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John Shaw and George Gorrell

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Article abstract

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SUBGLACIALLY FORMED DUNES WITH BIMODAL AND GRADED GRAVEL IN THE TRENTON DRUMLIN FIELD, ONTARIO

John SHAW* and George GORRELL, Department of Geography, Queen's University, Kingston, Ontario K7L 3N6, and RR # 2, Oxford Mills, Ontario K0G 1S0.

ABSTRACT Large gravel bedforms, gravel dunes, are described from a site between drumlins in the Trenton drumlin field, Ontario. The forms are up to about 10 m high, occur in groups, are asymmetrical and contain large-scale cross-bedding. Gravel dunes occur elsewhere in the drumlin field where they are found in subglacial tunnel channels and are commonly associated with eskers. The internal structures of the dunes show reactivation surfaces like those described from large-scale eolian, marine and fluvial bedforms. Distinctive graded foreset beds in the dunes show a fining of the clasts and either coarsening or reduced volume of matrix upwards. These relationships are explained in terms of longitudinal sorting of bedload and deposition of suspended load in a return flow beneath a separation eddy to the lee of the dune. Finer sediment, mainly sand, is found downstream from the dunes. Both bedload deposits and suspension deposits are found in the produne beds, depending on the location relative to the attachment point. The dunes are interpreted to have formed subglacially in tunnel channels with flow depths of several tens of metres.

RÉSUMÉ *Les dunes graveleuses formées sous le glacier dans le champ de drumlins de Trenton, en Ontario.* On fait ici la description de grandes structures sédimentaires du lit, soit des dunes graveleuses, que l'on trouve dans un site situé entre les drumlins du champ de drumlins de Trenton. Ces formes asymétriques et regroupées, qui font jusqu'à 10 m de haut, renferment d'importantes stratifications entrecroisées. Les dunes graveleuses occupent des conduits sous-glaciaires et sont souvent associées aux eskers. La structure interne des dunes laisse voir des surfaces de réactivation comme celles qui ont été décrites pour les structures sédimentaires en milieux éolien, marin et fluviatile. Les lits frontaux distincts et granoclassés sont caractérisés par une diminution verticale de la taille des matériaux grossiers, accompagnée soit d'une augmentation de la taille des particules de la matrice, soit d'une diminution du volume matriciel. Ces relations s'expliquent par le tri longitudinal de la charge de fond et le dépôt des particules en suspension dans la zone de division du courant formée du côté abrité de la dune. Les sédiments plus fins, surtout du sable, se trouvent en aval des dunes. Des matériaux provenant de la charge de fond et du transport des particules en suspension sont accumulés dans les lits en avant des dunes et ce, en fonction de la position par rapport à l'emplacement du point de raccordement du vortex de séparation. On croit que les dunes ont été formées dans des conduits sous-glaciaires sous des courants d'une profondeur de plusieurs dizaines de mètres.

ZUSAMMENFASSUNG *Subglazial gebildete Kiesdünen im Drumlin-Feld von Trenton, Ontario.* Breite Kiesschichtformen, Kiesdünen, werden von einem Platz zwischen Drumlins im Trenton Drumlin-Feld beschrieben. Die Formen sind bis zu etwa 10m hoch, treten in Gruppen auf, sind asymmetrisch und enthalten umfangreiche Kreuzschichtung. Kiesdünen treten auch anderswo in dem Drumlinfeld auf, wo man sie in subglazialen Tunnelrinnen vorfindet und gewöhnlich mit Eskern in Verbindung bringt. Die inneren Strukturen der Dünen weisen Reaktivierungsoberflächen auf wie diejenigen, die bei ausgedehnten durch Wind, Meer und Fluss gebildeten Schichtformen beschrieben werden. Ausgeprägte abgeflachte frontale Schichten in den Dünen weisen eine vertikale Verfeinerung der Trümmer auf und entweder eine Vergröberung oder ein verringertes Volumen der Gesteinshülle. Diese Beziehungen lassen sich erklären im Sinne von einer Längensortierung der Geschiebelast und Ablagerung des Suspensionsstoffes in einem Rückfluss unter einem Trennungswirbel am Lee der Düne. Feinere Sedimente, vor allem Sand, findet man unterhalb der Dünen. Beides, Geschiebelast-und Suspensionsstoff-Ablagerungen, findet man in den Betten vor den Dünen, entsprechend der Lage in Bezug auf den Anschlusspunkt des Trennungswirbels. Man nimmt an, dass die Dünen sich subglazial in Tunnelrinnen mit Strömungstiefen von mehrmals 10 Metern gebildet haben.

* New address: Department of Geography, University of Alberta, Edmonton (Alberta) T6G 2H4

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INTRODUCTION

There are large-scale asymmetric gravel bedforms, referred to here as gravel dunes, between the drumlins of the Trenton, Ontario drumlin field (Fig. 1). These bedforms lie in tunnel channels eroded into the drumlins and are, in places, adjacent to eskers. The sequence of formation appears to have been: 1) drumlins, 2) tunnel channels, 3) eskers, and 4) gravel dunes, although the gravel dunes may have preceded the eskers. The gravel dunes at the Trout Creek site near Campbellford (Fig. 1) are interpreted as bedforms produced by subglacial meltwater flow. Details of the internal structure and grain size of these dunes are used in a discussion on their formative conditions.

LANDSCAPE SETTING AND MORPHOLOGY

The Trenton drumlin field is part of a much larger complex of drumlins in south-eastern Ontario (Fig. 1, Chapman and Putnam, 1966). These drumlins have been explained as resulting from: erosion by ice (Gravenor, 1957), erosion by meltwater (Shaw and Sharpe, 1987a), moulding by subglacial processes of deformation (Crozier, 1975; Eyles and Westgate, 1987), and deposition in subglacial cavities (Sharpe, 1987; Shaw and Sharpe, 1987b). The drumlins are largely composed of diamicton, but some contain considerable thicknesses of stratified and laminated sorted sediment (Crozier, 1975; Shaw, 1983; Sharpe, 1987; Shaw and Sharpe, 1987b).

There is evidence from air photographs of systematic erosion of the drumlins where powerful meltwater streams have cut anastomosing channels through the drumlin field (Fig. 2). These channels predate the eskers which lie within them and postdate the drumlins into which they are cut. This widely reported temporal relationship between drumlins, channels, and eskers signifies a subglacial origin for the channels, which, although referred to here as tunnel channels, are usually termed tunnel valleys (Wright, 1973; Grube, 1982; Shaw, 1983; Dardis and McCabe, 1983). This distinction is made to draw attention to the inference that these conduits, like channels, had their full width occupied by meltwater flow (Wright, 1973; Shaw, 1983; Boyd *et al.*, 1988), whereas valleys commonly contain channels but are seldom, if ever, fully inundated.

The gravel dunes (Fig. 3) are found commonly, as at Trout Creek, where tunnel channels widen downstream of a constriction (Fig. 4). They are most common in groups, although there are some single forms. Dune crests are straight, or slightly sinuous, or linguoid in plan view. Dunes show an asymmetrical profile, with stoss slopes of about 4° and steeper lee slopes of about 11°. Angle of repose cross-beds within the dunes indicate that the present lee slopes are somewhat degraded with respect to the primary slopes of the active dune. This degradation is probably related to wave action during the falling stages of Glacial Lake Iroquois, the precursor to present-day Lake Ontario. Small spits and beaches seen on 1:10 000 scale air photographs are evidence for wave reworking of the fluvioglacial deposits.

Heights of the largest dunes are about 10 m and, at the Trout Creek site, these have a wavelength of about 200 m. Smaller dunes with wave heights of 1 to 2 m occur together with the larger ones.

