (1962).

Subsample aliquots of 3-4 g were weighed to 0.1 mg and digested for 30 min in an excess (40 ml) of 2M HCl. The weight loss during digestion was assumed to be due to i) evaporation of water and ii) evolution of CO_2*(g)*according to

$$CaCO_3 + 2\,H^+ \rightarrow Ca^{2+} + H_2O + CO_2(g) \qquad (1)$$

Note that CO_3^{2-} and HCO_3^- ions, if produced, will themselves react with the H^+.

The evaporative loss of H_2O was corrected by subtracting the average weight loss of several "blank" beakers, containing 2M HCl but no sand, from the weight loss of each acid-digested sample. The fractional carbonate abundance was calculated as:

$$c = M_c\ h\ (w_t - w_b)/W_s \qquad (2)$$

where w_t is the measured weight loss from the sample beaker, w_b is the blank correction, *i.e.* the simultaneous weight loss from the blank beaker, W_s is the original weight of the aliquot of sand, and M_c = 100.09/44.01 = 2.274 is the ratio of molecular weights of $CaCO_3$ and CO_2.

Reaction 1 releases heat. Although the heat balance of the sample system (sand, acid and water, beaker, evolving gas and superjacent air) is actually quite complicated, there will certainly be more evaporation from the hotter sample beaker, and the blank correction will be too small. We derive an estimate of the heating elsewhere (Cogley and Aikman 1997), and find that the excess evaporation can be corrected for simply, by setting the factor *h* in equation 2 to 0.925±0.012.

Estimates of carbonate abundance would be too high by 8-9 % if all the carbonate were dolomite and not calcite. Chapman and Dell (1963) report petrographic estimates of calcite/dolomite ratios in samples which, although not *in situ*, must have derived from Black River and Trenton limestones (100-150 km west of the Peterborough area). Calcite is several to many times more abundant than dolomite in these samples. Winder (1954) does not mention dolomite in his stratigraphic report on the Peterborough area. Thus we conclude that dolomite is unlikely to affect our results significantly.

w_t and w_b are measured independently, and w_b may vary from negligible to dominant in relative importance. For the results reported below, $M_c\ w_b/W_s$ ranged from 0.2 to 28 %, while $M_c\ (w_t\text{-}w_b)/W_s$ ranged from -11 to 90 % and $M_c\ h\ (w_t\text{-}w_b)/W_s$ ranged from -10 to 84 %.

Several samples yielded reproducible negative estimates of carbonate abundance, implying *reduced* evaporation in the sample beaker by comparison with the blank beaker. We think that the anomalous samples must have contained an evaporation-retarding substance, such as a wax or resin, which collected as a film on the water surface. We cannot exclude the possibility that such evaporation retardants were also present in other, more soluble samples, and had the effect of turning the evaporative correction into an over-correction by up to a few percent. This difficulty requires further investigation. Our approach here is to retain and display the spurious negative estimates of carbonate abundance, so that the reader may judge the possible significance of the effect.

RESULTS

Figure 1 shows the distribution of sample sites: 33 triplicate, 7 duplicate and 51 non-replicated clast counts were made on small-pebble samples; 33 triplicate, 7 duplicate and 42 non-replicated clast counts were made on large-pebble samples; 112 triplicate samples were taken for sand-class carbonate abundance, with 14 collocated gravel (>8 mm) samples for clast counts. We had to repeat many of the carbonate abundance measurements because of a procedural error; the repeated measurements showed that many of the original measurements had not in fact been compromised, and thus we have 48 sets of duplicate measurements which sample the variability within single sample bags.

