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Mass flow deposits in a Quaternary succession near Ottawa, Canada: diagnostic criteria for subaqueous outwash

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Stratigraphic relationships indicate that late Quaternary outwash near Ottawa, Canada, was deposited close to the ice front and below wave base in the Champlain Sea and/or an earlier ice-dammed lake. Distinct sand and coarse gravel facies are present, the latter with clast long axes parallel to flow, indicating deposition from a high energy current with high clast concentration.

The sand facies contain channels up to 10 m deep and 40 m wide, filled with essentially massive sand. In some cases the base and basal fill are contorted into ball-and-pillow structures, and the channels contain dish structures and scattered pebbles. Similar features occur in the channeled sands of deep sea submarine fan valleys, and are thought to indicate rapid deposition by a mass flow mechanism, with high sediment concentration and low turbulence. In the present case, deformation at the channel bases probably resulted from liquefaction due to rapid sediment loading; dewatering gave rise to dish structures at higher levels. Possible mechanisms for initiating mass flows include shock waves generated by iceberg calving, and the effects of rapid changes in water level and salinity as the Champlain Sea invaded the area.

Les observations stratigraphiques indiquent que le fluvio-glaciaire de la fin du Quaternaire, près d'Ottawa, s'est déposé près du front glaciaire et au-dessous de la limite d'action des vagues dans la mer Champlain ou encore dans un lac de barrage glaciaire plus ancien. On reconnait des faciès distincts de sable et de gravier grossier, ce dernier présentant les axes longs de ses galets parallèles à l'écoulement, indiquant par là un dépôt provenant d'un courant à haute énergie avec concentrations élevées en galets.

Les faciès sableux contiennent des chenaux d'une profondeur atteignant 10 m et d'une largeur de 40 m remplis surtout de sable massif. Dans certains cas, la base et le remplissage à la base sont déformés et on observe des structures en boules et oreillers, alors que les chenaux contiennent des structures en assiettes et des cailloux dispersés. Des observations semblables se font dans les sables des chenaux dans les vallées en éventail des fonds marins profonds, et elles semblent indiquer un dépôt rapide à la suite d'un mouvement de masse avec haute teneur en sédiments et faible turbulence. Dans le cas présent, la déformation à la base des chenaux résulte probablement de la liquéfaction causée par l'accumulation rapide des sédiments; l'expulsion de l'eau est responsable des structures en assiettes aux niveaux plus élevés. Parmi les mécanismes probables à l'origine des mouvements de masse, on peut citer les vagues de choc engendrées par l'affaissement d'un iceberg, et les effets des changements rapides des niveaux d'eau et de la salinité lors de l'invasion de cette région par la mer Champlain.

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Introduction and Stratigraphic Setting

The Quaternary deposits of the area around Ottawa, Canada (Fig. 1) were described and mapped by Johnston (1917) and Gadd (1962). These authors recognized a number of map units, which can be grouped into four stratigraphic units as follows:

4. Post-marine deposits.
3. Stratified sediments with marine fossils (Champlain Sea sediments).
2. Nonfossiliferous stratified deposits.
1. Till.

Radiocarbon dating of the marine fossils yields ages varying from about 12 000 to 9500 yr BP. There are no datable materials in units 1 and 2, but Gadd (1962, p. 1) concluded that they were "... mainly contemporaneous with the last glaciation", and mapped the till and overlying materials as Wisconsin and younger. On this basis the units above the till were formed during the retreat of the Wisconsin ice sheet, except for a short-lived readvance about 11 200 yr BP (Richard 1975).

Unit 3 accumulated during the Champlain Sea episode (Elson 1968), and comprises thin wave-worked gravels formed on pre-existing highs, thicker sand deposits in adjacent deeper water, and thick marine clays in the deepest parts of the sea. Isostatic uplift eventually brought about a change to non-marine conditions, in which the