In the confined section of the tunnel channel, just upstream from the dunes, there are large, subrounded boulders, some with diameters >1 m, in places piled one upon another. These boulders are not striated which, together with their roundness and stacking, suggests transport and deposition by running water rather than ice. Minimum water flow velocities of between 2 and 10 m/s are required to transport boulders of this size (Williams, 1983; Elfstrom, 1987).

A small esker occupies the central part of the tunnel channel in the distal zone of the dune field (Fig. 4). From surface samples, it appears to be composed of rounded cobble gravel. It has steep sides and a fairly sharp and undulating crest with one prominent col about halfway along its length. These attributes suggest subglacial rather than englacial or supraglacial formation of the esker; deposition over ice would probably have produced a less pronounced landform. However, there does seem to have been some reworking of the esker sediment at its proximal end where a linear concentration of boulders extends as a lag in continuation of the esker trend.

There are two large mounds of sand and gravel, also with a col between them, to the north of the esker (Fig. 4). These, too, appear to have originated subglacially since they are dissected by tunnel channels and have gravel dunes superimposed on their flanks; the tunnel channels and the gravel dunes are interpreted to be subglacial since they represent a drainage

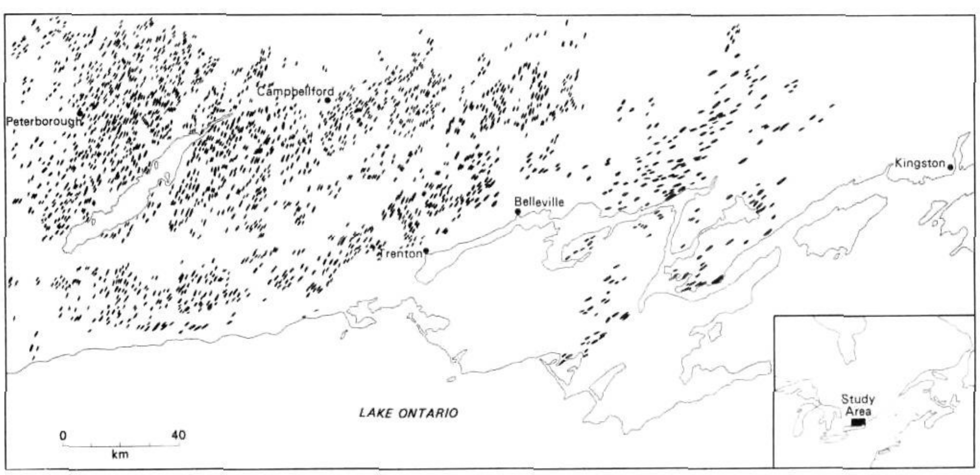


FIGURE 1. The Trenton drumlin field, Ontario.

Le champ de drumlins de Trenton, en Ontario.

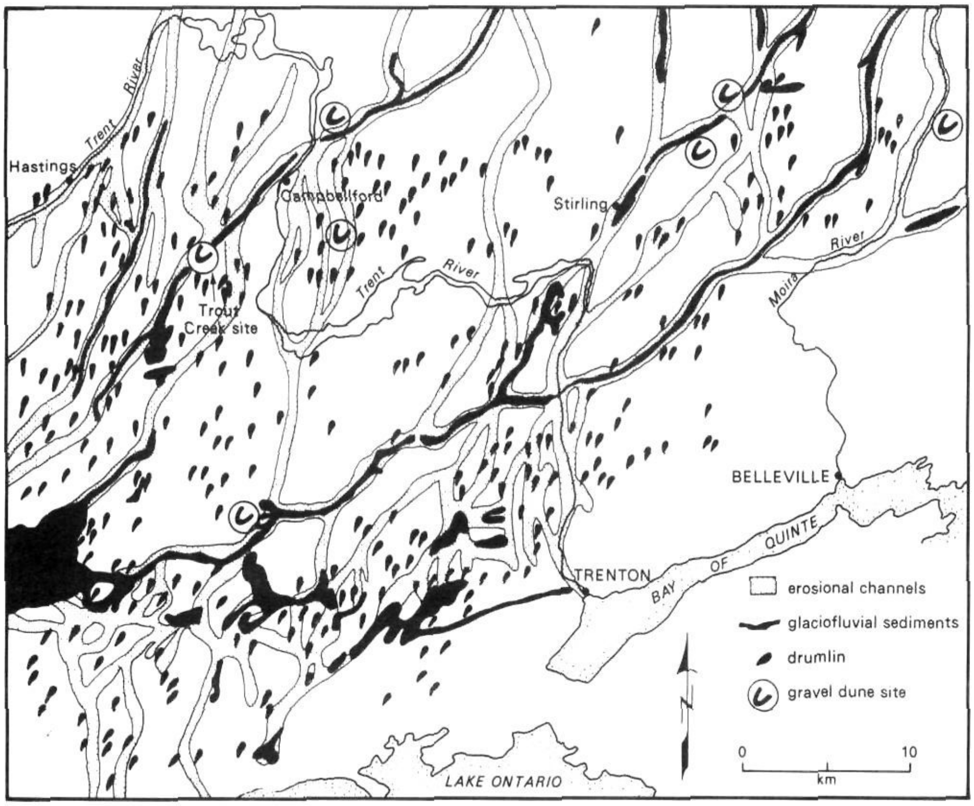


FIGURE 2. Drumlins, tunnel channels (erosional channels), glaciofluvial deposits and gravel dunes sites in the Trenton-Campbellford area.

Les drumlins, les conduits (chenaux d'érosion), les dépôts fluvioglaciaires et les sites de dunes graveleuses de la région de Trenton-Campbellford.

FIGURE 3. Gravel dune at Trout Creek. The dune is approximately 10 m high (flow from left to right).

Dune graveleuse au Trout Creek. La dune mesure à peu près 10 m de haut (le courant passait de gauche à droite).

system that could not have evolved subaerially given the regional slope.

GRAVEL DUNES: INTERNAL STRUCTURE AND GRAIN SIZE

Stratification

The gravel dunes contain mainly large-scale cross-stratified beds, which resemble Gilbert-delta foresets, cross-cut by topset beds (Fig. 5). But, on closer inspection, the foresets show considerable variation in angle and direction of dip with numerous unconformities, the e_1 surfaces of Figure 6. Overlying beds may be steeper or gentler than those below these unconformities. This bedding geometry and the related unconformities are similar to those associated with reactivation surfaces in eolian dunes (McKee, 1966; Bigarella *et al.*, 1969; Thompson, 1969; Vacher, 1973; Brookfield, 1984) and fluvial deposits (Collinson, 1970). Similar relationships between bedding and reactivation surfaces occur in marine sandwaves (Allen, 1980; Kohsiek and Terwindt, 1981; Dalrymple, 1984; Walker, 1984).

