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DISTINGUISHING CHARACTERISTICS OF DIAMICTONS AT THE MARGIN OF THE MATANUSKA GLACIER, ALASKA

by

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ABSTRACT

The origins of diamictons deposited at the Matanuska Glacier are identified in stratigraphic sequences mainly by the presence or absence of a pebble fabric, internal structure, and variation in gravel-size clast distribution. These properties correlate with major differences in depositional mechanisms and source material. Melt-out till mostly inherits fabric, internal structure, and grain-size distribution from its debris-laden basal ice source. Sediment flow deposits and ice-slope colluvium (deposited by ablational slope processes) have properties developed by resedimentation mechanisms. Melt-out till ranges from structureless to stratified with interspersed lenses and discontinuous laminae, and generally possesses a well-defined pebble fabric. Sediment flow deposits show various combinations of six sedimentologic units with distinct sedimentary features and clast dispersion. Pebble fabric is absent or poorly defined, depending upon the unit's origin. Ice-slope colluvium is usually featureless, except for randomly-dispersed laminated lenses and irregularly-shaped gravelly zones in an otherwise disarrayed assemblage of particles, and is without a pebble fabric.

INTRODUCTION

Studies of sedimentation at active glaciers have shown that a number of different processes may form diamictons in the glacial environment (e.g. Hartshorn 1958, Boulton 1968, 1970,1975, Johnson 1971, Shaw 1977 [a], Lawson 1979 [b], German and others 1979, Eyles 1979). These processes can be differentiated according to whether they involve the direct release of debris from the glacier or cause remobilization, transport, and resedimentation of debris following this release.

This distinction separates glacial deposits into two groups, one with characteristics mainly related to those of the debris and ice, and the other with properties developed by the subsequent resedimentation processes (e.g. Shaw 1977[a], 1977[b], Boulton 1978, Lawson 1979[a]).

I suggest that only those deposits formed through the direct release of debris from glacial ice should be called till because the resedimentation processes modify or destroy sedimentological properties developed by the glacier. Formally, I would define till as: sediment deposited directly from glacier ice which has not undergone subsequent disaggregation and resedimentation.

In this paper I describe the development of three key sedimentological properties: presence or absence of pebble fabric, internal structure, and variation in gravel-size clast distributions. These properties reflect the origin of individual diamictons within stratigraphic sequences deposited along the active ice margin of Matanuska Glacier. Only one of these deposits, that formed by melting of buried glacier ice, is considered a till. The criteria for distinguishing the diamictons are based upon continuing extensive analyses of the depositional processes and deposits of the glacier (Lawson 1977, 1979[b]).

FIELD SITE

Matanuska Glacier originates in the ice fields of the Chugach Mountains in south-central Alaska (61°47'N, 147°45'W). It flows north approximately 40 km to its terminus at the head of the Matanuska River valley, about 138 km north-east of Anchorage (Fig.1). Its width ranges from 2 km near the ice fields to a maximum of 5 km at the terminal lobe.

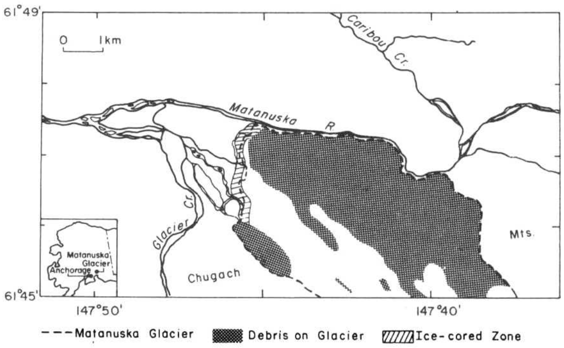

Fig.1. Index map showing location of study area with ice-cored marginal zone indicated.

Over the last 400 years, the terminus margin has remained near its present location owing to relatively stable flow conditions (Williams and Ferrians 1961). Repetitive localized advance and retreat of this margin, coupled with thrusting of active ice over marginal stagnant ice of the basal zone and the overlying

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sediments, have formed an ice-cored end moraine complex of 100 to 500 m width. Much of the debris in the glacier is released and deposited in this marginal zone which was the site of sedimentological analyses cited below.