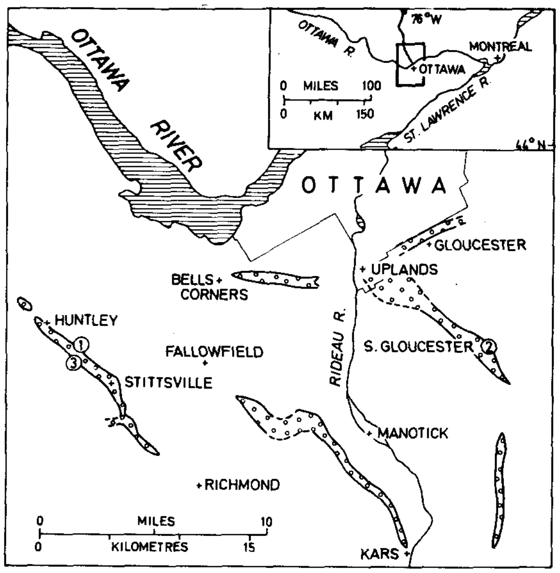

FIG. 1. Location map. Circle ornament indicates ridge features in which subaqueous outwash is present south of the Ottawa River. Circled numbers refer to localities described in the text: (1) Spratt's Pit, Huntley; (2) Spratt's Pits, South Gloucester; (3) Rump's and Bradley's Pits.

fluvial, lacustrine, and bog deposits of unit 4 were formed (Gadd 1962).

The origin of unit 2 is less clear. It is well exposed in pits along northwest-trending ridges south of Ottawa (Fig. 1), where it comprises non-fossiliferous stratified sand and gravel, overlain unconformably by a thin fossiliferous gravel of unit 3 (Rust and Romanelli 1975, Fig. 3). Johnston (1917, p. 15 and Pl. IV) described a similar succession in a pit near Uplands; he noted the lack of fossils in the stratified deposits, and interpreted them as glaciofluvial. Gadd (1962) included the same material in his map-unit 2, together with minor marine deposits, which in this paper are regarded as part of unit 3, because wherever observed they were separated from unit 2 by an unconformity.

Rust and Romanelli (1975) compared rates of post-glacial uplift for the Ottawa area with Shepard's (1963) curve of eustatic rise in sea level. They concluded that relative sea level fell throughout the Champlain Sea episode, and that the post-glacial succession reflects continuous marine offlap. The sands and gravels of unit 2 were therefore deposited in standing water in the Champlain Sea and/or a preceding ice-dammed lake. The unconformity between units 2 and 3 represents a period during which sea level fell until the ridge summits were reworked by waves, and unit 3 was formed as a lag gravel. It is therefore concluded that unit 2 was deposited below wave base. It occurs as distinct sand and gravel facies, and has many features typical of outwash: good sorting, stratification, and rounding of the larger clasts. However, formation below wave base is unusual for outwash deposits, as is the presence of large channels filled with massive sand. Rust and Romanelli (1975) therefore introduced the term 'subaqueous outwash', to differentiate these from glaciofluvial deposits formed by subaerial flow. The aim of this paper is to examine the nature and origin of subaqueous outwash, with particular reference to the large channels in the Ottawa succession.

Subaqueous Outwash

Gravel Facies

Exposures of the gravel facies are much fewer than those of sand, but this is partly a function of lesser commercial value rather than actual abundance. The gravel is clast-supported, locally boulder-rich, and exhibits poorly defined horizontal stratification. Channels have not been observed, but they would be difficult to distinguish in such coarse material. Preferred clast fabric is present, for example at locality 1 (Fig. 1), where large (a axes up to 1.8 m) discoidal slabs are particularly abundant. The a axes of more elongate clasts dip upstream, as indicated by the a–b dip directions of the slabs (Fig. 2, B); abundant cross-strata in the sand facies nearby show an essentially parallel paleocurrent system (Fig. 2, A). The fabric is unlike that of most fluvial or glaciofluvial gravels, in which the preferred a-axis orientation is transverse to flow due to rolling on the bed (Sedimentary Petrology Seminar 1965; Rust 1972). However, Johansson (1963) observed in experiments that saltating elongate pebbles tend to settle with a axes parallel to flow. For a given particle size saltation requires more powerful flow than rolling; hence clast fabrics with a axes parallel to flow indicate deposition from relatively high energy currents. Similar fabrics were observed in flood gravels by Krumbein (1942) and in conglomerates associated with turbidites by Davies and Walker (1974). In all these cases, clasts must have been deposited without appreciable deceleration of the transporting current, or a transverse a-axis orientation would have developed. Walker (1975) suggested that this can

