CHAPTER 3

GLACIERS, GLACIAL ENVIRONMENTS, AND TILL

3.1 Aspects of the Physics of Glaciers

3.1.1. Introduction

An understanding of the properties of glaciers is essential for the interpretation of the features of glacial deposits. Two works, Principles of Structural Glaciology (Shumskii, 1964), and The Physics of Glaciers (Paterson, 1969) are extremely valuable, and have been used extensively by the present author.

The processes described below will be referred to in the interpretation of glacial sediment.

3.1.2. Physical Properties

A) The Formation of Glacier Ice

The means by which snow is transformed into ice have been summarized by Paterson (1969). The important processes are water percolation and refreezing which cause the gradual buildup of ice layers as more snow accumulates above. The final product, glacier ice, consists of interlocking ice crystals with isolated air bubbles. It is impermeable to air and water.

B) The Deformation of Polycrystalline Ice

This complex topic has been discussed in detail by Shumskii (1964) and many other authors. Initial laboratory studies carried out by Glen (1952, 1953, 1955) established the flow law of ice, now referred to as Glen's Law:

$$\epsilon = B \exp(-Q/RT)\tau^{n},$$

where B is a constant, ϵ is the strain rate, Q the activation energy for creep, R the gas constant, T the absolute temperature, τ the shear stress, and n a constant found experimentally to be between 1.5 and 3.9, averaging about 2.5 (Paterson, 1969, p.82).

For a constant temperature this simplifies to:

$$\epsilon = A\tau^n,$$

where A is a constant.

Thus the strain rate of ice increases with increasing temperature and increases exponentially as the applied stress increases. The latter property is characteristic of the deformation of a plastic solid, and Glen's experiments showed that ice is a solid, rather than a viscous liquid (in which case n would be equal to 1).

Deformation of glacier ice occurs by basal slip within ice crystals, slip between crystals, (Paterson, 1969, p.22), and by other processes referred to as dynamic metamorphism by Shumskii (1964, p.253) which includes recrystallization according to Riecke's principle.

C) Glacier Flow

The theory of glacier flow has been developed largely by Nye (see Paterson, 1969 for references). For a slab of ice of uniform temperature, with no basal sliding, the velocity of ice at each point is determined by the shear stress at that point. Under these conditions the shear stress depends on the thickness of ice above the point and the slope of the upper surface of the ice sheet:

$$\tau = \rho gh \sin \alpha \text{ , and when } \alpha \text{ tends to 0,}$$

$$\tau = \rho gh\alpha ,$$

where ρ is the density of ice, g is the gravitational constant, h is the thickness of ice above the point, and α is the slope of the upper surface (fig. 9). Thus, the upper part of the glacier has the highest velocity and the lowest strain rate, while the lower part of the ice has the lowest velocity and the highest strain rate (fig. 9). Ice flow caused by shear stress alone is called laminar flow.

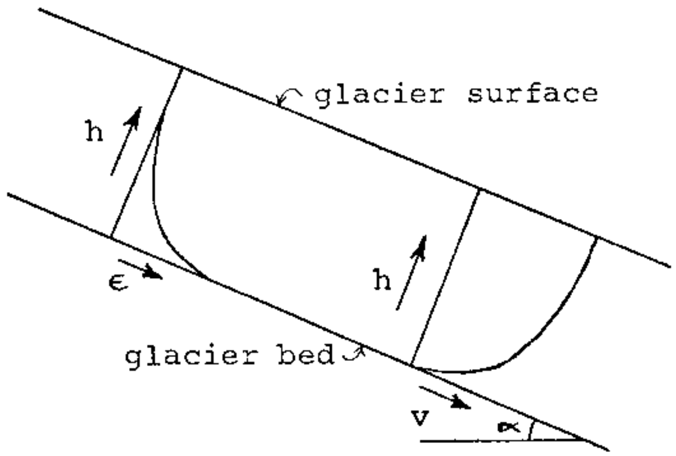

Figure 9. Relationship between strain rate (ϵ) and velocity (v) with height (h) in a glacier inclined with a slope (α) to horizontal.