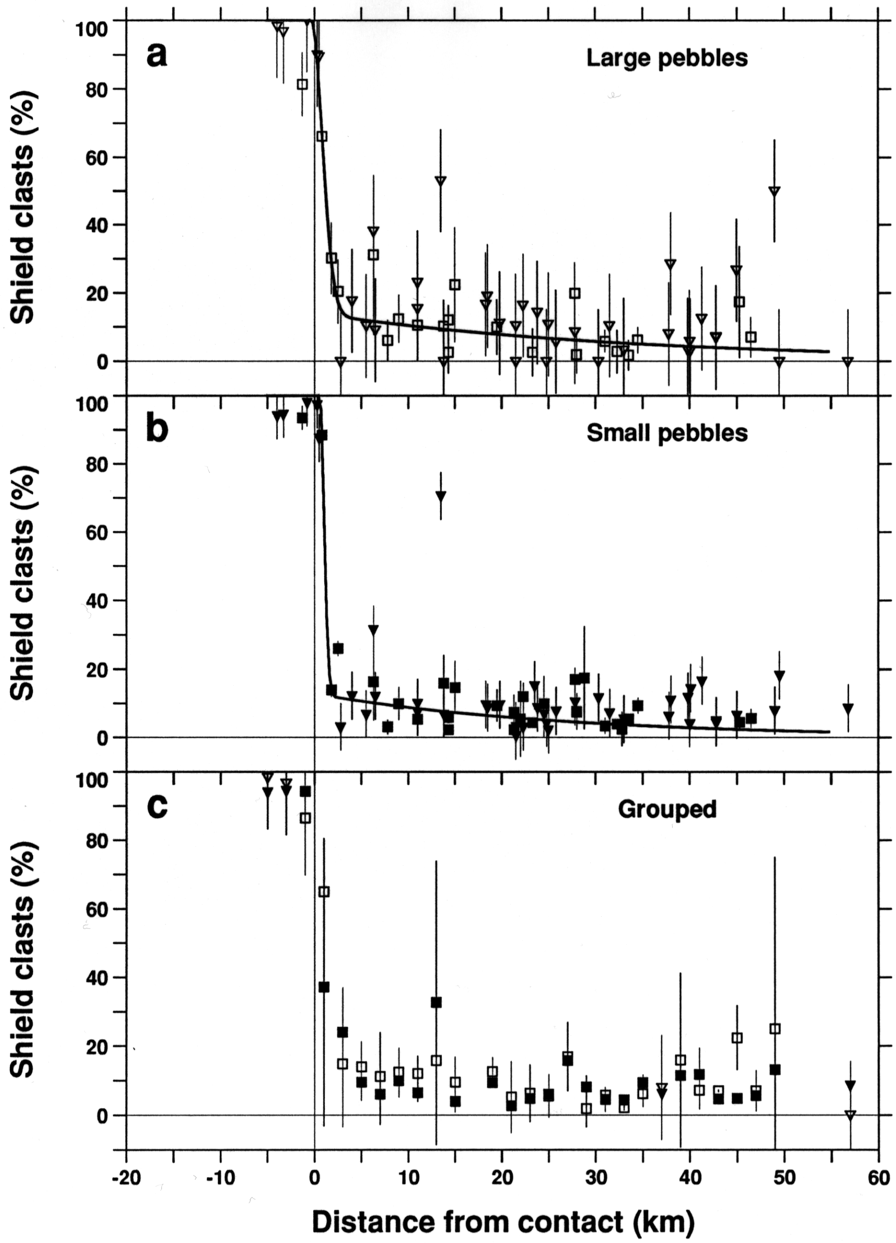

FIGURE 2. Abundance of Precambrian clasts as a function of distance *d*down-ice from the Shield boundary. Error bars (both in and in the text) give ± twice the standard error of the estimate of the abundance. In calculating the standard error, replicate clast counts are assumed to be independent samples from Poisson distributions. The usual number of replicates is three (squares). Sites with only one measurement (triangles) are assigned the average standard deviation across the full set of samples. The curves fitted to the points in panels (a) and (b) are explained in the Discussion. (a) Large pebbles (16-32 mm) at single sites; (b) small pebbles (8-16 mm) at single sites; (c) average abundances of large (open symbols) and small (solid symbols) Precambrian pebbles within 2 km intervals on the distance axis.

Abondance des fragments précambriens en fonction de la distance d *vers l'aval à partir de la limite du Bouclier. Les barres d'erreur (dans les et le texte) représentent plus ou moins deux fois l'erreur type de l'estimation de l'abondance. Pour le calcul de l'erreur type, on suppose que tous les cailloux sont des échantillons indépendants selon la distribution de Poisson. Le nombre habituel de spécimens est de 3 (carrés). On attribue l'écart type moyen à tous les échantillons aux sites pour lesquels il n'y a eu qu'une seule mesure. Les courbes des graphiques (a) et (b) sont expliquées dans la discussion. (a) Gros cailloux (16-32 mm) aux sites uniques ; (b) petits cailloux (8-16 mm) aux sites uniques ; (c) abondance moyenne de gros (symboles vides) et petits (symboles pleins) cailloux précambriens à l'intérieur d'un intervalle de 2 km sur l'axe de la distance.*

PEBBLES

The large-pebble (Fig. 2a) and small-pebble (Fig. 2b) abundances of erratic clasts both decrease from near 100 % to near-constant values of a few percent within a few kilometres down-ice from the Shield boundary. The spatial pattern is easier to see when we group the abundances into 2 km-wide classes on the distance axis (Fig. 2c). It remains highly variable but, although some of the classes appear to differ from their neighbours statistically, we do not think that these differences have broad physical significance. They could be explained, for example, by some of the sample sites happening to lie down-ice from where an allochthonous stone broke up during transport.