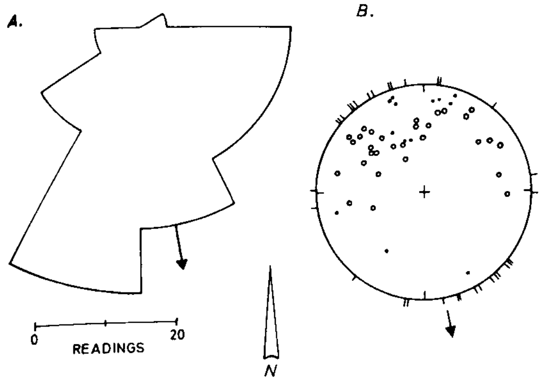

FIG. 2. (A) Paleocurrent rose diagram derived from ripples and cross-strata at locality 3; arrow indicates mean paleocurrent vector. (B) Stereoplot of megaclast fabric in boulder gravel at locality 1, about 200 m northeast of locality 3. Open circles are dip directions of *ab* planes of slabs; dots are *a*-axis orientations of elongate clasts; arrow indicates mean paleocurrent vector. Channel trends in the sand facies are shown outside the stereoplot perimeter.

occur when gravel is carried in high concentration near the bed, as a clast dispersion.

Sand Facies

The gravel facies passes upward and laterally through a narrow interbedded zone into sand with numerous sedimentary structures, mostly typical of outwash deposits. Cross-beds of medium to coarse, locally pebbly sand occur as tabular, horizontally bound sets 10 to 40 cm thick, or as trough cosets with curved lower bounding surfaces, the sets being up to 1 m thick. Sand units with faint horizontal lamination, and horizontal units without apparent internal structure are less common; they are 20–40 cm thick, with fining-upward grading in some cases (Rust and Romanelli 1975, Fig. 8).

All four types of ripple-drift cross-lamination of Jopling and Walker (1968) are present; the most significant are type C examples. They grade upward through increasing silt content, and commonly show upward increase in the angle of climb, but little variation in ripple amplitude. Graded ripple-drift units have not been reported from recent subaerial outwash; their presence in the Ottawa succession is regarded as evidence for deposition from decelerating currents below standing water, as described by Banerjee (1973) for glacial lakes.

Another sand facies is massive and channeled, as described below.

Channel Deposits

Introduction

Channels containing massive sand are thought to be the most environmentally significant features of the subaqueous outwash south of Ottawa. Widths and depths of up to 40 m and 10 m have been observed; several examples have been traced longitudinally for more than 100 m, and trends can be measured without difficulty. In most cases the channels are truncated above by the unconformity below unit 3 (Fig. 3), but an exception illustrated by Rust and Romanelli (1975, Fig. 6) is succeeded conformably by about 3 m of stratified sand, which is in turn truncated by the unconformity. These channels are unlike those of subaerial outwash, which are much shallower relative to width, and contain a well-stratified fill (Williams and Rust 1969).

Two different types of channel were observed. Those in Spratt's Pits at South Gloucester (Fig. 1, locality 2) have sharp, erosional, undeformed bases and relatively steep walls (Fig. 3), with a maximum observed side slope of 37°. The sand in the channels is structureless or has faint horizontal lamination, in which mineralogical rather than grain size variations are apparent. Deformation structures such as load casts are rare, and are found within the channel rather than at its base. The sand is well sorted and lacks silt (Fig. 4, A); it is commonly slightly coarser than the stratified deposits into which the channels are cut. Clasts larger than sand size are rare and are entirely extraformational.

The second type of channel is exposed in several pits on the southwest side of the Stittsville to Huntley road, the two best localities being Rump's Pit and Bradley's Pit (loc. 3, Fig. 1). The channels have gently sloping sides, commonly 10° or less, which together with the base, are highly deformed (Fig. 5). As a result, channel trends can be determined less readily than at South Gloucester, but they generally agree with the numerous paleocurrent data from associated cross-stratified sands (Fig. 2, B). The channel fill is silty sand (Fig. 4, B) with numerous scattered pebbles and larger clasts of extra- and intraformational origin, and consolidation structures termed dishes (Wentworth 1967; Stauffer 1967).