Often superimposed on shear stresses are uniaxial stresses, compressive or extensive in the direction of glacier flow. These are influenced by variations in the slope of the glacier bed, by variation of velocity within the glacier as a response to changing accumulation rates or valley profile, and by other factors. If the slope of the glacier bed increases downstream, then extensive stresses are created, but if the slope decreases, then compressive stresses develop.

Laminar flow is one mechanism responsible for the formation of glacier banding (Shumskii, 1964, p.360), and it may cause the dispersion of debris within the ice (Weertman,

1968) or sort debris by size, the finer sediment in rapidly shearing layers, the coarser sediment in slowly shearing layers (Boulton, 1967, p.720). Sufficient compressive strain can result in tight folds (Shumskii, 1964, p.321-323), and overthrusts if the elastic limit is exceeded (Shumskii, 1964, p.323-326, where it is called "block slipping"; Boulton, 1970a, p.225).

D) The Basal Zone

Theories concerning the processes at the base of a glacier have been developed mainly by Weertman and Lliboutry, and the history of most of their work is summarized by Lliboutry (1968).

A dry-based glacier (see below, thermal properties) is frozen to the substrate, and the velocity is due entirely to internal flow.

The basal zone of a wet-based glacier (see below) is much more complex. If the bottom is relatively smooth, then most of the velocity may be due to basal sliding, particularly if the velocity is high, from several hundred to several thousand m per year (Lliboutry, 1968, p.22). Sliding is aided by the presence of a basal-water layer (Lliboutry, 1968, p.24).

The presence of obstructions introduces several additional processes (fig. 10). Pressure melting occurs at the upstream face of obstacles due to the increase in pressure. Water formed by this process follows the pressure gradient to the downstream side of the obstacle where it refreezes as regelation ice. Enhanced plastic flow is due to the increased stresses in the ice around the obstacle. It is simply a more intense version of normal plastic deformation within the glacier.

Near the margins of glaciers, subglacial cavities downstream from obstructions have been observed and studied (Lliboutry, 1968; Boulton, 1970a). They are more common near the snout