FORMATION OF DIAMICTON PROPERTIES

Significant amounts of diamictons are deposited in the ice marginal zone of Matanuska Glacier by three groups of processes: sediment flow, melt-out, and ablation-induced slope erosion processes. I will briefly describe each process in terms of development of critical sedimentologic characteristics that distinguish the deposits. More detailed descriptions of each process are presented elsewhere (Lawson 1979 [b], in press, and in preparation*).

Melt-out

Melt-out is the gradual *in situ* melting of the upper and lower surfaces of buried, debris-laden ice from the basal zone of a glacier (Harrison 1957, Boulton 1970). As the horizon of melting moves upward or downward into the ice mass, debris is released under confining conditions that limit redistribution and modification of its properties. In general, the interaction of debris particles as the ice melts modifies the orientation of the particles and increases packing, with finer-grained material migrating into pore spaces between larger grains.

Although the melt-out process has not been observed directly, detailed examination of exposures of melt-out till currently forming on or below its ice source (Fig.2) at Matanuska Glacier indicates that the distribution, volume, and texture of the debris in the ice largely determine the sedimentological character of the resulting deposit. In most cases, the process tends to preserve sedimentary features in ice highly charged with debris.

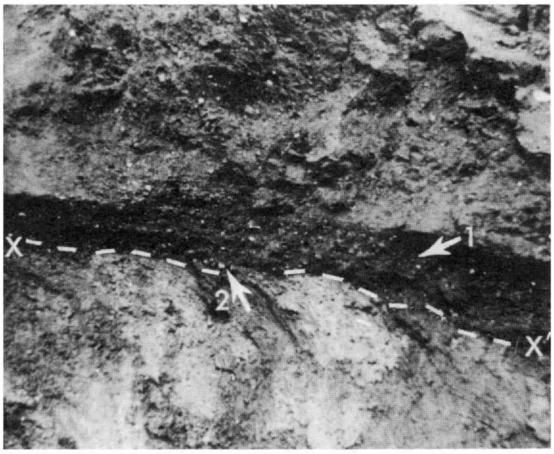

Fig.2. Mostly massive melt-out till currently forming by top melting of basal-zone ice. Dashed line (x-x') marks till and ice contact. Arrow at (1) locates a gravel-rich band in the till, while (2) locates a pebbly sand lens melting out of the basal ice.

The basal-zone ice of this glacier is stratified, with debris distributed in alternating debris-rich and debris-poor layers of relatively pure ice. These strata may contain clay- to boulder-size particles and irregular aggregates, or they may be composed of lenses and discontinuous layers of clay- to sand-size sediment bonded by interstitial ice only. Blocks of sediment incorporated subglacially from the bed may preserve sedimentary structures such as graded bedding and parallel laminations. The grain-size distribution of the debris may be relatively homogeneous through large thicknesses of the ice, or may be interstratified, with strata of poorly-sorted and well-sorted pebbly silt, silty sand, and silty or sandy gravel. Strata vary from about 1 mm thick to over 2 m thick. Their debris content ranges from less than 0.01% to greater than 74% by volume (Lawson 1979[b]). Both the debris content and thickness of strata often vary laterally over short distances in exposures of the basal ice.

Observations of till and ice outcrops indicate that there are three typical variations of melt-out till (Fig.3). Typically, they vary

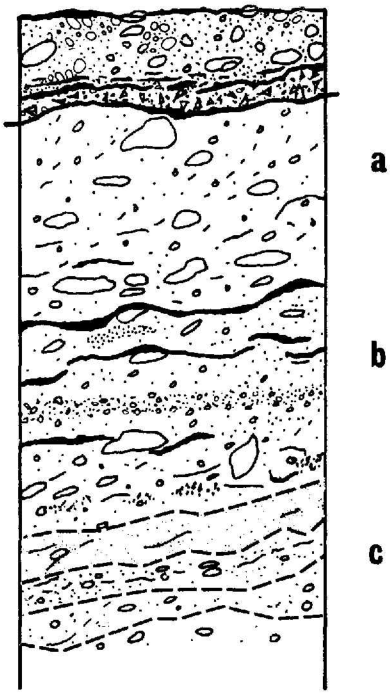

Fig.3. Idealized cross-section of typical features of melt-out till at Matanuska Glacier: a. structureless pebbly sandy silt, b. discontinuous laminae, stratified lenses and pods of texturally distinct sediment in massive pebbly silt, c. bands or layers of texturally-, compositionally-, or color-contrasted sediment. Laminae and layers may appear draped over large clasts. Pebbles are preferentially oriented throughout the deposit. Deposits of other origins overlie all melt-out tills except where they have been removed by erosion.