Small erratic pebbles are less abundant than large ones over most of the span of Figure 2, although usually the error bars for the two classes overlap (*cf. Fig. 2c).* At sites more than 2 km down-ice from the Shield boundary, the average abundance of erratics is 5.5±1.26 % for small pebbles and 8.4±2.11 % for large pebbles.

We assume that the clast counts are samples from Poisson distributions (*e.g.* Bevington, 1969), and therefore that the standard error of the clast count is _n_e/n_t, where n_e is the number of erratic clasts and n_t the total number of clasts counted in the size class. When estimating the standard error for the site, however, we assign to sites without replicate clast counts the average standard deviation (given above) among sites which do have replicate counts; for sites with replicates the standard error is calculated on the assumption that the clast counts are random samples from a Gaussian distribution. Data from non-replicate sites are thus more uncertain and have considerably less weight, particularly in the assemblage of large-pebble samples.

Erratic abundance should be 100 % where the ice flowed over the source of the erratics, *i.e.* where $d < 0$, yet it is not. At sites with $d < 0$ the abundance of limestone clasts is 9.7±9.86 % for large and 5.6±1.77 % for small pebbles. Limestone pebbles at $d < 0$ indicate errors in both identification of clasts and measurement of distances. The distances, in particular, are suspect because we have no way of estimating glacier flow paths in detail, nor can we appraise the rate of cross-flow diffusion of clasts being transported by the ice. Unfortunately it is not possible to disentangle the distance and misidentification errors, and the reader should be aware that neither is accounted for by the error bars in the . Some limestone clasts may have been transported from the Ottawa valley, 200 km ENE of the study area, but this is unlikely in view of what is known of ice flow directions during the latest Wisconsinan; we cannot exclude such a provenance dating from earlier glacial history.

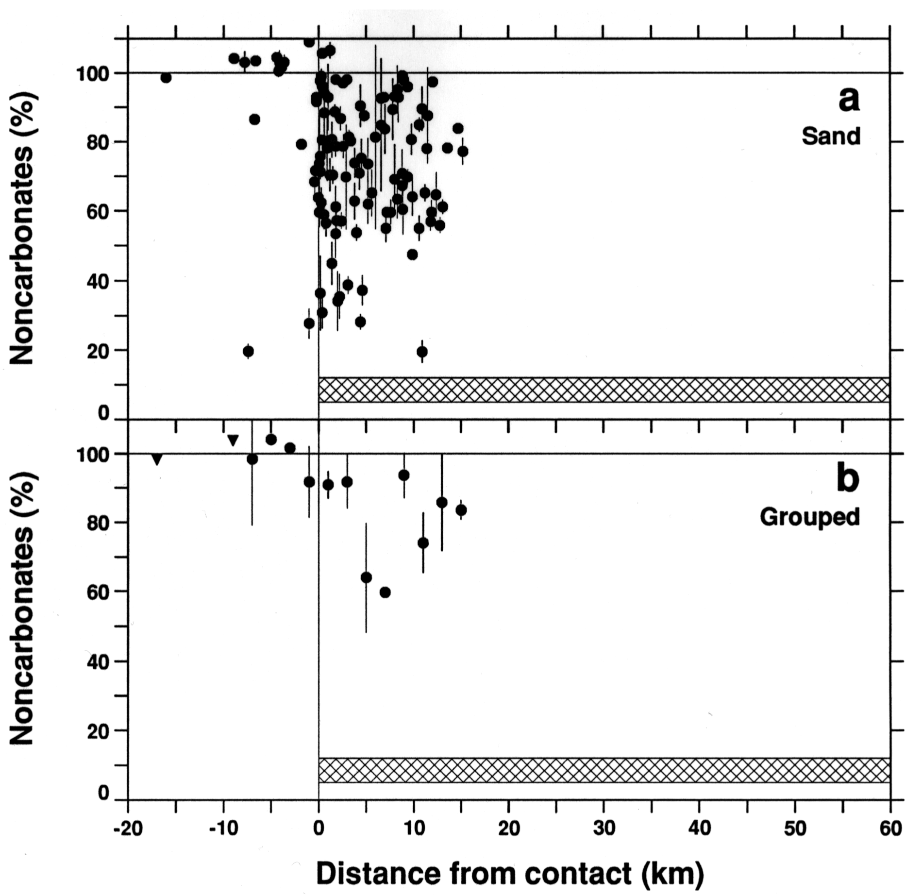

FIGURE 3. Insoluble fraction of the sand size class in till samples as a function of distance *d* down-ice from the Shield boundary. Samples with noncarbonate percentages spuriously exceeding 100 are retained for reasons explained in the text. Shaded bars: range of insoluble fraction (5-12 %) in limestone pebbles separated from till samples and digested in acid (Gravenor 1957); the 11 samples were taken on a transect across the study area, and beyond to the south of the Oak Ridges Moraine. (a) Single sample sites; (b) grouped means for 2-km distance intervals; triangles represent distance intervals containing only one site.