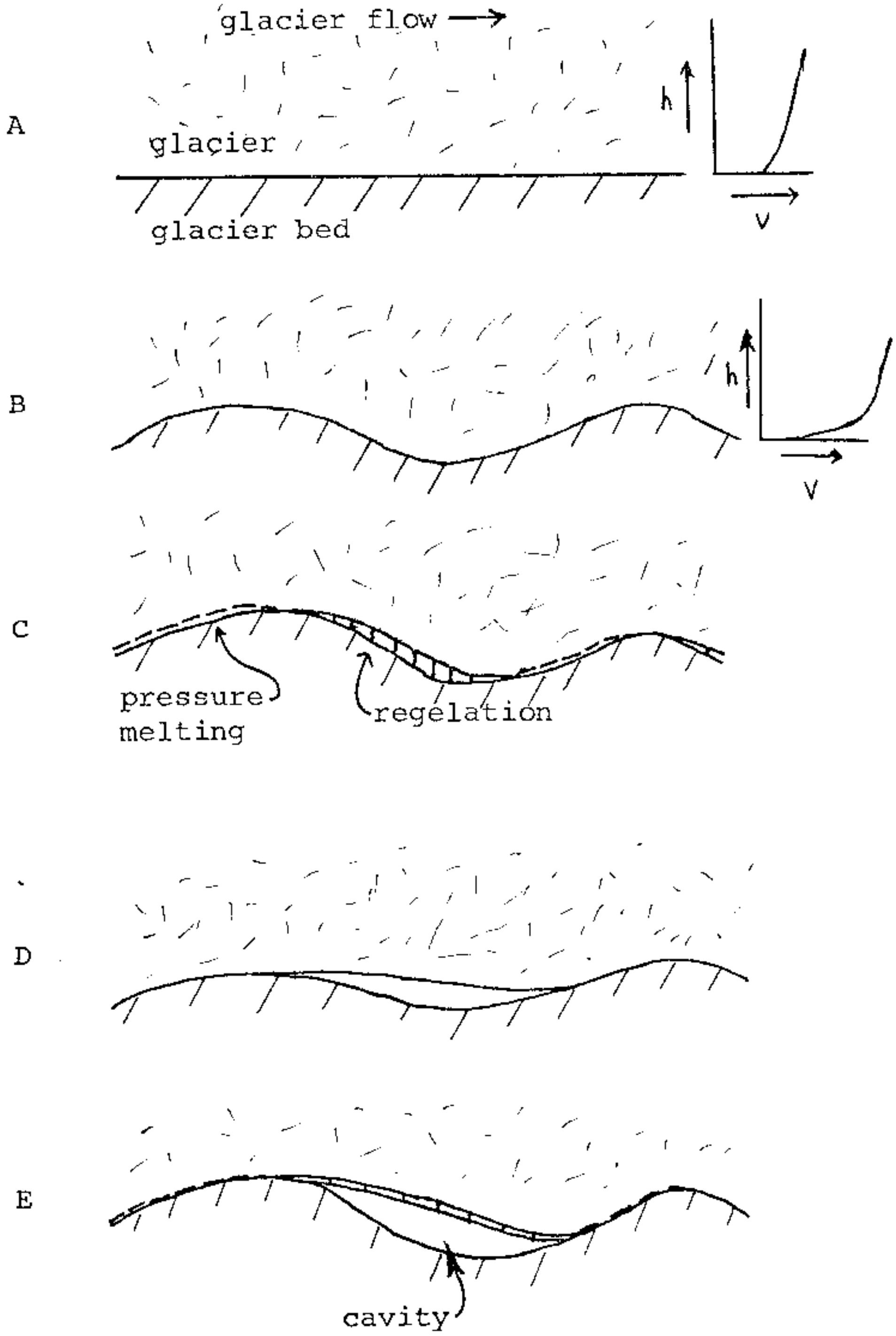

Figure 10. Diagrammatic portrayal of subglacial processes. h=height above base, v=velocity. A) basal sliding with minor plastic flow. B) enhanced plastic flow. C) pressure melting and regelation. D) cavitation with plastic flow. E) cavitation with pressure melting and regelation. Subglacial cavities are probably water filled (see text).

(Lliboutry, 1968) possibly due to the lower strain rates associated with reduced thickness (Paterson, 1969, p.123), and to lower temperatures.

Geological consequences of these processes are discussed below.

3.1.3. Thermal Properties

A) Glacier Classification

The broad classification of glaciers used by many workers includes cold (or polar) glaciers which are below the pressure melting point, and temperate glaciers which are at the pressure melting point (fig. 11). However, it is now well known that the same glacier may be temperate and cold in different parts (fig. 12). The great influence of conditions at the base of the glacier, rather than within the glacier led Carey and Ahmed (1961) to formulate a classification related to whether the base of the glacier is at, or below the pressure melting point. Glaciers whose base is at the pressure melting point are wet-based, while those whose base is below it are dry-based. As discussed above, the thermal properties strongly influence the kind of processes occurring at the glacier base.

It is apparent that the climate, including temperature, amount and kind of accumulation, rate of ablation, and many other factors determine the thermal regime of a glacier.

B) Sources of Heat

External heat is supplied to the base of the glacier by the normal geothermal heat flux, which may melt about 6 mm of ice a year (Paterson, 1969, p.126). The amount of external heat supplied to the upper surface of the glacier depends on the climate and position on the glacier and is thus very variable, but seasonal effects do not generally extend deeper