Where beds underlying an unconformity are truncated and overlain by angle of rest foreset beds, an erosional phase intervened between depositional events (Fig. 6a). In one case, a gravel foreset unit rests unconformably on a sand bed which, in turn, rests conformably on underlying gravel foresets (Fig. 6b). Here, the sand deposited on a foreset gravel slope represents a temporary reduction in flow strength followed by the deposition of foresets with a different strike. The sand rep-

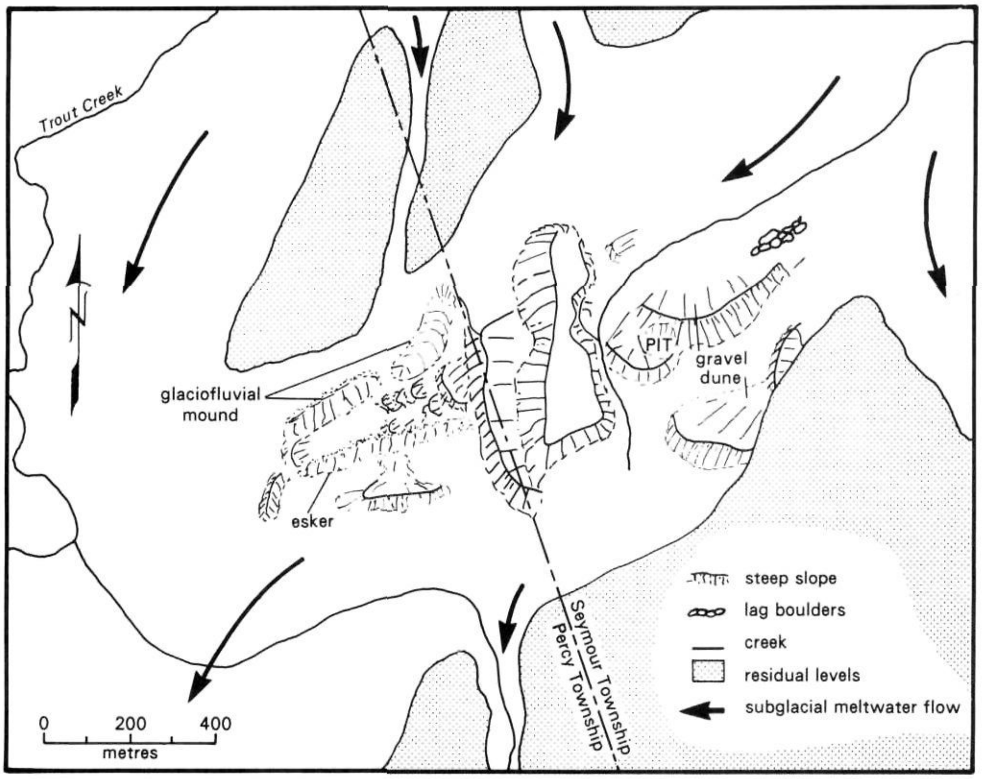


FIGURE 4. Gravel dunes and associated glaciofluvial landforms and sediment, Trout Creek. The pit (also shown in Fig. 3) is the site of most of the sedimentological observation reported in this paper.

Les dunes graveleuses ainsi que les formes fluvio-glaciaires et les sédiments qui leur sont associés, à Trout Creek. La plupart des observations d'ordre sédimentologique ont été faites à la gravière, aussi illustrée à la figure 3.

FIGURE 5. Large-scale cross bedding in a gravel dune, Trout Creek. Height of face about 8 m.

Stratification entrecroisée à grande échelle dans une dune graveleuse, à Trout Creek. Le front mesure à peu près 8 m de hauteur.

resents a pause plane (Terwindt and Kohsiek, 1981) and the change in strike of the foresets is best explained in terms of the migration of a dune with a complex and changing crestline.

Such complex superimposition is even more strikingly displayed in Figure 6c which illustrates three unconformably superimposed sets of cross-bedded gravel and a coset of trough cross-stratified pebbly sand which marks the migration of superimposed sand bedforms down the lee face of the gravel dune. This interpretation of superimposed bedforms follows Allen (1982, fig. 11-27b) and Rubin (1987, fig. 25).

The complex relationships amongst sediment packages contained between e_1 surfaces (Fig. 6a,b,c) represents the migration of bedforms with superimposition of foreset beds (e_2) caused by the variation in crest orientation (Rubin, 1987). Erosional e_1 surfaces may represent scouring in advance of avalanche faces of superimposed bedforms (Dalrymple, 1984), but later discussion in this paper on details of the grain-sizes of the large-scale foresets does not support this explanation.

Grain size

The gravel in exposed cross-beds at Trout Creek shows remarkable grain-size characteristics with, in places, opposite trends for the large clasts and matrix. Beds about 1 m thick may be strongly graded or have no detectable grading (Fig. 7).

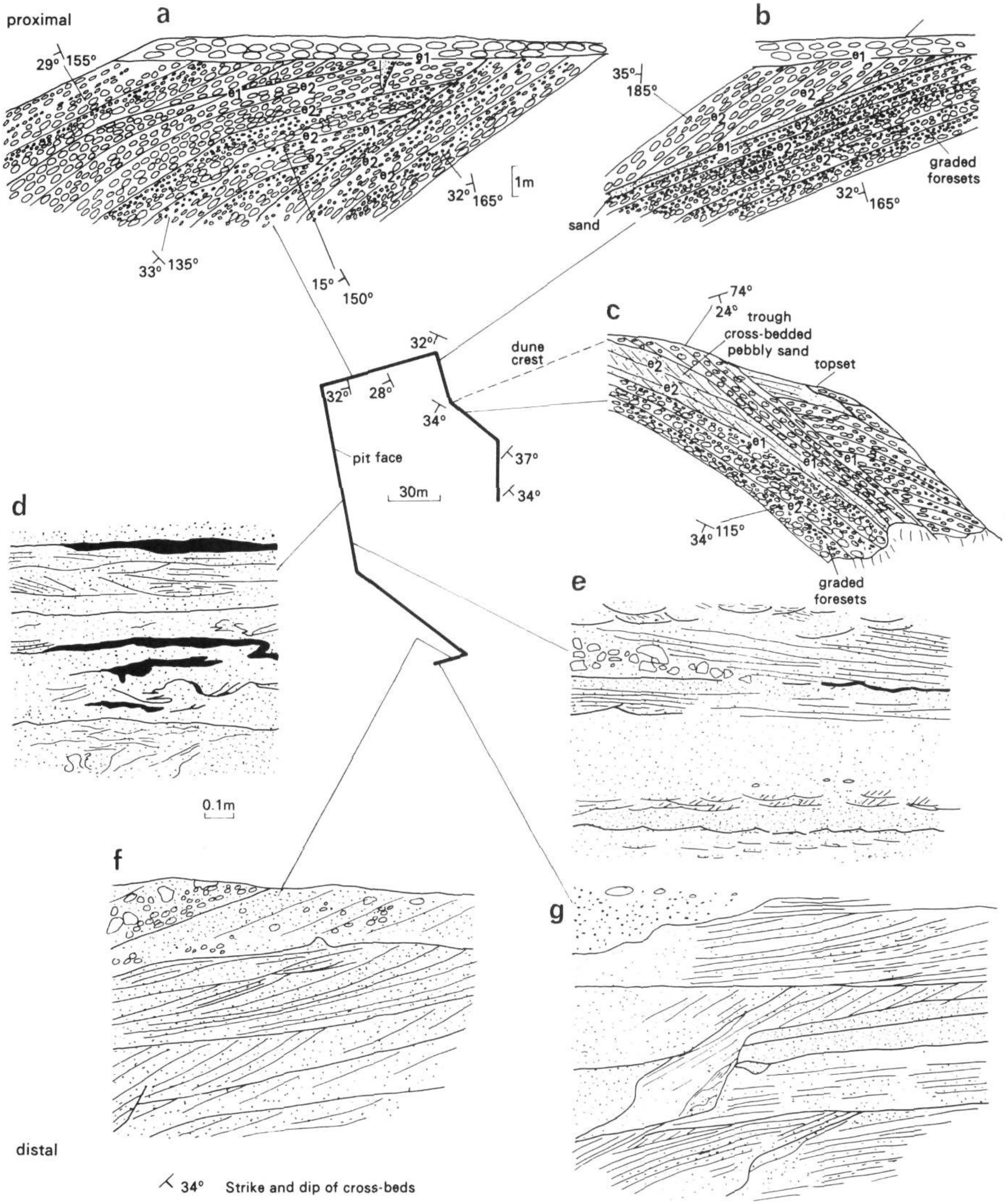


FIGURE 6. Internal structure of a gravel dune and associated pro-dune deposits at Trout Creek. Note the change in scale between the proximal cross-beds in gravel and the sandy or silty (solid black) distal deposits. The e_1 surfaces are major unconformities, the e_2 surfaces are major bedding planes or set boundaries.