from structureless pebbly silts to pebbly sandy silt containing disturbed, discontinuous laminae and lenses of sorted and stratified sediment, or distinct bands or layers of variable grain size or composition. The effects on the sedimentologic properties of melting the debris-rich and debris-poor ice strata of the till vary as follows:

1. The particle-by-particle deposition of individual grains and small aggregates from debris-poor basal ice eliminates ice and debris features, generally producing a deposit without internal structure. The bulk grain size distribution of the source material remains unchanged.

* In preparation: "Depositional processes in the western terminus region, Matanuska Glacier, Alaska".

2. Strata of lenses and layers of fine-grained, cohesive debris that contain little ice are deposited mostly intact, but are deformed by subsequent differential settlement due to the melting of underlying ice that contains variable amounts of debris.

3. Melting of several alternating ice-poor layers of granular material of mixed grain sizes produces strata or laminae in the till with poorly-defined, indistinct contacts. Blurring of the layer contacts results from movement of fine- and coarse-grained particles into pore spaces of the underlying layer during the general readjustment of particles accompanying melt-out. Sand layers and lenses bonded by pore ice only are preserved with more distinct bed contacts than those with higher ice contents.

4. Thick sections of basal ice containing debris of similar texture throughout (usually a pebbly sandy silt) produce a structureless deposit of the same texture upon melt-out. Well-drained coarse sediments favor some redistribution of fine silt and clay by melt water, with a thin clayey silt horizon forming at the ice/sediment interface at some locations.

5. The unimodal distribution of pebble orientations in the basal-zone ice is preserved during deposition, but is changed as melting lowers the angle of imbrication of the particles to near-horizontal and increases the scatter of individual particle orientations about the calculated mean (Lawson 1979[a]). This increase in dispersion is greatest for pebbles released from debris-poor ice strata. If the strata in the basal ice dip up- or down-glacier, melting also lowers the angle of layers or discontinuous strata preserved in the till.

Sediment flow

Sediment flow is the down-slope transport of sediment-water mixtures under the force of gravity. Most flows at Matanuska Glacier occur subaerially. The sedimentologic properties of their deposits are determined by the mechanics of flow and depositional modes. Flow mobilization serves to disaggregate source materials and destroy their original properties. The mode of deposition generally determines the geometry and thickness of the deposits.

Flow mobilization nearly always involves two distinct stages. First, previously deposited glacial materials of diverse origins lying on stagnant or active glacier ice are released through a combination of erosional processes which I term *backwasting* (Lawson, unpublished). Lateral retreat of near-vertical slopes of ice and sediment releases melt water and debris which combine at the base of the slope with disaggregated sediment that is simultaneously undermined by melting. This first stage may also involve slumping of sediments lying on thawing glacier ice. In the second stage, the continued influx of melt water from the slope and the thawing of ice beneath the accumulating sediment piles develop high pore pressures and generate seepage pressures that tend to cause the sediment to fail again, and then to flow.

The mechanics of flow are complex, with several different mechanisms of grain support and of transport potentially operating in the same flow during movement (Lawson, in press). In flows characterized by low water content, high density, and measurable shear strengths, shearing appears to be localized in a thin zone at the base. The upper sediments do not deform and the strength of the matrix material supports larger grains during movement. As the volume of water in the matrix increases, this shearing zone increases in thickness to encompass the entire mass. The traction and saltation of coarse bedload material, localized fluidization, transient turbulent mixing with flow over steep channel bed irregularities, and grain-to-grain interactions occur in these more fluid flows. As the water content increases, the density, thickness, and mean grain size decrease, and the rate of movement, erosiveness, and degree of channelization of the flow generally increase. With the exception of localized temporary turbulence, flow appears to be laminar.