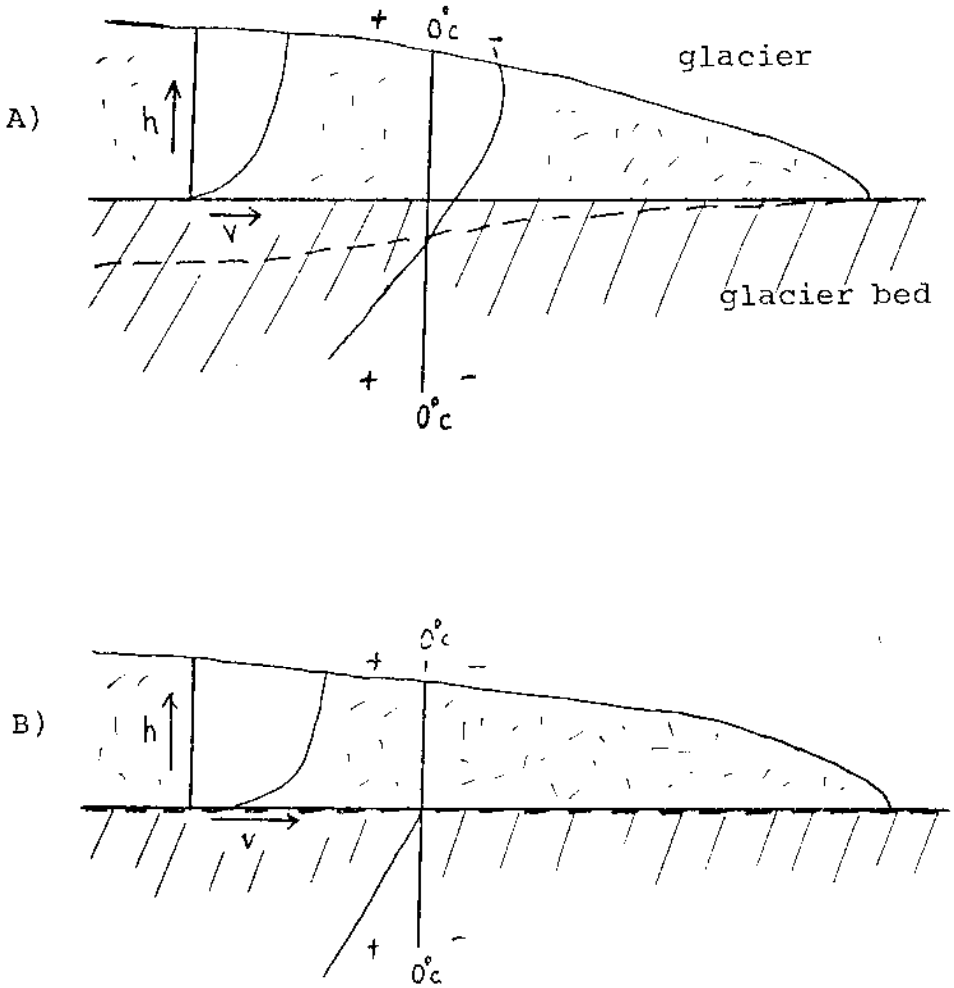

Figure 11. Velocity and temperature profiles through A) a dry-based coldglacier, and B) a wet-based temperate glacier. Dashed line is the pressure-melting point surface, and h=height above glacier base, v=velocity