Fraction insoluble de la classe granulométrique des sables dans les échantillons de till en fonction de la distance d *en aval de la limite du Bouclier. Les échantillons dont les pourcentages de non-carbonates dépassent faussement les 100% sont aussi retenus (voir texte). Barre tramée : intervalle de la fraction insoluble (5-12%) des cailloux de calcaire extraits des échantillons de till et digérés dans l'acide (Gravenor, 1957) ; les 11 échantillons ont été recueillis le long d'un transect dans la région à l'étude et au-delà, au sud de la Moraine d'Oak Ridges. (a) Sites à échantillon unique ; (b) moyennes regroupées à des intervalles de 2 km. Les triangles représentent des intervalles de distance ne comprenant qu'un seul site.*

SAND

The abundance of non-carbonate (*sc.* insoluble) material in the sand class, as shown for single sites in Figure 3a and for 2-km classes in Figure 3b, has a very different distribution from the abundance of erratic pebbles. On the limestone ($d \geq 2$ km) the average non-carbonate abundance is 61 % and on the Shield ($d < 0$ km) it is 87 %, but more striking than this difference is the extreme variability. The insoluble fraction of the sand varies from spurious values exceeding 100 % down to only 20 %, and the standard deviation of the observations ($d \geq 2$ km) is 44 %. There is little sign of coherent variation with distance, although abundances are less for $d > 4$ km; the dip at $d = 5$ km and $d = 7$ km in Figure 3b is apparently significant but is not related to any known feature of the bedrock or the glacial landscape.

There is no clear spatial signal arising from the lithological contrast across the Shield boundary, and indeed the most obvious feature of Figure 3 is that there appears to be no spatial signal at all. The irregular but definite decrease in insoluble sand across the boundary means that the sand fraction of the till on the limestone cannot be derived solely from the Shield. Nor can it be derived solely from mechanical weathering of the limestone, for the 5-12 % of insoluble material in the limestone is much less than the abundance of non-carbonate material in the sand. We will try to account for these puzzling observations in the next section.

SPATIAL VARIABILITY

As presented so far, the measurements show no obvious evidence of spatial structure away from the Shield boundary. It is nevertheless reasonable to want to know more about two-dimensional patterns of variation. The variance between pairs of samples, as a function of the distance *s* separating them, may convey such information, and is illus-