Structure interne d'une dune graveleuse et dépôts produnaires associés, à Trout Creek. Noter le changement d'échelle entre les couches obliques proximales dans le gravier et celles des dépôts sableux ou silteux (en noir) distaux. Les surfaces e_1 sont les principales surfaces de discordance et les surfaces e_2 sont les principaux plans de stratification.

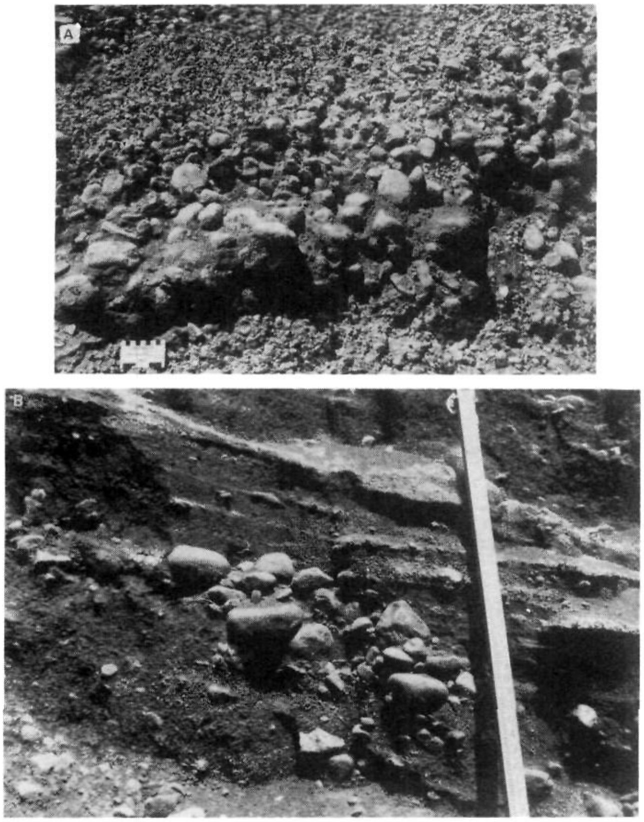


FIGURE 7. A) Graded gravel with matrix-rich cobble gravel (above the scale) fining upwards to openwork fine gravel. Scale in centimetres and inches. B) Sandy gravel with clustered cobbles and pebbles; granule-rich zones are prominent. Scale in feet (31 cm) and tenths of feet.

A) Unité de gravier granoclassé avec à la base de gros cailloux et des galets contenus dans une matrice (au-dessus de l'échelle) passant à un fin gravier à cailloux jointifs. Échelle en centimètres et en pouces. B) Gravier sablonneux parsemé de petits amas de gros cailloux et de galets; les parties renfermant de nombreux gravillons sont en saillie. Échelle en pieds (31 cm).

GRADED, BIMODAL GRAVEL

Observation

Graded bimodal gravel is a most unusual deposit because fine matrix and coarse clasts occur with virtually no intervening sizes. The bimodality is much more marked than that reported in fluvial gravel (Shaw and Kellerhals, 1982). These graded units are also unusual in that, whereas the large clasts show normal grading, the matrix shows inverse grading. Consequently, the coarsest gravel has the finest matrix. It also has the highest proportion of matrix such that many clasts are matrix supported (Fig. 9).

In parts of the matrix-supported beds, the matrix itself is laminated with graded laminae about 2 to 3 mm thick (Fig. 9 just above the scale). These matrix laminae are usually convoluted. In some cases, the upper, finer parts of the metre or so thick graded gravel beds contain so little matrix as to be open work (Figs. 6 and 7A).

Matrix-supported, extremely bimodal gravel (Figs. 8 and 9) has been reported from other glaciofluvial deposits. Sandgren (1983, p. 44), writing on ice-contact deposits, described large-scale foreset beds composed of pebbles and boulders in a silty fine sandy matrix. Although not reported in this thesis, he also observed similar deposits with supercritical ripple cross-lamination of high angle of climb, indicating the relative importance of deposition from suspension for the matrix material (Sandgren, 1978, personal communication). Robison (1983, fig. 91) illustrated a cobble bed supported by a sand matrix in "subaqueous esker" deposits. Lindstrom (1985, p. 27, figs. 5 and 6), in a study of esker sediment, described and illustrated matrix supported, bimodal gravel composed of cobbles with a sand matrix showing convoluted, graded laminae. He interpreted these as products of sliding-bed transport in full-pipe flow (Saunderson, 1977). Further examples of matrix supported cobble gravels are noted in the deposits of the so-called Harricana interlobate moraine, Québec (Veillette, 1986) and glaciofluvial deposits near Exshaw, Alberta (Proudfoot *et al.*, 1982) in which the matrix is coarse sand and medium sand respectively. In both cases, the matrix supported gravel passes upwards to gravel with smaller clasts and coarser matrix; the grading of the clasts and matrix again being opposite.

It is usually, but not always, the case to find such bimodal matrix supported gravel on foreset slopes. At Trout Creek, the matrix supported beds normally thicken toward the foreset base.

Interpretation

The sequence of matrix-rich, highly bimodal gravels grading upward to openwork gravel is intriguing, since there does not seem to be analogous sediment in non-glacial fluvial deposits. We are left to believe that the intensity of subglacial fluvial processes is such that a novel explanation is required.

As Lindstrom (1985) indicated, the two modes were clearly deposited simultaneously; the laminae in the matrix-supported clasts discount matrix emplacement by void filling subsequent to the deposition of the framework clasts. However, Lindstrom's appeal to sliding-bed deposition cannot, by itself, explain the sorting of the clasts and matrix and is, indeed, refuted by the matrix lamination. Some other explanation is required for the sorting and the cross-lamination.

The association of the matrix-rich, bimodal gravel with angular foresets attests to the importance of bedload transport for the coarse component of the bed (Jopling, 1965a). It would be simple, then, to suggest that the matrix was deposited from suspension on a foreset avalanche face. However, the awkward question remains: What processes produced the various styles of grading in the matrix and the clasts.

There are plausible but necessarily speculative answers to this question. The steep foresets imply flow separation and a separation eddy, with return flow at the bed to the lee of the dune (Fig. 12). The grading implies pulses of sediment transport and deposition. It is tempting to imagine each sediment pulse resulting from a flow event of decreasing power with time. At the beginning of a pulse suspended sediment concentrations are high; sediment availability is not a limiting factor in the subglacial environment. At this time, most of the suspended sed-