Deformation Structures

The base and the lower part of the fill of channels in the Stittsville pits are deformed, although the base is commonly less highly con-

FIG. 3. Channel in Spratt's Pit, South Gloucester (locality 2). It is approximately 4.5 m deep, and is overlain unconformably by marine gravel of unit 3, although the nature of the unconformity is not apparent in the photograph.

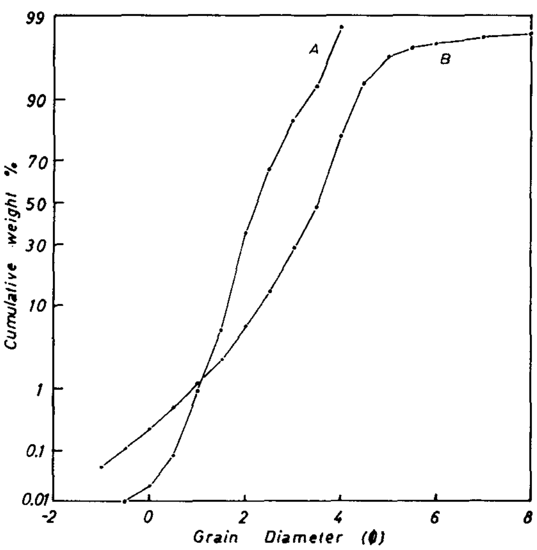

FIG. 4. Grain size distributions of typical channel sands. A: Spratt's Pits, South Gloucester (sample X-17); B: Bradley's Pit, near Stittsville (sample X-32).

torted than the fill, and may still show an erosional relationship to the underlying sediment (Fig. 5). The deformed structures vary considerably in shape, but generally take the form of rounded, detached, synclinal folds up to 2 m in width, with the limbs bent inward towards the axial plane, and commonly without intervening anticlines. Internal lamination is parallel to the external margins of the synclines, but terminates at the disrupted tops of the folds. As seen in vertical section, the axial planes vary about the vertical, while three-dimensional exposures show that the structures vary from approximately spherical to cylindrical and more complex forms. The axes of the more cylindrical types are commonly sub-horizontal, with variable trends.

The structures differ from convolute bedding or lamination (Potter and Pettijohn 1963, p. 153) in their lack of intervening anticlines, and most closely correspond to ball-and-pillow structures (Potter and Pettijohn, pp. 148–152). Several authors have noted convolute lamination or ball-and-pillow associated with ripple-drift cross-lamination (Coleman and Gagliano 1965; McArthur and Onesti 1970), and concluded that deformation was closely related to current flow. Because the present structures lack this association and are commonly symmetrical about the vertical, they were probably formed by dewatering of the sediment in response to purely vertical loading. Kuenen (1958) made convincing analogues by pouring sand onto water-saturated finer sediment; when shaken the sand sank to form kidney-shaped masses identical to natural ball-and-pillow structures.

Loading in the Stittsville channels was probably due to rapid deposition of a large mass of sediment, which forced closer packing of grains in underconsolidated sand beneath the channels. There are no complete exposures of channel bases, but exposed margins show that the underlying material contains a high proportion of

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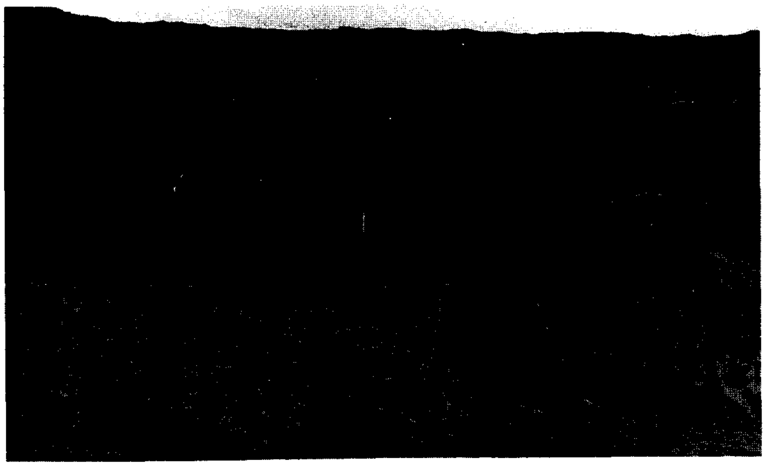