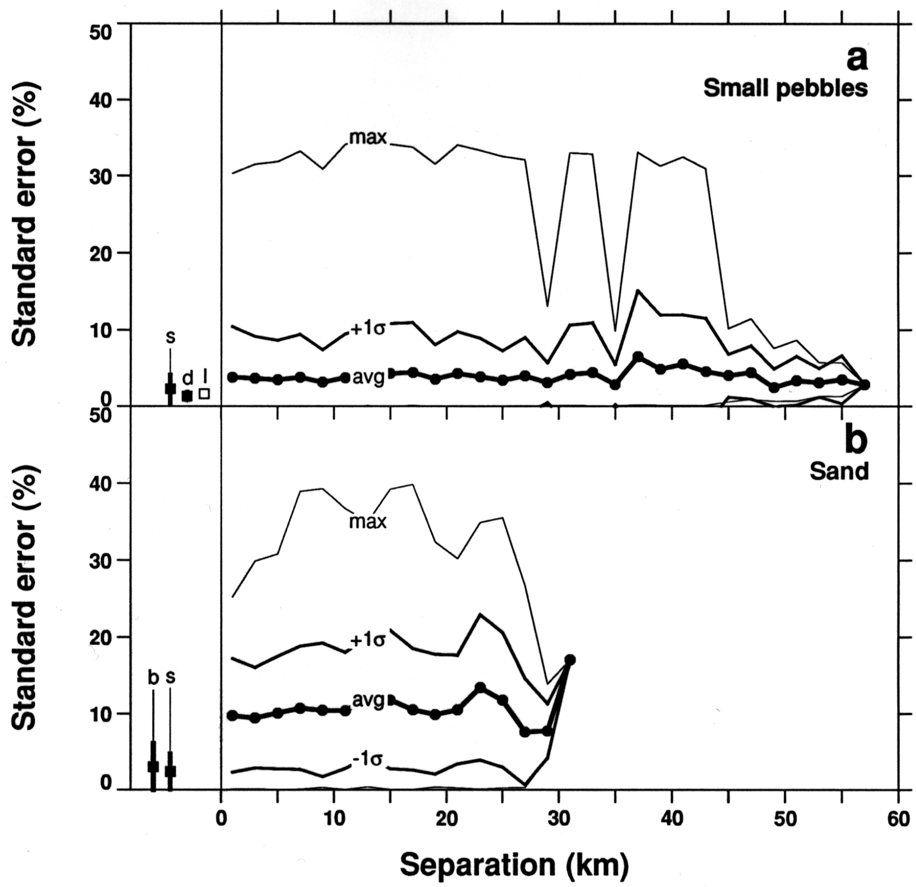

FIGURE 4. A semivariogram, illustrating the variability between pairs of sample sites as a function of their distance apart, *s*. The sites are all 2 km or more down-ice from the Shield boundary. The chosen measure of variability is actually the standard error, not the semivariance (or standard error squared, because $n = 2$ in each comparison). *a:* the abundance of Precambrian clasts in small-pebble samples; the semivariogram for large-pebble samples (not shown) is similar in appearance. *b:* the insoluble fraction of sand samples. Symbolism — dots connected by thick line: average standard error, se(*s*), for all sample sites separated by distances between $s-{}^1/_2 ds$ and $s+{}^1/_2 ds$, with $ds = 2$ km; medium lines: se(*s*)$\pm$ σ(se), where σ(se) is the standard deviation of the standard errors in each separation interval; thin lines: minimum and maximum standard errors in each separation interval. In the left panel of each graph are shown the standard errors of: b, replicate measurements from the same sand sample bag (*i.e.* spatial separation scale *s* ~0.1 m); s, subsample averages from the same sample site (*s* ~ 1 m); d, dense local sampling (*s* ~ 10 m) of pebbles at a site south of Peterborough (Fig. 1); l, linear sampling (*s*~ 100 m) of pebbles at a site north of Peterborough (Fig. 1). (Square: average; thick error bars: average ± one standard deviation; thin error bars: observed range of standard errors).

Semi-variogramme illustrant la variabilité entre des sites d'échantillonnage pairs en fonction de la distance qui les sépare, s. *Les sites sont tous situés à 2 km ou plus en aval de la limite du Bouclier. La mesure de variabilité choisie est celle de l'erreur type et non de la semi-variance (ou erreur type au carré, car* n = 2 *à chacune des comparaisons). (a) L'abondance de fragments précambriens dans chacun des échantillons de petits cailloux ; le semi-variogramme (non illustré) des échantillons de gros cailloux est similaire en apparence. (b) La fraction insoluble des échantillons de sable. Points réunis par la ligne épaisse : erreur type moyenne, se(s), pour tous les sites d'échantillonnage distants entre* s - ${}^1/_2$ ds *et* s + ${}^1/_2$ ds, ds *= 2 km ; les lignes médianes : se(*s*) ± σ(se), où σ(se) est l'écart type des erreurs types dans chaque intervalle d'écart ; lignes fines : erreurs types minimales et maximales dans chaque intervalle d'écart. Dans la portion gauche des deux graphiques apparaissent les erreurs types de : b, mesures de spécimens non uniques prélevés dans le même sac d'échantillon de sable (échelle spatiale d'écart,* s *~0,1 m) : s, moyennes des sous-échantillons prélevés au même site (* s *~1 m) ; d, échantillonage dense (*s *~10 m) de cailloux à un site au sud de Peterborough (fig.1) ;l, échantillonage linéaire (* s *~100 m) de cailloux à un site au nord de Peterborough (fig. 1). (Carrés : moyenne ; barres d'erreur épaisses : moyenne ± un écart type ; barres d'erreur fines : intervalle des erreurs types observé.)*

trated in Figure 4. To draw contours of any quantity which is sampled at a number of points in a region, we have to assume that the quantity exhibits spatial correlation, such that the point estimates are reliable guides for interpolation between the points. Spatial correlation generally decreases with the separation s between points, and is found to become negligible at separations greater than some maximum s_{max}. For mapping to be meaningful, each contour must have everywhere at least two sample sites no further away from it than s_{max}. (The more sample sites within this distance, the more reliable the contour.)

We expect the quantity plotted in Figure 4 to increase from some minimum (and preferably low) value at zero separation to a maximum at and beyond s_{max}. The minimum is sometimes called the “nugget” and the maximum the “sill”. The minimum may be regarded as an index of measurement error; the larger it is, the more freely may contours disagree with estimates at sample points (in the interest of improving their regional goodness of fit). The distance to the sill is the distance to which we may reliably go, from any unsampled point, in search of sample sites to guide us in estimating the magnitude of the field at the unsampled point. Figure 4 shows that, both for erratic pebbles and non-carbonate sand, the sill must be at a separation less than about 2 km; at greater separations the variability between sample sites is independent of their separation. It shows also, at the left of each graph, that the nugget is not far, if at all, below the sill. In other words, no map can be drawn of the quantities we have measured, because the sample sites convey no useful information about values at points between sample sites. The spatial fields are not only homogeneous but also random, and moreover they are random at all resolvable spatial scales between s ~ 0.1 m and s = tens of kilometres.