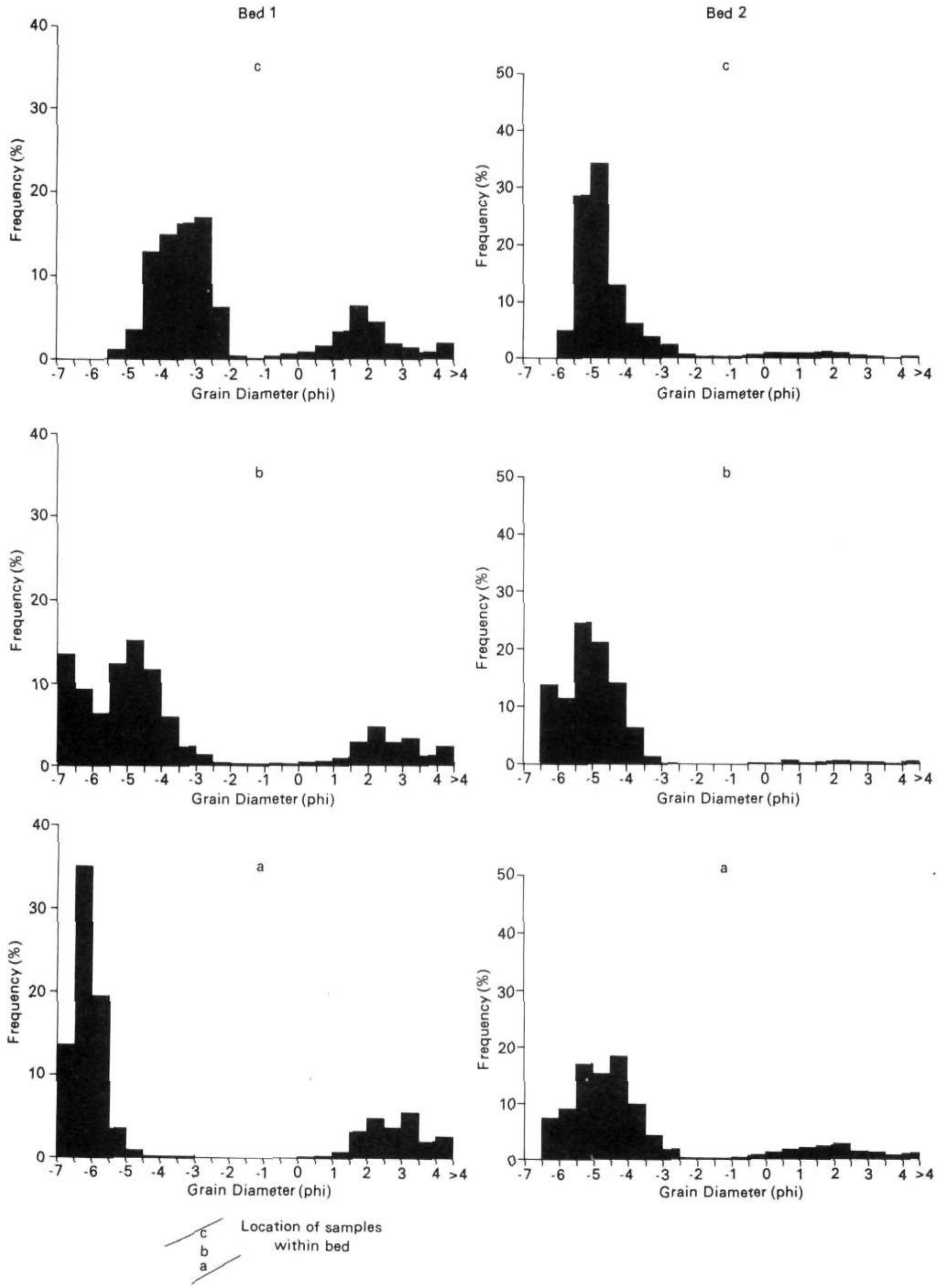


FIGURE 8. Grain size histograms for foreset beds within a gravel dune. Beds a,b,c show an upward fining in the coarse mode and an upward decrease in matrix size (bed 1) or decrease in matrix volume (bed 2).

Histogramme granulométrique des lits frontaux à l'intérieur d'une dune graveleuse. Les lits a, b et c montrent verticalement un affinement dans la partie grossière et soit une diminution de la taille des particules de la matrice (lit 1), soit une diminution du volume matriciel (lit 2).

iment by-passes the dune and only the finest material makes its way back in the return flow to the foreset slope, where it is deposited from suspension in graded beds or by a combination of suspension and bedload deposition to form regressive cross-laminae. In essence, the fine sediment is deposited as toeset beds decreasing in thickness up the foreset (Jopling, 1965a).

Unfortunately, this does not explain the sorting of the coarse clasts. It is most unlikely that all sizes smaller than cobbles were able to by-pass the dune as suspended sediment. If the smaller sizes, which form a size continuum with cobbles, had been transported in suspension they would be expected on the foresets given their probable trajectories (Jopling, 1965b). Thus, at certain times when the matrix-rich beds were accumulating, the coarsest clasts were being delivered preferentially to the dune brink. Explaining this preferential delivery is the crux of the problem of the bimodal gravel.

The notion of a sediment pulse may be helpful here and also explains the normal grading of the coarse clasts in some foreset beds. Experiments show that, for mixed bedload with shear velocities well above critical values for all sizes in the mixture, large clasts have higher velocities than small ones (Meland and Norrman, 1969; Shaw, 1969). This provides a powerful sorting mechanism in pulsating flow with localised scour such as would be expected in the vicinity of flow reattachment zones downstream of the gravel dunes (Meland and Norrman, 1969). This situation corresponds to experimental tracer models using a

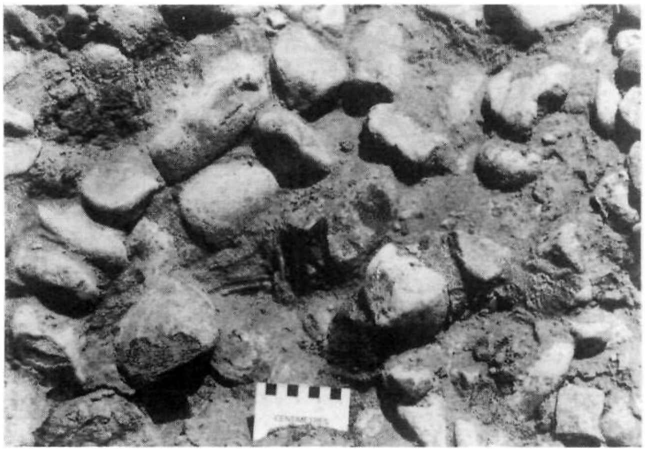


FIGURE 9. Matrix-rich cobble gravel; note graded bedding in the matrix above the scale (in cm).

Gravier avec matrice riche en gros cailloux; noter les lits granoclassés dans la matrice au-dessus de l'échelle (en cm).

single input method (Crickmore, 1967; Shaw, 1969), as opposed to the continuous input method (Meland and Norrman, 1969). The single input method gives higher absolute velocities and greater relative velocities between large and small particles. The relationship between grain size, d mm, and transport velocity, v m/s, for a given shear velocity, v_* m/s, is of the form (Meland and Norrman, 1969 fig. 9):

$$v = a\ d^n \qquad (1)$$

where a and n are constants equal, for example, to 0.05 and 2.48 respectively for $v_* = 0.07$ m/s.

Consider particles of two sizes, d_1 and d_2, with transport velocities, v_1 and v_2, eroded rapidly by a spatially restricted scour located at a distance, x m, from the crest of the next dune downstream. Let the duration of the scouring process competent to erode the larger size be T s. Particles of diameter d_1 will first arrive at the dune crest after a time $t_1 = x/v_1$ and will continue to do so for a further period, T. Particles of diameter d_2 will first arrive after a time $t_2 = x/v_2$ and, provided that $t_2 - t_1 < T$, there will be perfect sorting of the two sizes. With a broad range of sizes, the coarsest sizes will arrive first, followed by bedload of decreasing size (Equation 1). Thus, a longitudinal sorting of bedload results.

The longitudinal sorting inferred above has been recently described for fluvial transport of poorly sorted gravel (Iseya and Ikeda, 1987; Whiting *et al.*, 1988). This occurs under constant flow discharge, but involves dramatic variation in bedload discharge. Gravel travels as sheets with a distinctive longitudinal sorting related to the different travel velocities discussed above. The coarsest clasts form an openwork leading zone which serves as a trap for coarse particles; finer particles fail to pass beyond the upstream limits of this coarse screen (Fig. 10; Iseya and Ikeda, 1987). Thus coarse sediment, cobbles in the Trout Creek case, arrives before fines and, with the addition of sediment transported over the dune crest in suspension and to the dune foreset by the return bottom current, forms the matrix-rich, bimodal unit at the base of each graded unit. The high proportion of matrix results from the low bedload transport rates associated with the leading coarse zones of the longitudinally sorted sheets (Fig. 10a; Iseya and Ikeda, 1987; Whiting *et al.*, 1988).