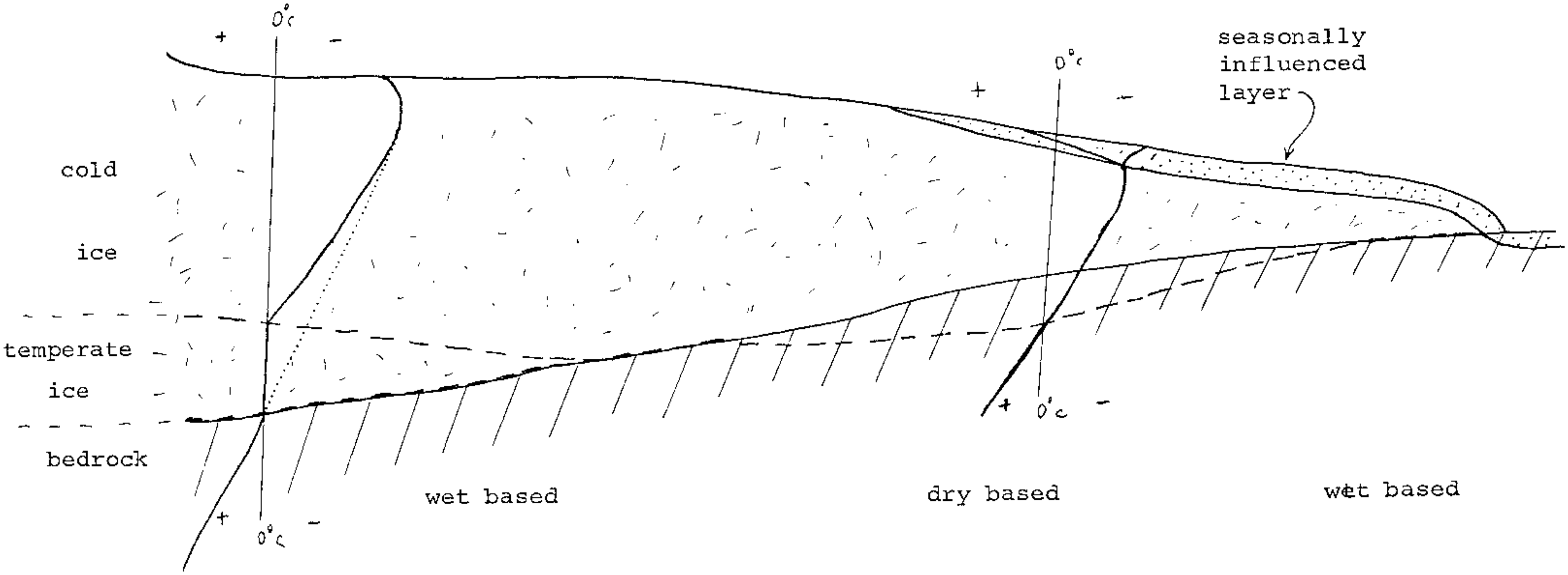

Figure 12. Profile through an ice sheet consisting of temperate and cold ice, and wet and dry based. (dynamic state). Steady state conditions shown by dotted line for which water would only occur at the base of the ice sheet.

than about 20 m (Paterson, 1969, p.170).

Internal heat is generated by sliding and plastic flow. Sliding may add as much heat as geothermal heat (Paterson, 1969, p.126), and internal flow may melt up to several cm a year (Lliboutry, 1968, p.53).

C) Heat Transfer

A dry-based glacier can conduct heat away as fast as it is generated. This heat is removed by the normal flow of the glacier which replenishes warm ice with newer, cold ice, and by heat conduction through the ice. The former process is demonstrated by the temperature reversals observed near the top of the Greenland Ice Cap (Weertman, 1968).

In addition to the above methods, a wet-based glacier removes heat by the melting of ice. The amount of heat removed depends on the amount of ice melted and the latent heat of fusion for ice. Heat is also removed by the draining away of meltwater.

The variation in melting point with pressure is about $1^{o}C/1,000$ m ice. A thick accumulation of ice will have a lowered melting point at the base. This is probably of little significance in determining the thermal regime of the glacier considering the large amounts of heat which are in transfer in a glacier.

3.2. Some Sedimentary Processes and Products of a Continental Glaciation

3.2.1. Introduction

The glaciation of a continental area includes both terrestrial and shallow marine environments, and as will be discussed below, the conditions of sedimentation may vary widely and rapidly. The following discussion adheres to the common subdivisions of glacial environments made by geologists of the Pleistocene and Recent. The glacial environment refers to the zone of active glacier ice and those areas where sediments are formed directly from it. The proglacial environment is at the snout of a glacier and in terrestrial conditions is dominated by the activity of meltwaters which maintain fluvial and lacustrine subenvironments. Buried stagnant ice is often present in this zone. In marine conditions the area adjacent to the glacier is influenced, or dominated by increased salinity, stronger currents, increased density, and other factors. The periglacial environment is the area influenced by the distinctive climatic zone adjacent to an ice sheet.

3.2.2. The Glacial Environment

A) Introduction

The glacial environment is subdivided into three major zones: subglacial, englacial, and supraglacial.

Subglacial refers to the lower part of the glacier which is influenced by contact with the bed. Cavitation, regelation, and other subglacial processes may occur.

Englacial refers to the interior part of the glacier which is not affected by the bed, nor by seasonal changes which occur at the upper surface.

Supraglacial refers to the upper part of the surface where there is strong seasonal influence. This zone is most important in the ablation area where deposition of till may occur.

Most of the processes occurring in a glacier may take place under conditions of net deposition, erosion, or neither, (transport rate decreasing, increasing, or unchanging along the flow path) and thus aspects of glacial processes, and the change in transport rate with distance may be considered as separate problems.

B) The Subglacial Environment

Ground moraine is the till which is deposited below the glacier and is relatively free of interstitial ice. Till formed by the accumulation of individual particles beneath an active glacier is termed lodgement till. The product of the melting of stagnant ice is called melt-out till (Boulton, 1970b). Subglacial deposition can occur by the raising of the ice-till interface under conditions of net melting, or by the stagnation of blocks of debris, or debris-laden ice which in this context form melt-out till.