For pebble samples the average distance to the nearest neighbour of any given site is 2.9 km; only 11 % of sites have a neighbour within 1 km. For sand samples the corresponding distance is 1.2 km, and 43 % of sites have a neighbour within 1 km. We have examined close-ups of variation along the innermost 2 km of the separation axis, and find no tendency for a decrease in the standard error of pairs of pebble samples, even at the smallest separations; for sand samples there is an irregular decrease, with low statistical confidence, as s drops from 1 km towards zero. Thus mapping the distribution of non-carbonate sand would be difficult and uninformative. For erratic pebbles a map would be pointless and even misleading.

DISCUSSION AND CONCLUSION

We consider that the measured abundances of allochthonous sand are too variable to warrant modelling, but that the measured pebble abundances offer a clear view of how the pebbles got where they are. The simplest model (Fig. 2) appears to require that the glacier's load be divided into three components:

- one which disappears rapidly as distance from the bedrock source increases;
- one whose abundance is constant or decreases very slowly with distance;
- and one which contributes sporadic outliers of abundant allochthonous clasts far from their sources.

We shall ignore the outliers, assuming that they derive from sparsely and randomly distributed comminution events for which our sampling density is inadequate. The first two components, however, can be described explicitly with a simple statistical model of the form

$$f = f_r + f_s \tag{3}$$

where f is the total fractional abundance of allochthonous clasts in a particular size class at distance d, and f_r and f_s are respectively the rapidly- and slowly-disappearing component abundances.

An appropriate functional form for the rapidly-disappearing component is the half-Gaussian

$$f_r = \begin{cases} f_{r0} & ,d < d_0 \\ f_{r0}\ \exp\left[-\left(\frac{d-d_0}{\delta r}\right)^2\right] & ,d \geq d_0 \end{cases} \tag{4}$$

which yields fr = constant = fr0 when the distance d is up-ice from the source d0, and a decrease down-ice from the source at a rate described by the squared e-folding scale δ_r.

Because the source is switched off abruptly at d = 0, it is likely that zero will be a good guess for the source location parameter d_0. Nevertheless we treat the source location as an unknown because distance and misidentification errors mean that the Shield boundary is not located very precisely by the available data. We also have no knowledge of rates of cross-flow diffusion of clasts in transport, and clasts deposited at sites with d< 0 may derive in part from source sites with d > 0, as sketched in Figure 5; in this interpretation d_0 is not the actual lithological boundary but the apparent source location.

Because there is no detailed physical guidance as to its functional form, we assume that the gradual loss (if any) of the slowly-disappearing component occurs at a constant fractional rate. This yields the exponential form

$$f_s = \begin{cases} f_{s0} & ,d < d_0 \\ f_{s0}\ \exp\left[-\left(\frac{d}{\delta s}\right)^2\right] & ,d \geq d_0 \end{cases} \tag{5}$$

δ_s is an exponential length scale for depletion of the glacier's pebble load by comminution, or by deposition, or, most plausibly, as a combination of the two. f_{s0} is the fractional abundance of the slowly-disappearing component at $d = d_0$. Note that f_{r0} and f_{s0} are redundant: f is necessarily 1 when $d < d_0$, and we therefore replace f_{r0} by (1 - f_{s0}).

The model thus has four parameters, f_{s0}, d_0, δ_r and δ_s. We estimated these parameters from the data on erratic abundances, using a version of the nonlinear least-squares algorithm of Marquardt. The results appear as the curves in Figure 2, and the parameter estimates are listed in Table I. The parameter f_{s0} — equal to about one part in 7 or 8 — and the length scale δ_s— about 30 km — appear to be statistically indistinguishable between the two size classes. In consequence f_{r0} is about 0.85-0.90, but f_r drops to zero within a distance of about $3\delta_r$, or 2-5 km, from the apparent source d_0. The apparent source is within 0.5 km of the nominal location of the Shield boundary at $d = 0$.

The simplest glaciological interpretation of these results is that the two components represent “bed load” and “suspended load” — metaphors which we choose deliberately because we do not think that the rapidly-disappearing component is lodgement till or the slowly-disappearing component meltout till. The bed load represents clast transport, evidently over short distances, by strong traction either within or just beneath the basal ice. The suspended load represents transport in a régime, presumably englacial, in which travel distances are orders of magnitude greater and rates of loss are orders of magnitude less than for the bed load. Making a reasonable extrapolation from the ratio inferred at distance d_0, deposits from bed load and from suspended load are *mixed intimately in the Peterborough till sheet*, in a ratio of about 8:1.