Because of these multiple grain support and transport mechanisms, properties of sediment flow deposits vary widely. Typically, however, a single flow deposit may be composed of some combination of up to six sedimentologically distinct units (Fig.4) depending on the water content of the matrix material of the active flow, as shown. Most sediment flows are accompanied by melt water flowing over their surfaces during movement and deposition. This association commonly results in a top layer of thinly laminated silt and sand (unit 5) that is generally critical to identifying individual flow deposits in depositional sequences. The examples of flow deposits shown in Figure 4 are idealized and I have observed transitions between them. The

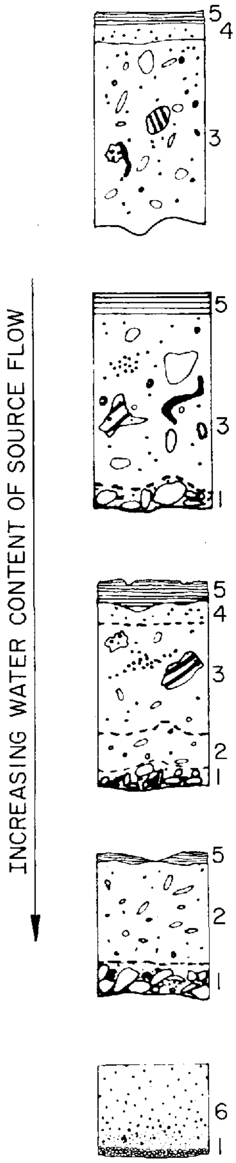

Fig.4. Idealized internal organization of five sediment-flow deposits. Six sedimentologic units are recognized, with the possibility that any may be missing due to erosion or absence from the source flow. The general characteristics of the units are: (1) texturally heterogeneous with a high gravel content, massive-to-graded, and weak-to-absent pebble fabric; (2) massive, texturally heterogeneous, but fewer large grains than units 1 or 3, possible decrease in silt and clay due to elutriation, and a weak pebble fabric; (3) massive, with lenses and discontinuous laminae of texturally distinct and sometimes structured sediments, pebble fabric absent, and vertically-oriented clasts common; (4) massive, texturally similar to matrix material of unit 2 without coarse clasts; (5) thinly laminated silts and sands, discontinuous where eroded, (6) massive-to-partially or fully graded, relatively well-sorted silty sand and pebble fabric absent. Thickness of deposits generally ranges from 0.2 to 2.0 m.

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contact between the stratified melt-water silts and the other units is sharp; other contacts are gradual and irregular in appearance.

The six units and their origins, as determined by observations of active flows and analysis of their deposits, are as follows:

Unit 1. Basal transport unit. This gravel-rich layer is mainly composed of pebble and cobble-size clasts in a structureless silty sand matrix and is usually derived from bedload material transported by traction and saltation in the lower-most part of the flow (Fig.5). Some clasts may have settled out during movement or deposition due to strength reduction of flow material by localized liquefaction, temporary turbulence, or increased shearing (Lowe 1975, 1976, Hampton 1975). Its upper contact with units 2 or 3 is gradational. Clasts sometimes show a poorly defined orientation and up-slope imbrication (Lawson 1979[a]).

Unit 2. Shear unit. This structureless, texturally heterogeneous zone probably develops by shearing and other mechanisms. There generally appears to be less coarse material (pebble-size and larger) in this unit than in the others. The frequent grain collisions that occur during shearing apparently account for the poorly-developed fabric in this zone (Lawson 1979[a]).

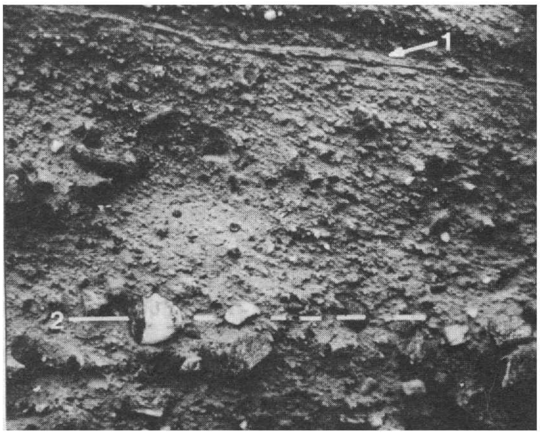

Fig.5 a. Sediment-flow deposit with sharp basal contact defined by tractional gravels (2) of unit 1 and upper surface marked by stratified melt-water silts and sands (1). Deposit possesses very poorly defined pebble orientation approximately parallel to flow movement. Deposit thickness 0.15 m.