Subglacial deformation of unconsolidated material by an overriding glacier may further consolidate that material (e.g. Sangrey, 1970), or deform it (e.g. Slater, 1927).

Dry-Based Glacier

As the dry-based glacier is frozen to its base, basal sliding, cavitation, pressure melting, and regelation do not occur.

The fact that the glacier is frozen to its bed suggests that it may exert tremendous shear stresses on the bed, plucking out any loose material (see Mercer, 1971). Furthermore, debris entrained in the rapidly flowing basal layer may gouge and striate the bed.

If net melting is accepted as a criteria for glacial deposition then it would seem unlikely that deposition could occur in a permanently dry-based glacier.

Beneath a dry-based glacier the pressure-melting point lies within the substrate. Above the point the bed is frozen. If the shear stress at the bed-glacier contact is greater than that in the substrate at the pressure-melting point, and if the glacier is under conditions of compressive stress, then upthrusting of the substrate may occur (Boulton, 1970a, p.223) (fig. 13). The material may undergo little deformation while being upthrust, but would deform after healing of the fault, due to normal laminar flow.

Such a process might cause considerable amounts of erosion beneath a dry-based glacier flowing over an unconsolidated bed. In this case net addition of water is not required for erosion as fresh glacier ice is continually replenished by glacier flow.

Wet-Based Glacier

Basal slip, whether over bedrock or unconsolidated material (Westgate, 1968) causes entrained particles to striate and gouge the bed. In this way, striated and facetted clasts may also form.

Regelation in the lee of obstacles on the bed is an important agent of glacial erosion for wet-based glaciers (Boulton, 1970a). Boulton refers to the glaciers he studied as polar (cold), and while the bulk of the glacier may be polar in the ablation zone, it is the thermal regime at the base which is here considered to be of greatest importance. The lower layers of the glacier which have been added to by regelation have debris bands.

As with dry-based glaciers, upthrusting can occur where a longitudinal compressive stress is developed. This could happen 1) behind a large end moraine or block of stagnant ice, 2) where there is a decrease in slope in the downstream direction, and 3) where the ice is frozen to the bed in a downstream direction. The result of thrusting would be