The rapid disappearance of bed load implies that any single clast in basal traction will travel no more than a few kilometres; the most probable travel distance, in fact, is $d_0 \sim 0$. The bed load may thus be interpreted as a “frictional gouge” built up by strong shearing at the interface between the ice sheet and its bed. But we cannot extract from the data the rate at which bed-load particles are lost from our pebble size classes by comminution. This loss may be balanced by an increase (in effect a delayed decrease) in the abundance of allochthonous sand (Fig. 3) and finer material, which may travel substantial distances.

The 30-km length scale for loss of suspended-load pebbles is comparable with some of the greater length scales estimated by Clark (1987). In particular, his half-distances based on Holmes's data (1952) from western New York translate to $\delta_s = 28$ km for sandstone clasts and $\delta_s = 21$ km for limestone clasts. It is not clear how Clark treated Holmes's data to arrive at his estimates, but it is worth pointing out that the model does not resolve δ_s with great sensitivity. For example if we set $\delta_s = \infty$ in equation 5 we can reduce the variance observed for our small-pebble data by 90.6 %, to be compared with 91.2 % for the set of parameters in Table I.

Our sampling design and protocol imply random sampling of different depths within the till sheet, and results suggest that our two components are intimately mixed. (Recall that the till is unstratified.) At one extreme, mixing may have been entirely proglacial or periglacial, and the till may be a form of flow till generated at or beyond the retreating ice margin from distinct fluidized subglacial and englacial/

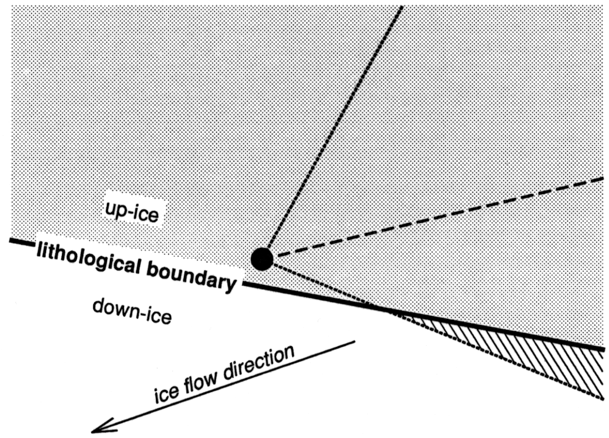

FIGURE 5. Sketch showing how cross-flow diffusion may introduce sediment from the down-ice side of a lithological boundary to a sample site (dot) on the up-ice side. The “source cone” for the sample site, delimited by dotted lines and with its axis shown as a dashed line, will extend onto the down-ice side of the boundary (hatching) if the strike of the cone boundary exceeds the strike of the lithological boundary. The source cone is that region from which sediment is delivered to the site of deposition, by any of several styles of off-axis ice flow; that is, it consists of all points whose dispersal trains include the site of deposition.

Schéma illustrant la façon dont la diffusion par écoulement en travers peut permettre à des sédiments de la partie de l'aval écoulement d'une limite lithologique de se retrouver à un site d'échantillonnage (point) en amont. Le “ cône d'origine ” au site d'échantillonnage, délimité par la ligne pointillée et son axe en tireté, s'étend jusqu'à la partie situé en aval de la limite (hachurée) quand la limite du cône franchit la limite lithologique. Le cône d'origine correspond à la zone à partir de laquelle le sédiment est transporté au site de dépôt, selon n'importe quel type d'écoulement hors axe, c'est-à-dire qu'il est constitué de tous les points dont les traînées de dispersion comprennent aussi le lieu du dépôt.

supraglacial components (although the drumlinization of the till sheet argues against this). At the other extreme, mixing may have been by steady subglacial accretion of englacial clasts into the (steadily accumulating) frictional gouge beneath.

Alternatively our measurements would be consistent with Boulton's (1987) conceptualization of deformation till, were it not that Boulton envisages deformation till as potentially travelling great distances. To accommodate Boulton's ideas to our observations it would be necessary to allow that as deformation till accumulates it may reduce sub-basal shear stresses dramatically — that is, to magnitudes such that most of the slip occurs at the ice-sediment interface rather than beneath it (but *cf.* Dreimanis, 1989; Hart, 1995). The sub-basal stress drop would presumably be due to the substitution of a smooth for a rough ice-bed interface. The Peterborough till sheet could, however, have formed during a very short episode of strong deformation. To limit transport distances to the observed 2-5 km, only 200-500 years are allowed at a nominal sediment velocity of 10 m a^{-1}. This is roughly the duration of a single (and presumably final) readvance of the ice sheet, and raises the question of what the ice was doing to its bed during the previous 10^4-10^5 a and during previous glacials.