FIG. 5. Margin of a channel at Bradley's Pit, locality 3. Ball-and-pillow structures in the channel fill decrease in size upwards, passing into structureless sand outside the field of view. The channel base is less strongly contorted, and clearly shows an erosional relationship to the underlying stratified sand, which is also slightly disturbed. Scale is 30 cm long.

cross-stratified sand. Sand cross-strata are loosely packed when deposited, and can be deformed easily to a more consolidated state (Allen 1972). This process expels water, and the increase in pore water pressure leads to instant liquefaction of the sand. As consolidation progresses, the expelled fluid (water, or a slurry of sand and water) rises and can cause fluidization of the overlying sediment (Lowe 1975). In the Stittsville channels the rising fluid induced hydroplastic deformation of relatively cohesive layers into folds; additional flow disrupted the anticlines, while synclinal troughs sank in compensation for the upward movement. In most cases the deformed structures in the Stittsville pits are lithologically similar to the surrounding and overlying channel sediment, except that they are generally laminated. They are presumed to have been formed by deformation of basal layers of the channel fill or of sediment immediately below it.

Another, much rarer type of deformed structure containing exotic fossiliferous blocks is exposed in Rump's Pit, and resembles those described by Johnston (1917, p. 15) and by Richard (1975) from several localities south of Ottawa. The structures have an irregular form, and occur throughout the channel rather than just towards its base; some are cut by the unconformity beneath unit 3, which is undisturbed. The sand bodies are up to 3 m across and are composed of contorted stratified sand, whose exotic nature is indicated by an unusual abundance of mafic minerals and the inclusion of irregular blocks of fossiliferous sandy silt (Fig. 6). The abundance of fossils in the blocks contrasts with their total absence from the surrounding outwash. Johnston (1917, p. 15) suggested that the exotic sand bodies were emplaced by melting of ice blocks, or glacial overriding. Recent evidence for a short, late-glacial readvance into the Champlain Sea (Richard 1975) favours the latter interpretation.

Dish Structures

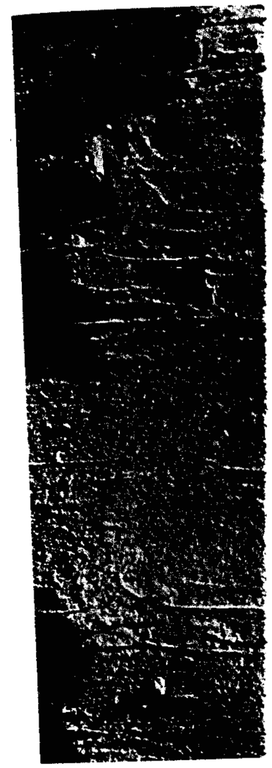
Passing upward from the base of a channel the individual ball-and-pillow structures decrease in size and become separated by relatively undeformed silty sand with scattered larger clasts (Fig. 7). The sand commonly contains a faint, discontinuous, sub-horizontal lamination, which is probably consolidation lamination (Lowe 1975). It passes vertically and laterally into apparently structureless sand, or in some cases (notably Rump's and Bradley's Pits near Stittsville) to dish structures (Fig. 8). The dish structures are composed of sharply-defined silt-rich layers about 0.2 mm thick, separated by silty sand which is generally structureless, but in some cases contains faint laminae. The vertical spacing between dish laminae varies from 1 to 8 cm, but is commonly 2 to 3 cm; apparent width of the structures varies between 2 to 20 cm, with a mean of 8 cm. They are concave upwards, and

FIG. 6. Block of fossiliferous sandy silt in deformed structure, Rump's Pit, locality 3. Scale is in inches and centimetres.