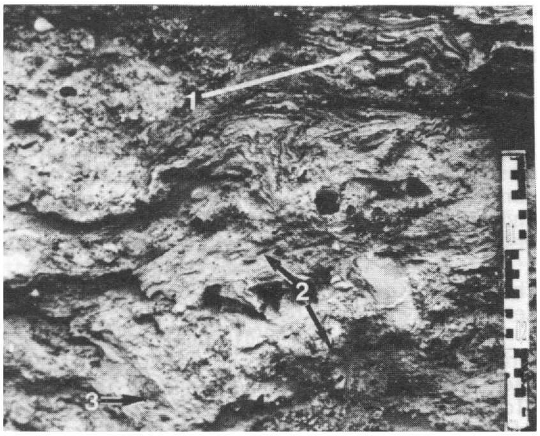

Fig.5 b. Multiple flow deposits with marginally deformed stratified silts (1), load structures (2), and conformable stratified gravelly sands. Intact blocks of source material (3) are present in several of these flow deposits.

Unit 3. Plug unit. This is a non-deforming region within the source flow. The lack of shear or other deformation produces a massive deposit that retains properties of the remolded material from which the sediment flow was derived. The strength of the matrix material maintains clasts up to boulder-size in suspension during movement. Aggregates and blocks of contorted laminated silts, stratified sands, and other sediments (mainly material that was not disaggregated during remolding) are also transported here without disaggregating (Fig.5). Blocks of granular and cohesive sediments are also eroded from channel walls and are preserved in this zone. Such clasts are particularly noticeable when structurally or texturally distinct from the remainder of the flow material. Gravel particles, as well as these aggregates, have random orientations and dispersal.

Unit 4. Dewatered unit. This thin unit found at the top of a flow deposit is generally structureless and contains fewer pebble-size and larger clasts than the body (units 2, 3) of the flow. Clasts apparently settle out as the result of strength reduction due to dewatering (seepage and/or fluidization) during consolidation and, possibly, movement. Similar dewatering effects may be observed locally in unit 2.

Unit 5. Melt-water deposits. These thinly laminated silts or sands are deposited by melt water flowing in sheets and rills over the sediment flow during movement and deposition. Subsequent erosion by melt water after deposition results in discontinuous laminated lenses that lie on the original flow surface.

Unit 6. Liquefied flow unit. This unit consists of silty sand or sandy silt solidified from liquefied flows. As a result of solidification, it is generally structureless or may exhibit distribution or coarse-tail grading (Lowe 1976). A coarse layer (generally granule-size particles) develops at the base of these deposits, apparently from grains that settle out during movement and from deposition of bedload material. Although pore-fluid expulsion has been observed in these flow materials during solidification, features developed by it, such as fluidization channels (Lowe 1975), have not yet been seen in deposits.

Also of importance are flow-induced deformational features. Movement may cause shearing and deformation of sediments beneath and adjacent to the sediment flow (Fig.5). Overburden pressures generated by flow masses moving onto saturated sediments also cause soft sediment deformation of these highly deformable materials; features such as load casts and complex folded strata are formed in the base of and beneath the deposit.

Ablational slope processes

Active basal-zone ice exposed in steep (>60°) to overhanging slopes along the frontal margin of the glacier releases its debris by ablation. This sediment then moves off the ice face through several processes, including rolling, sliding, and falling of individual clasts and still-frozen aggregates of mixed grain size, the transport of silt and clay in melt water flowing in thin sheets and small rills, and occasionally small (20 to 100 mm wide) grain and debris flows. Most of this sediment accumulates in a pile along the base of the ice slope.