Grading results from the passage of succeedingly finer sediment of the sorted sheet over the dune crest. This sediment is associated with maximum bedload transport rates (Fig. 10; Iseya and Ikeda, 1987) which may account for the openwork gravel above matrix-rich cobble gravel; the bedload supply is much greater than deposition from the backflow at this stage (Fig. 10b).

Finally, sand-rich sediment but with occasional cobbles and very poor sorting represents the trailing, poorly sorted part of the bedload sheet with relatively low sediment transport rates and perhaps some erosion of the underlying stoss slope of the dune (Fig. 10c).

The combination of short-lived scour at a point, waning flow, and separated flow downstream from a dune crest provide a plausible explanation for the grain-size characteristics of the graded foreset beds. The bedload sorting mechanism explains the grading of the coarse clasts. Deposition, when flow was strongest, of suspended load from the return flow of the separation eddy accounts for the fine matrix (Fig. 9). Subsequent deposition of fines directly from the mixing zone of the separated flows, together with deposition from the return eddy, explains the coarsening of the coarse tail of the matrix (Fig. 8). The coarsening of the matrix is thus explained as resulting from an increasing relative contribution of sediment from suspension in the mixing layer with declining flow.

This poses the question of why there is little or no direct suspension deposition from the mixing layer at the highest flow. The answer probably relates to the deficiency of grain sizes around –1 ∅ in all samples (Fig. 8). This deficiency has been explained in a number of ways, but Shaw and Kellerhals (1982) argued that, during bedload transport of gravel, crushing of the smallest bedload particles causes a deficiency around 2 mm in grain-size distributions. Such a deficiency is noted in the grain-size histograms for the foreset gravel (Fig. 8). Consequently, at the highest rates of gravel transport, the direct suspension deposits expected on the foresets were of the smallest size transported as bedload at slightly lower flows. Perhaps because of the deficiency, these simply did not exist in appreciable quantities and, in the virtual absence of direct deposition of suspension load from the mixing layer, highly bimodal sediment resulted from a combination of coarse bedload and fine return-current suspension load deposition.

MULTIMODAL GRAVEL

Observation

Multimodal gravel also accumulated as dune foreset beds and are found, as well, in sets of trough cross-bedded gravel and pebbly sand (Fig. 7). These beds are not graded and show only poorly defined cross-stratification, although there is commonly some clustering of the largest clasts (Fig. 7).

Interpretation

The multimodal gravels are interpreted to represent the continuous deposition of bedload and suspended load on the

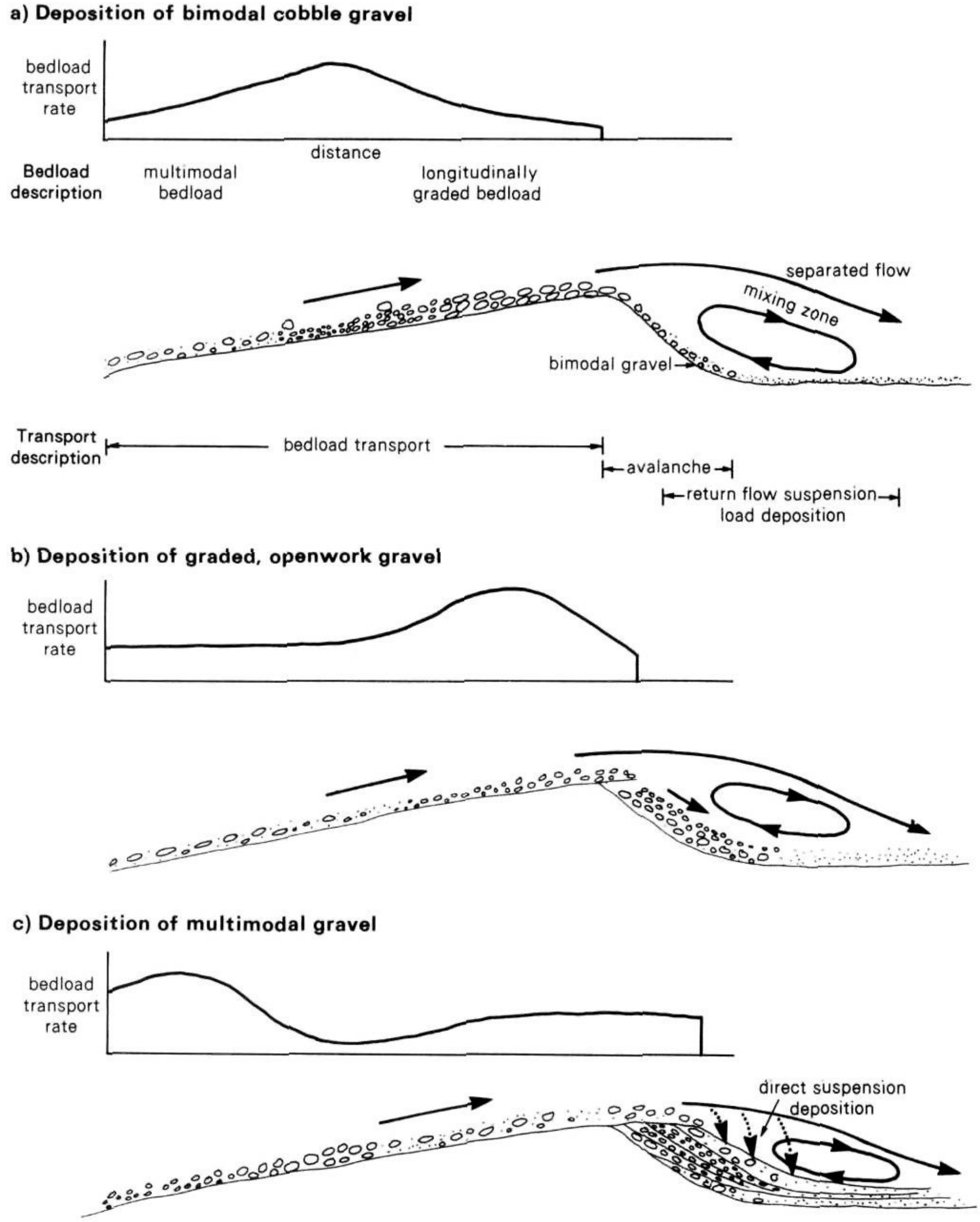


FIGURE 10. Foreset deposition related to longitudinal sorting and bedload transport rates (Iseya and Ikeda, 1987) and suspended sediment deposition from two sources. Note that, at the time of bimodal gravel deposition, suspended sediment is derived mainly from the return flow; direct deposition from the mixing layer is of increased importance during deposition of the bimodal gravel.

Dépôt des lits frontaux relié au tri longitudinal et aux taux de transport de la charge de fond (Iseya et Ikeda, 1987) ainsi qu'au dépôt des particules en suspension à partir de deux sources. À noter qu'au moment du dépôt du gravier bimodal, les particules en suspension proviennent en grande partie de la zone de séparation; le dépôt direct à partir de la zone de mélange est plus important pendant la mise en place du gravier bimodal.

foreset beds (Fig. 10c) with a continuum of sizes such that the commonly applied terms matrix-supported and clast-supported gravel are meaningless (Christian, 1988); the distinction between clast and matrix, which was so clear for the bimodal gravels, is totally arbitrary for these multimodal beds. In many ways, they resemble the disorganised gravel of Walker (1975).

Clustering of the largest clasts may represent a kind of jamming process whereby one large clast comes to rest and causes others to pile up behind it. However, the delivery of a number of large clasts to the foreset at about the same time speaks for some longitudinal sorting in the feeding bedload. Perhaps this represents an incipient stage in the more pronounced longitudinal sorting reported by Iseya and Ikeda (1987).