FIG. 7. Succession in a channel at Bradley's Pit (locality 3) in which ball-and-pillow structures are overlain by faintly laminated sand containing dish structures. The channel is overlain unconformably by gravel of unit 3. Arrowed scale is 30 cm long.

are commonly symmetrical about the vertical, although in some cases there is consistent local asymmetry. The concavity is commonly gentle and uniform in the smaller dishes, whereas the larger ones tend to be flat-bottomed, with a relatively abrupt upward curvature at the extremities (Fig. 8). In some cases the extremities steepen to the vertical, but very few are overturned. Successive dish laminae nearly meet at their margins, but rarely do so; the individual structures appear to 'float' in massive silty sand, apparently without intervening pillar structures. Erosion by wind-blown sand has exposed a few dish laminae in three dimensions; they vary from circular to elliptical depressions with long axes about three times short axes, and are commonly compound, with several overlapping. The latter effect can also be seen in vertical section; it appears as though smaller dish laminae were prevented from extending laterally by the presence of adjacent larger structures.

The successions within channels show an upward change from ball-and-pillow to dish structure, with apparent inter-gradation in some cases. Within the dish-structured part of the succession there is, in contrast with Stauffer's observations (1967, p. 493), a poorly-defined tendency to upward decrease in dish concavity, and pillar structures have not been observed. Lowe and LoPiccolo (1974) concluded that dish structures result from upward movement of water and sediment during consolidation, which is supported by the association of dishes and ball-and-pillow structures at Stittsville. Dish structures have not been formed experimentally, but Kuenen (1958) produced ball-and-pillow by vertical loading of underconsolidated sediment. The origin of dish structures can reasonably be ascribed to the same mechanisms, but involving smaller vertical movements of water and sediment, generally at higher levels in the bed.



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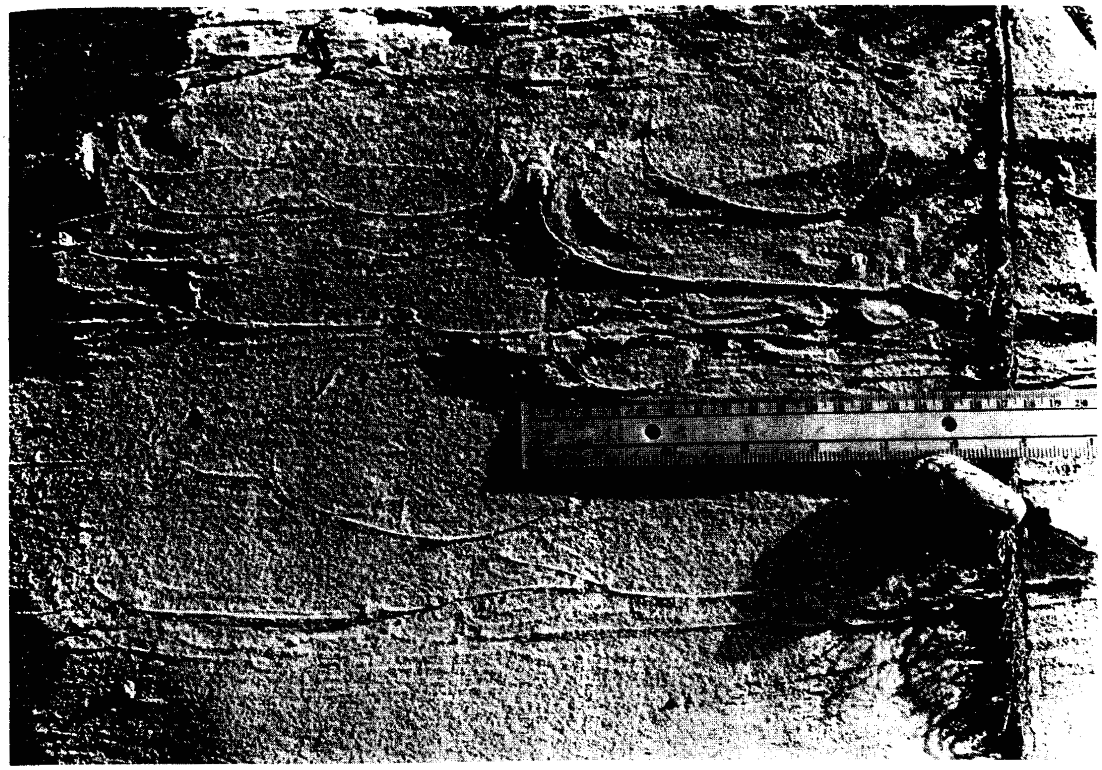


FIG. 8. Dish structures in silty sand with outsize clasts of intraformational mud (extraformational pebbles are present elsewhere in this channel). Rump's Pit (locality 3). Scale is in inches and centimetres.