The resulting deposit, which I term *ice-slope colluvium*, is mostly a structureless and heterogeneous dispersal of clay-to-boulder-size particles that looks as if it were simply dumped in place (Fig.6). Two variations are common, depending upon whether deposition took place in

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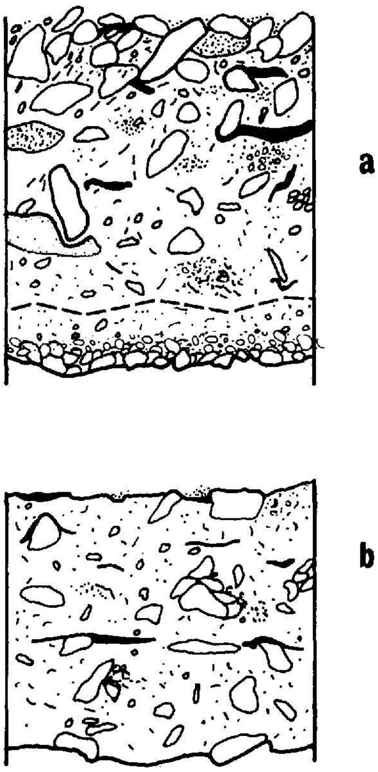

Fig.6. Two idealized deposits of ice-slope processes. The gravel-rich zone at the top of (a) develops by continuous melt-water run-off during the latter stages of deposition. Sand lenses are deposited by melt-water rill deposits, with silt and clay lenses deposited from suspended sediments in melt water pooled on the deposit surface. Deformed laminae develop by penetration of falling clasts. (b) represents deposition on unsaturated sediments without significant melt-water run-off. The sediments are structureless with occasional irregular gravelly and sandy zones.

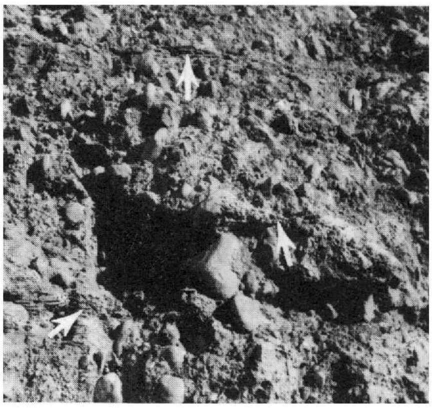

Fig.7. Coarse ice-slope colluvium. Arrows indicate small lenses and channel fills of laminated silt. Vertical clast orientations are abundant. Thickness shown is 2.5 m.

well-drained areas or in poorly drained areas that generally overlie stagnant ice.

The uppermost material is very coarse and nearly clast-supported where the finer particles are removed by melt water flowing from the ablating ice across the deposit. Fine-grained particles are displaced downward into the deposit by melt water percolating into unsaturated sediment, resulting in a general increase in the fine-grained sediment component at depth. Irregular stratified or massive lenses and small channel fills of clayey silt and sand may be deposited by the melt water flowing in sheets and rills (Fig.7).

In poorly drained locations, and particularly those underlain by ice, melt water saturates the material fully, so that pools of water stand in depressions on the surface. Suspended clay and silt are deposited here and develop generally massive, thin silt lenses in the deposit. Continuing flux of debris from the ice buries these lenses and preserves the fine-grained component of the debris in the deposit. Occasionally liquefaction of sediments above the ice surface causes grain settlement and concentration of coarse clasts on the underlying ice surface. Pore-fluid expulsion brings fine-grained particles to the surface; these are then usually dispelled by melt-water run-off.

Clasts exhibit all orientations from horizontal to vertical. The long axes of clasts parallel to the trend of the ice slope show a poorly defined alignment, which is apparently the product of their rolling and falling from the ice face (Lawson 1979[a]).

CRITERIA

The process-related attributes that separate melt-out till, sediment flow deposits, and ice-slope colluvium fall into three groups:

1. Pebble fabric. Pebbles are aligned preferentially in a regionally systematic pattern in melt-out till, but exhibit either no preferential orientation or a poorly defined one in flow deposits and ice-slope colluvium (Lawson 1979[a]).. Pebbles in shear zones of flow deposits may show a polymodal distribution with a large amount of scatter in individual pebble orientations and the principal orientation lying either transverse or parallel to the direction of sediment flow movement. Gravel-size clasts in colluvium may be weakly aligned parallel to the trend of the depositing ice slope.