Within the sand size class, the abundance of insoluble grains today must represent a balance between: 1) gains from up-ice by glacial transport; 2) gains from coarser size classes, and losses to finer classes, by comminution during glacial transport; 3) selective losses to fluvioglacial or postglacial agents of erosion and removal, *i.e.* loss or relative gain of apparently allochthonous material by comparison with local clasts; an obvious mechanism is dissolution of the soluble local material; 4) gains from the insoluble component of local bedrock by weathering, either pre-glacial, syn-glacial or postglacial. Our measurements cannot determine the relative importance of these processes. They do, however, show that at least two of them must be significant.

TABLE I

Estimates of parameters in the model of erratic clast transport.

Size class	f_{s0} (pct)	δ_s (km)	d_0 (km)	δ_r (km)
Small pebbles	12.9 ± 1.67	26.8 ± 4.14	0.56 ± 0.065	0.64 ± 0.124
Large pebbles	14.1 ± 4.73	33.8 ± 18.47	-0.34 ± 0.400	1.64 ± 0.568

Errors are presented as twice the standard error of each parameter. However, only an *assumed* normal distribution of uncorrelated errors would permit us to interpret these estimates as 95 % confidence limits.

We might have obtained a clearer picture had we sampled the Dreimanis-Vagners terminal grades for calcite. Dreimanis and Vagners (1971) showed that calcite grain size distributions in basal tills tend to have maxima in the coarse silt and fine silt grades. They interpret the maxima as sizes below which comminution becomes ineffective, so that a calcareous till with abundant terminal-grade calcite may be regarded as mature. Measurements of the silt class would certainly be valuable, but they would not answer the question why the sand-class abundances are so variable. As was found for the pebble data, processes 1 and 2 are not distinguishable in the sand measurements. We can, however, speculate about processes 3 and 4.

Suppose that the picture conveyed by the pebbles were true also of the sand. That is, at sites down-ice from the Shield boundary, 10 % of the sand was allochthonous (and insoluble) and 90 % was local upon deglaciation. Of the local sand, about 5-10 % is insoluble, so 14-19 % of any one sample should be insoluble. It may not be a coincidence that the *minimum* insoluble fraction we have measured is just slightly greater than this (Fig. 3a), in which case the observed range, from 20 to 100 %, may be explained by postglacial removal of soluble sand — process 3. But there is a difficulty here: typical modern solute loads in runoff are about 10-100 g m^{-2} a^{-1} (*e.g.* Meybeck (1979), for the Saint Lawrence basin as a whole, gives 20 g m^{-2} a^{-1}). Allowing 10 ka for dissolution, 100-1000 kg m^{-2} can be removed in postglacial runoff. Taking 5 m as a typical thickness and 1500 kg m^{-3} as a typical bulk density for the till sheet, and assuming all of it to be sand, the loss to dissolution can raise the insoluble fraction above the estimated minimum of 14-19 % by no more than a few percent.

Thus process 3 by itself cannot account for the observations. However, we sampled wherever contemporary exposures were available, and do not know the depth of each sample beneath the land surface exposed by retreat of the ice. This means that areally selective dissolution in upper horizons of the regolith (*e.g.* Shilts and Kettles, 1990), possible reprecipitation of carbonate in lower horizons, and later selective removal of the upper horizons, could, in principle, explain the observations. On the other hand, we think it likely that *pre*-glacial history may help to explain Figure 3. At present, landscape evolution in central Ontario is transport-limited: removal rates of clastic sediments are low by comparison with potential weathering rates. Given the low regional relief and tectonic stability, this is likely to have been true in previous interglacials and in preglacial times. The landscape is thought to have been above sea level at least since the Cretaceous and perhaps longer, which is abundant time for the transport-limited growth of an insoluble regolith much thicker than the Peterborough till sheet.

It is beyond our scope to discuss how a pre-glacial regolith might survive repeated glaciation. But examples of the protective geomorphic role of glaciers are not unknown (*e.g.* Sugden and John, 1976; Glasser, 1995), and at least one recent analysis argues that a till is partly pre-glacial: Bédard (1993) described a till, formed under sluggish ice flow near an ice divide, which appears to consist in part of reworked regolith. Process 4 — the long-term accumulation of insoluble residues of weathering — appears to be needed as part of a composite explanation for the observed variability in the insoluble fraction of sand in the Peterborough till sheet. Whatever the relative importance of the contributing processes, we think that the model offered here is an advance over that of Clark (1987), which may be too parsimonious. Intimately mixed englacial and subglacial populations of allochthonous sediment are likely to be distinguishable by sufficiently dense sampling of other tills which sit astride lithological boundaries.

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