Discussion

The major features of the Stittsville channels, namely massive sand fills with scattered larger clasts, deformation and dish structures, have been recognised in ancient rocks associated with turbidite successions. They were termed fluxoturbidites by Dzulynski *et al.* (1959), and are commonly found as deposits within channels, interpreted as ancient submarine fan channels by Bartow (1966), Stanley and Unrug (1972), and others. Sediments with similar features have been recovered from modern submarine fans by many workers, including Normark and Piper (1969), and Stanley and Unrug (1972). Lowe and LoPiccolo (1974, p. 492) reported unpublished accounts of dish structures in alluvial sediments, but the great majority have been described from flysch deposits. The Ottawa examples show that subaqueous mass flows can occur in relatively shallow water, and imply that certain environmental conditions similar to those of deep sea fans must prevail.

Middleton and Hampton (1973) discussed mechanisms of mass flow or sediment gravity flow, distinguishing four gradational types: turbidity currents, fluidized sediment flows, grain flows, and debris flows. They are characterised, in that order, by increasing sediment concentration, and a decreasing role of turbulence as a grain support mechanism. They suggested that fluidized sediment flows should produce liquefaction phenomena such as pseudonodules (essentially ball-and-pillow structures), and also contain dish structures and faint plane lamination. On the other hand, scattered larger clasts are typical of debris flow deposits, although faint lamination and dish structures can also be expected (Middleton and Hampton 1973, p. 25). At the present time there seems to be insufficient information to distinguish between the deposits of these related mechanisms; the term mass flow is preferred here because it was used inclusively by Middleton and Hampton, and is relatively non-committal as to the precise depositional mechanism.

The channels at South Gloucester lack dish structures and abundant deformed structures, but their large size and massive nature suggest that the contained sediment was also deposited by mass flow. The lack of abundant post-depositional features is probably due to the fact that the sand fill is coarser, and lacks silt (Fig. 4, A). Middleton (1969, p. 266) showed that sediment consolidation rates increase with increasing grain size. He did not take sorting into consideration, but the presence of a silt-sized matrix presumably would retard consolidation. Thus the coarse, well-sorted texture of the South Gloucester channel fills would allow more rapid loss of excess pore pressure, and a quick return to a stable condition. Lowe and LoPiccolo (1974, p. 494) suggested that semi-permeable, generally argillaceous laminations are a prerequisite for dish structures. It is concluded that the lack of fine matrix probably accounts for the absence of dish structures and abundant deformation from the South Gloucester channel deposits, but that their primary depositional mechanism was the same as at Stittsville.

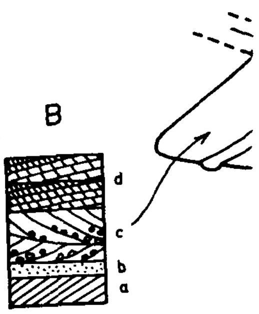
In some cases mass flows may be generated by continuous sediment flux, but probably most originate by sudden liquefaction of underconsolidated sediment on a slope. Subaerially exposed sediment is rapidly dewatered; hence mass flows are predominantly a subaqueous phenomenon, although Carter (1975) observed small mass flows on steep subaerial slopes. Earthquakes could be a trigger mechanism, but Lowe (1975, p. 191) warned against regarding them as the sole or even major cause of sediment liquefaction. Amongst other mechanisms, he suggested that breaking waves, storm surges, and allied phenomena could induce liquefaction in metastable surface sediments. In the environment close to a submerged ice front, a major source of disturbance, which I have observed in a proglacial lake in southeast Iceland, is the calving of icebergs. Enormous waves are generated, and the larger icebergs may impact on the bed. In either case, liquefaction of underlying sediment would probably result, initiating mass flows even from gentle slopes.