2. Sedimentary structure. This is generally absent in ice-slope colluvium. Sporadic irregular to dish-shaped lenses and rill-size channel fills of massive or laminated silt and sand may be randomly dispersed within the otherwise structureless deposit.

Debris stratification of the basal ice source may be preserved in melt-out till as individual, often deformed, lenses and discontinuous laminae that lie along sub-horizontal or dipping planes representing the debris distribution in the ice source. Texturally similar, pebbly clayey silts may exhibit a foliation of similar origin that was derived from slowly melting and sublimating (Shaw 1977[b]) ice. Individual relatively continuous subparallel layers or bands develop from contrasts in composition, texture, or color in strata of the ice source. Typically, their contacts are indistinct or gradual. Lenses and individual strata are readily distinguishable when well-sorted or possessing relict sedimentary structures derived from subglacial sediments. These structures are typically unconformably terminated at their bases.

The presence of individual sedimentary units in flow deposits is distinctive, especially when occurring within a sequence of interbedded flow deposits, each separated by laminated silts and sands. Lenses, irregular aggregates, and other exotic clasts of variable, sometimes contorted, orientation occur in the central mass of flows characterized by a non-deforming zone. Clast-poor matrix material occurs in horizontally continuous units and in irregular zones with gradual contacts with adjacent sediments. Clasts may be concentrated beneath these layers or zones by settlement from this material.

3. Clast concentrations. Melt-out till generally lacks concentrated zones of pebbles or larger-size clasts; they may, however, be found in discontinuous strata derived from gravel-rich strata in the ice source. Flow deposits commonly have a basal gravel-rich layer, generally with gravel embedded in matrix material similar to that of the overlying unit. Clast-rich or clast-poor zones may develop from localized liquefaction or other processes causing clast settlement during flow or deposition. The uppermost materials of ice-slope colluvium are often gravel-rich, with a decrease in gravel content at depth. Thick colluvial deposits contain numerous irregularly shaped gravelly zones representing former locations of melt-water erosion during its formation. Occasionally, gravels are also concentrated in a layer at the base of the deposit, usually in association with a gravel-poor, but otherwise texturally similar, zone above it.

The distinctions reported in this paper, although identified in part in other studies of processes and deposits at other active glaciers (e.g. Boulton 1968, 1970, 1971, Shaw 1977[a], 1977[b], German and others 1979, Boulton and Eyles 1979, Eyles 1979), need to be tested for applicability to older stratigraphic sequences. The occurrence of "stratified" diamictons in Quaternary deposits is widely reported (recently by Francis 1975, Dreimanis 1976, Lundqvist 1977, Garnes and Bergerson 1977, May 1977, to name a few), as are other sedimentologic features, some interpreted in the context of sediment-flow deposits (often referenced as "flow till") and melt-out till (e.g. Marcussen 1973, 1975, Evenson and others 1977, Shaw 1979, Gibbard 1980). Similarly, stratification, stratified lenses, deformed laminae, graded bedding, and other features clearly indicative of multiple resedimentation and till origins have been reported in Pre-Cambrian diamictites (e.g. Schermerhorn 1974, Edwards 1975, Spencer 1975). The origins of these sedimentologic features and deposits, regardless of age, remain controversial.

I do not consider that these three criteria are mutually exclusive because of the complex nature of sedimentation in the glacial environment. These criteria should be used with other physical properties of the deposits, including overall texture, geometry, stratigraphic associations, bed contacts, and surface forms, in order to evaluate fully individual deposits and the local stratigraphic sequences within which they occur. I would also caution that glacial stratigraphic sequences should be interpreted only after detailed analyses of a full suite of sedimentologic properties in order to assess fully their origin and the environment of deposition (e.g. Lawson 1979[b] table XIII: 106-107). Certain properties, such as deposit geometry and bed forms, are more informative than others, such as clast shape and bulk texture, in analyzing stratigraphic sequences of Matanuska Glacier.

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