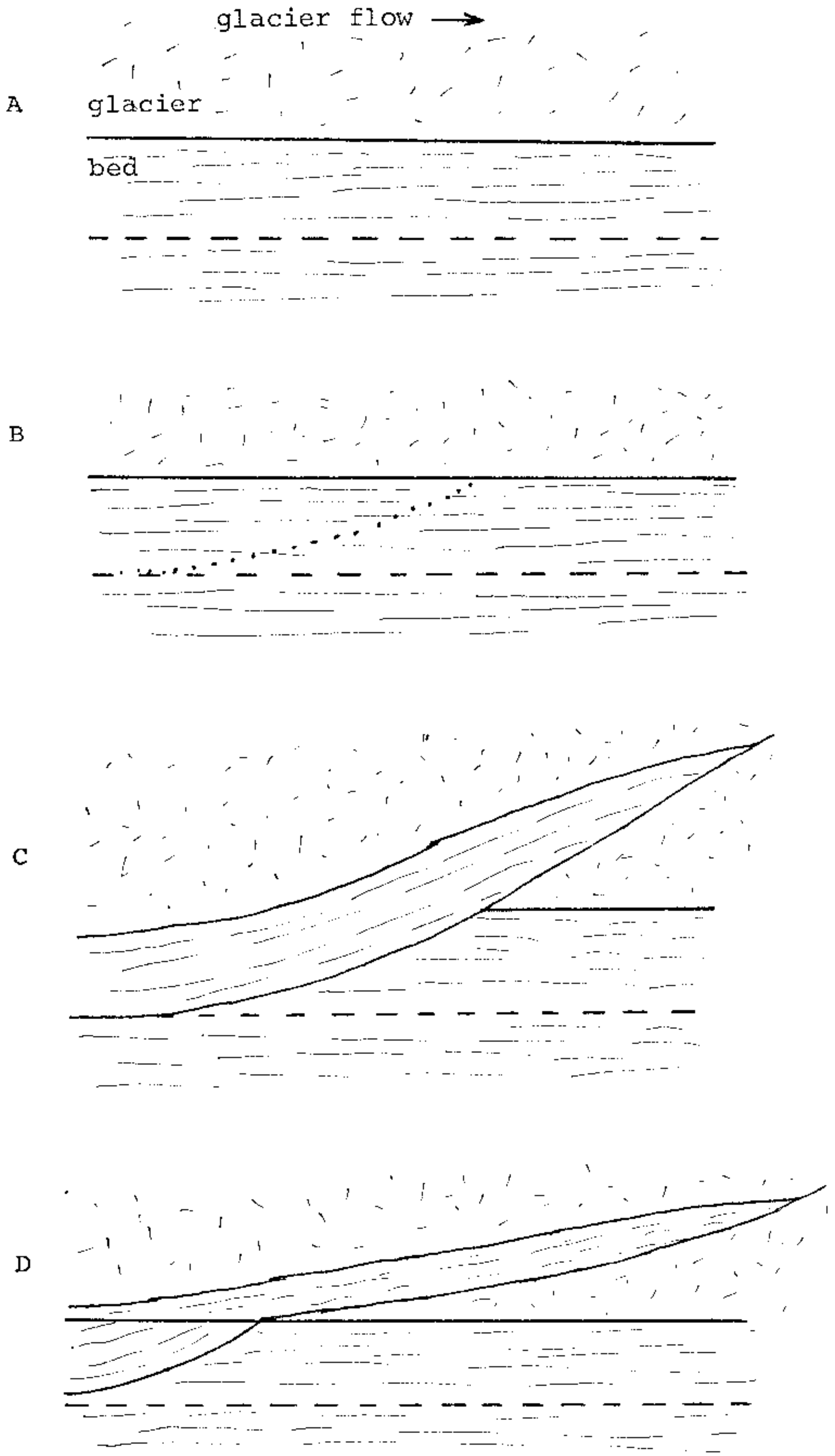

Figure 13. Upthrusting of the bed of a dry-based glacier. A) initial state, B) formation of incipient thrust, C) upthrusting, D) return to normal laminar flow, deforming the upthrust sediment. Dashed line is the pressure-melting point surface.

similar to that depicted for a dry-based glacier.

Fluctuations in ice movement may cause local pressure changes resulting in alternations of melting and freezing at the base of a glacier (Shumskii, 1964, p.355). This might cause frost weathering in the substrate and thus contribute to the rate of subglacial erosion. This process is probably important for glaciers which are thermally balanced between dry- and wet-based, and also where the substrate is too hard to be readily eroded by the other processes described.

Water-filled cavities on subglacial streams may also be sites of deposition beneath wet-based glaciers, forming sorted and stratified deposits. The interconnection of subglacial cavities (Lliboutry, 1968, p.55) suggests that the water flowing, in some cases via moulins into subglacial streams, constitutes a permanent but changing subglacial drainage net. Such streams are at least partially responsible for the widely distributed esker deposits (Charlesworth, 1957, referred to as osar). It is doubtful that the seepage mechanism described by Carey and Ahmed (1961, p.882) is an important process of subglacial stream formation.

C) The Englacial Environment

Laminar flow, and thrusting and folding may occur within an ice sheet. The melting of large blocks of stagnant ice may result in the preservation of englacial features in a melt-out till. However, in the absence of the structures diagnostic of a subglacial origin, it is difficult to see how an englacial, as opposed to a subglacial origin for the till could be determined.

Although englacial streams are known, it is unlikely that these would be associated with debris, and consequently would have little influence on sediment deposition.

D) The Supraglacial Environment

Supraglacial deposition is important in forming end moraines behind rapidly ablating, retreating and stationary glaciers (see Boulton, 1967, 1968). Lateral and medial moraines are important in valley glaciers, but are uncommon in ice sheets.

Debris is brought to the surface of the glacier in thrusts (discussed above), by the ablation of debris bands, and by the squeezing up of saturated till through fissures (Clapperton, 1971; Price, 1969). The supraglacial accumulation may be stable, but often it responds to the sloping surface in the proglacial zone by flowing into topographic lows where the flow tills may become intercalated with lacustrine and fluvial sediments (fig. 14). Such flows may take place over slopes as little as 1-2°, and move very rapidly, or move gently downslope as a thick, viscous sheet (Boulton, 1968, p.398-9).