Other possibilities that relate to the Ottawa Quaternary succession involve sudden changes of the whole water column. Breaching of the ice dam holding the pre-Champlain Sea lake probably caused sudden lowering of the water surface, followed by an influx of saline water over sediment with interstitial fresh water. Both processes might induce liquefaction of the basin floor over a relatively large area, and at a specific horizon in the succession. The presence of channels within as well as at the top of unit 2 implies that filling of the channels with mass flow deposits occurred during continuous deposition of proximal stratified outwash. This alternative is also favoured by the presence within the stratified succession of thin beds of massive sand, which are thought to be overbank deposits from channelized mass flows. It is concluded that there are several potential sources of instability in the subaqueous outwash environment, but there is insufficient evidence to single out a particular cause of mass flows.

A Depositional Model for Subaqueous Outwash

The depositional model proposed here is based on the interpretation of transport mechanisms discussed above, and the sedimentary environment proposed by Rust and Romanelli (1975). They suggested, largely on the basis of parallelism of the ridges, internal paleocurrents, and the ice transport direction, that the contained subaqueous outwash was deposited on esker fans near the mouths of submerged englacial tunnels. The lack of fossils is probably due to proximity to the ice front, where marine life was inhibited by low temperature and salinity, and by the high turbidity and vigorous flow of the water.

On this basis, the gravel facies was probably deposited at the fan apex, perhaps in a wide, shallow channel in front of a tunnel mouth (Fig. 9, A). Flow in the tunnel was powerful enough to erode boulders from till, and probably from bedrock, creating a concentrated flow of large clasts over the fan apex, on which they accreted with long axes parallel to flow. Downfan the flow energy was rapidly dissipated by turbulent mixing with the standing water. A rapid facies transition to pebbly sand, sand, and silt resulted; channels bifurcated and became more distinct. Most of the sand was deposited on inter-channel areas as cross-stratal sets of varied size and texture. Due to its underconsolidated and water-saturated state, this material was easily liquified by sudden shock. The resultant loss of strength, combined with the slope of the fan surface, was sufficient to induce mass flows of sand and silty sand, particularly from channel margins. Frictional losses in the mass flows led to rapid deposition in channels, resulting in defor-



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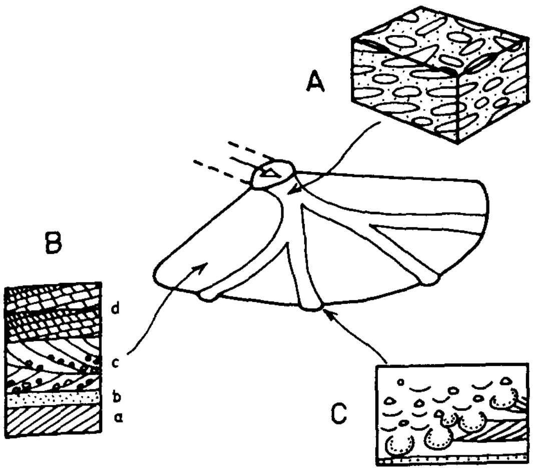

FIG. 9. Depositional model for subaqueous outwash south of Ottawa. For simplicity, only one esker fan is shown, and ice-contact features are omitted. A: Gravel facies. B: Stratified sand facies. a: planar cross-stratified sand; b: structureless sand; c: trough cross-stratified pebbly sand; d: graded ripple-drift units. C: Massive sand facies in a channel.

mation at and beneath the channel base, and the formation of dish structures by dewatering. Mass flow over inter-channel areas gave rise to extensive thin sheets of massive or faintly-laminated sand (Fig. 9, B and C).

Conclusion

The large scale, massive sand fill, dish and deformation structures of channels in subaqueous outwash near Ottawa indicate that they were filled by processes of mass flow. Mechanisms of this type and scale are not known, and are considered unlikely to operate in subaerial environments; it is concluded that the flows were initiated below standing water. In the present case this conclusion is supported by the stratigraphic relationship of the outwash to marine deposits in an offlap succession. Similar deposits that cannot be related directly to subsequent sea or lake levels could be misinterpreted as subaerial outwash. In such cases, however, the channels and other features described here could be used to diagnose the submerged nature of the environment. Subaqueous outwash is probably common in successions formed during continental deglaciation, because the isostatic effect of a large ice mass tends to cause ponding of marine or fresh water against the glacial margin.

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