Fabric

Observation

Clasts with a distinct long axis are usually arranged with this axis aligned downslope and slightly imbricate with respect to the foreset beds. While major planes of clasts and their long axes dip and plunge, respectively, at a wide range of angles to the bedding in the matrix supported beds.

At a second gravel dune site south-east of Campbellford (Fig. 11), clast long axes and major planes in angle of repose foresets are inclined at approximately 90° to the bedding and, thus, plunged or dipped steeply into the foreset slope (Fig. 12). A similar arrangement of clasts is seen on backset beds in the Harricana Moraine, at Val d'Or, Québec (Veillette, 1986).

Interpretation

The fabric mode in the matrix-supported beds with clast long-axes parallel to the slope and imbricate corresponds to the arrangement of clasts deposited after sliding down foreset slopes (Johansson, 1976). It is assumed that the clasts were carried by bedload to the foreset brink.

The rather disorganised fabric of clasts in matrix-supported beds is thought to result from their foundering in underconsolidated suspension deposits. The presence of convoluted laminae in the associated matrix supports this interpretation.

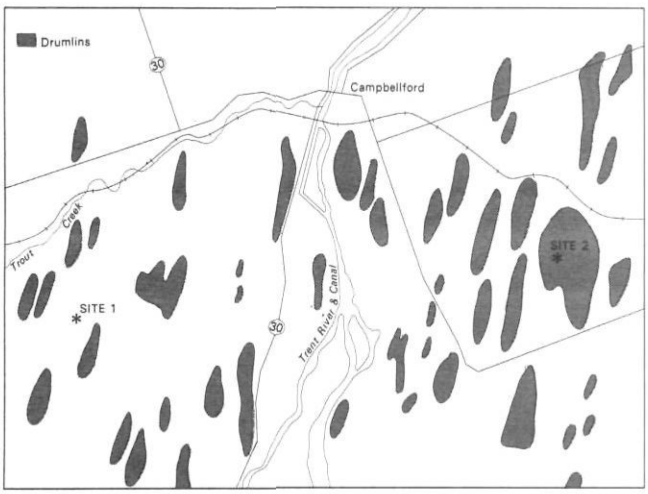
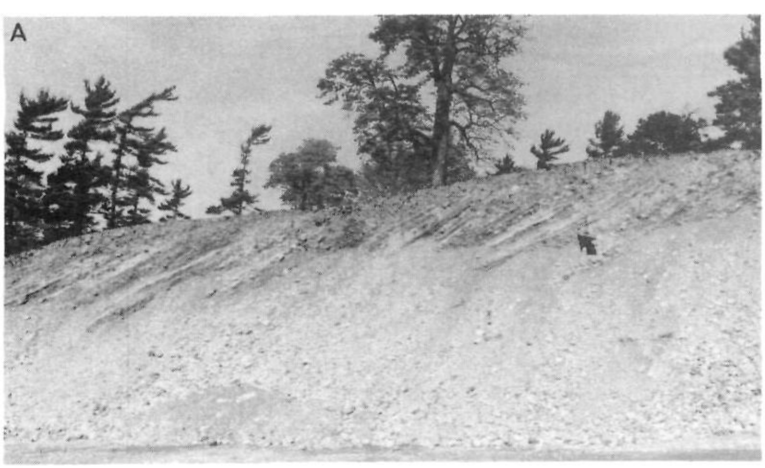


FIGURE 11. Location of site 2 related to site 1 at Trout Creek.
Localisation du site n° 2 par rapport à celle du site n° 1.

The peculiar clast fabric, with clast long axes and major planes at right angles to the bedding, occurs in multimodal beds (Fig. 12). Johansson (1976) observed a similar arrangement of clasts on experimental backset beds produced in a flume in zones of rapid flow expansion. In these experiments, the particles were held in a position in which the moment on the particle generated by the shear stress acting up slope just balanced the countervailing moment on the same particle generated by gravity. The particles could be seen to oscillate as the shear stress varied. A backset origin for the dune gravels is clearly unlikely, but the same effect could be generated by flow separation producing reverse currents on the foreset slope. It is notable that the fine sizes in the bed with high angle of plunge clasts are much coarser than those in the bimodal gravels. This suggests direct deposition of the coarse suspension load in trajectories like those described by Jopling (1965b) for the multimodal gravel. On the other hand, the bimodal gravel matrix is inferred to be a suspension deposit, mainly from the return current of the separation eddy.

LEE DEPOSITS

Relatively fine-grained deposits are found to the lee of the gravel dunes and these are well exposed in the pit at the Trout Creek site (Fig. 6d, e, f, and g.). Sand predominates with minor amounts of gravel and silt. Distinct styles of bedding are found at different positions with respect to the gravel foresets. Closest to the foresets are relatively fine deposits with numerous silt bands and mainly massive or graded sand (Figs. 6d and e, and 13a). Paleocurrent directions determined from cross-lamination and ripple formsets indicate deposition under bidirectional currents, normal and regressive. Convolute bedding and dewat-



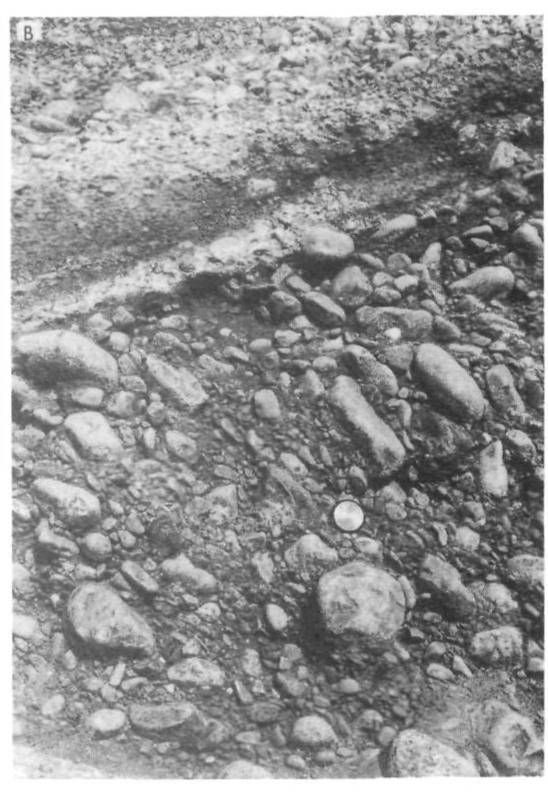


FIGURE 12. A) Gravel dune foreset beds at site 2 (Fig. 11); the arrow marks the position of the bed shown in B. B) Gravel foreset bed with clast long axes and major planes at a high angle to the foreset dip.

A) Lits dunaires frontaux au site n° 2 (fig. 11); la flèche montre l'emplacement du lit illustré en B. B) Lit frontal graveleux dont le grand axe des cailloux et les principales surfaces planes sont obliques au pendage.

ering pipes are common at the most proximal site (Fig. 6d). These are less common immediately downflow where diffusely graded to massive medium sand alternates with thin cross-laminated cosets of fine to medium sand near the base of the section, coarsening upwards to trough cross-stratification and low-angle plane beds in pebbly sand (Fig. 6e). There are also minor amounts of fine gravel.

These lee deposits indicate high rates of deposition from suspension with only minor bedload transport of the sediment closest to the foresets. Suspension deposition is indicated by the graded beds, convolutions and dewatering structures. Bidirectional flow is expected in an attachment zone downflow from separation at the bedform crest, fluctuations in flow strength cause the attachment zone to shift, producing local reversals of flow direction. Thus the fine-grained deposits are as expected for deposition mainly from suspension to the lee of a bed form.

There is a marked coarsening and increase in flow regime for deposits a few tens of metres downflow from those just described (Fig. 6f and g). Medium to coarse sand and pebbly sand predominate. Bedding is mainly trough cross-stratification with tangential foresets, graded beds, and upper flow regime plane beds (Fig. 13b). Scours are common and appear to have given rise to local bed failure which produced slump blocks (Fig. 13c). The flows were unidirectional to the south west, similar to the flow directions indicated by the dips of the gravel foresets. Tabular cross-stratification in gravel (Fig. 6f) also indicates a southwesterly flow direction.

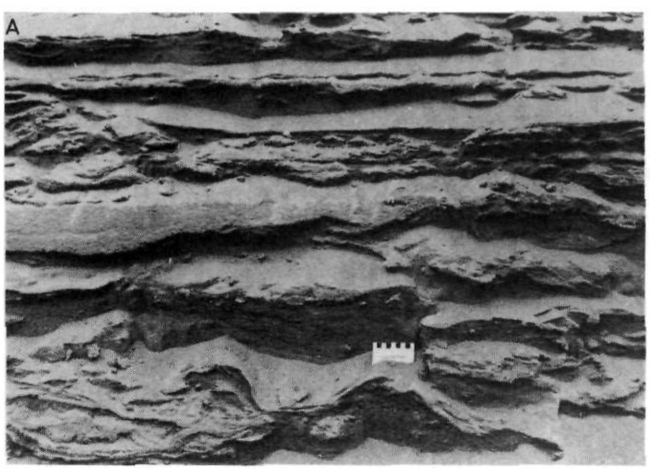
The characteristics of the more distal lee deposits correspond to those expected for deposition downstream from flow reattachment. The unidirectional currents, coarse grain-size compared to deposits from beneath the separation eddy, scouring and large-scale bedforms support this interpretation.

DISCUSSION AND CONCLUSIONS

The form, internal structure and textural characteristics of the gravel dunes are inferred to represent the migration of a large-scale bed form under extremely powerful flows. The setting of the dunes in a tunnel valley and their association with eskers point to a subglacial origin. The only reasonable alternative, given that the dunes lie below the level of Glacial Lake Iroquois, which occupied the area upon ice retreat, is that the landforms are elements of sub-aqueous fans or are small ice-marginal Gilbert-deltas.

However, such fans are common in the area and their sedimentary characteristics are similar to subaqueous fans described from elsewhere (Rust and Romanelli, 1975; Shaw, 1975; Rust, 1977; Shaw, 1985; Henderson, 1988; Burbidge and Rust, 1989; Rust, 1989). The sediment of such fans is very different in texture, structure and architecture from those described here for the gravel bedforms. Furthermore, the train of the gravel forms is unlike the reported distribution of fans, but is as expected for bedforms.

The gravel forms are more like Gilbert-deltas than fans, but the evidence for flow reattachment and the absence of fine-



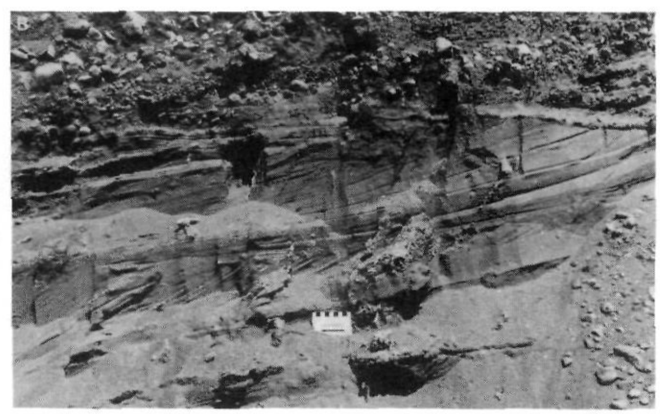


FIGURE 13. A) Lee-side sand and silt with pebbles (location d, Fig. 6). Silt layers are cohesive and stand out, whereas sand beds have been winnowed. B) Trough cross-bedded sand overlain by tabular cross-bedding in gravel (location f, Fig. 6). C) Graded and cross-bedded sand with syndepositional slump failure (location g, Fig. 6). Arrow marks failure plane. Plane beds (P).

A) Sable et silt parsemés de galets du côté abrité (site d de la fig. 6). Les couches de silt sont cohésives et saillantes, tandis que les lits de sable ont été triés. B) Couche de sable à stratification oblique en auge sous-jacente à une unité à stratification entrecroisée tabulaire (site f de la fig. 6). C) Couches de sables granoclassées et entrecroisées, qui renferme une surface de glissement (flèche) contemporaine de la mise en place (site g de la fig. 6). P = lit horizontal.

grained lacustrine sediment distal to the large-scale cross beds speak against a delta interpretation. As well, the up-flow dip of the topset beds and the reverse surface slope of the landform contradict a delta interpretation.

The gravel dunes at Trout Creek thus support the suggestion, based on observations of eroded drumlin flanks, that broad tunnel channels carried large volumes of subglacial meltwater. Similar tunnel channels are reported from other drumlinised areas and this association is taken to support the hypothesis that the drumlins themselves were formed by meltwater (Shaw, 1983; Shaw and Kvill, 1984; Sharpe, 1987; Shaw and Sharpe, 1987). Of course, this evidence is purely circumstantial and cannot be taken as positive proof of a meltwater origin for drumlins; it merely highlights the importance of large, and probably short-lived drainage events for features associated with drumlins.

Besides their associations, the form and bedding pattern of the gravel dunes are interesting in their own right. They imply flows with depths of several tens of metres and flow velocities of several metres per second. Each channel probably carried discharges on the order of 10^5 m^3/s, and, given the anastomosing nature of the channels (Fig. 2), the total discharge of the system probably reached 10^6 m^3/s or more.

The local variation in dip of the dune cross-strata indicates a complex, lobate crest line and breaks in deposition are marked by fine sediment and pause planes. Some unconformable surfaces within the foresets indicate erosional events.

Foreset beds show systematic sorting with bimodal matrix-rich cobble gravel grading gradually into openwork gravel which fines to granules. Other beds are polymodal, containing the full range of sizes noted in the dunes. These bedding types and sorting patterns are related to relative transport velocities with respect to clast size. This is thought to have given rise to longitudinal sorting patterns on the stoss transporting surface and distinctive cross-strata were deposited on the lee side of dunes. Powerful reverse eddies to the lee of the dunes are thought to have rotated clasts to steep dips relative to the cross-strata.

Suspension load was transported to the lee of the dune and deposited either from suspension in graded beds with numerous dewatering and consolidation structures, or transported partially as bedload in normal and regressive ripples. Down flow from the reattachment, unidirectional currents produced dunes giving rise to cross-stratified sands and pebbly sands, and upper-flow-regime plane beds which produced low-angled lamination.

Large-scale cross-bedding in gravel is generally considered to represent Gilbert-delta foresets, however, the gravel in the "giant ripples" of the Channeled Scabland are also cross-stratified (Baker, 1978). Thus, cross-stratification alone is not diagnostic of Gilbert-deltas since similar cross-stratification is also produced in gravel dunes. Clearly, then, only detailed examination of the associated sediment and landform allows differentiation of two very different sedimentary environments. For example, large-scale cross beds observed in eskers and interpreted as deltaic, may actually represent bedforms in a purely fluvial environment (Shaw, 1972; Banerjee and McDonald, 1975; Saunderson, 1975).

Whereas deltaic cross-bedding is expected to grade distally into fine-grained lake-bed sediment, fluvial cross-beds climb over preceding high-flow-power fluvial sediment. This criterion, together with the form and pattern of the Trout Creek landforms, strongly supports their interpretation as fluvial dunes. Their relationship to tunnel channels and eskers and the fact that they predate Glacial Lake Iroquois support a subglacial origin for the dunes.

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