Alternatively, till remaining directly on the glacier surface or on stagnant ice may come to rest directly on ground moraine as the intervening ice melts.

3.2.3. The Proglacial Environment

A) Introduction

The terrestrial proglacial zone is dominated by aqueous processes, both fluvial and lacustrine, and also by melting of buried, stagnant ice (see West, 1968). All of these features occur locally, unlike ground moraine which may have a wide distribution. Little is known about marine glacial environments.

B) Fluvial Environment

Rivers supplied by glacial meltwater, construct the outwash plains that frequently fringe glaciers and ice sheets. The channel pattern is typically braided (e.g. Fahnstock, 1963), probably because of a combination of factors, such

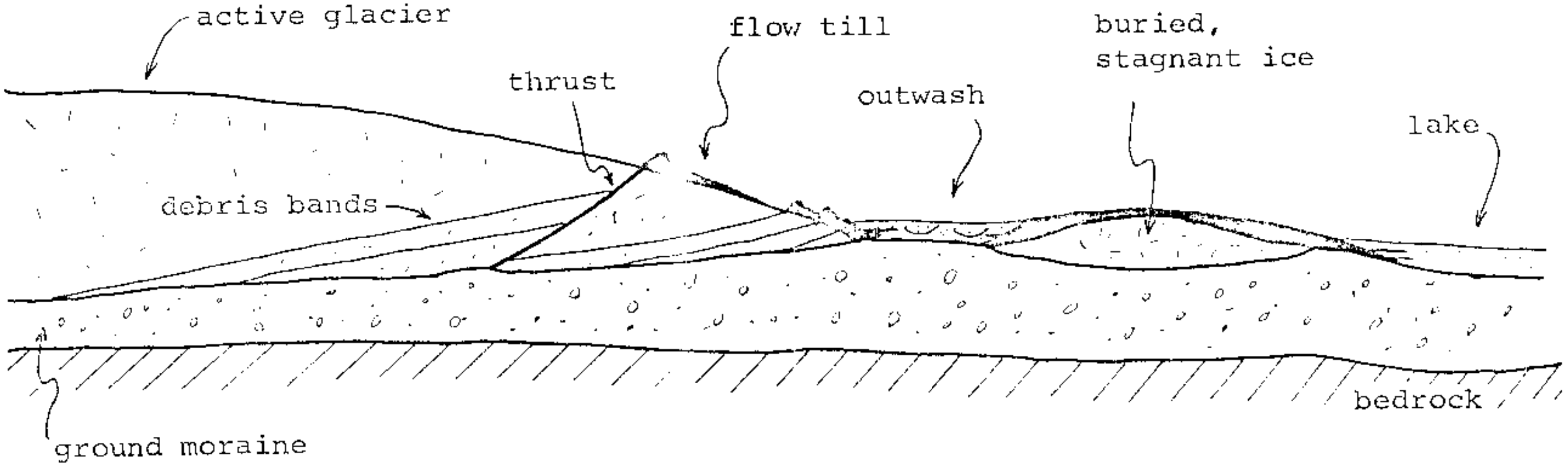

Figure 14. The formation of supraglacial flow till by the ablation of debris bands and the upthrsuting of debris rich ice. (modified from Boulton, 1967, 1970a).

as the coarse load derived from the winnowing of till, the variable discharge associated with seasonal climatic changes and the short term variation in summer weather (Williams and Rust, 1969, p.649), and relatively high slopes.

Braided stream deposits are stratified gravels and sands with channel structures on many scales, and a wide variety of stratification types. Channel deposits form the bulk of the deposit, and fining upward sequences are poorly developed (Doeglas, 1962; Williams and Rust, 1969; Smith, 1970; fluvial sedimentation is discussed at greater length in chapter 8).

Compositionally, outwash deposits resemble the till from which they were derived, and hence tend to include locally derived material (Gillberg, 1968).

C) Lacustrine Environment

Lakes commonly form adjacent to the glacier margin. Small lakes may form within topographic depressions in a hummocky moraine. Larger lakes may occur behind prominent end moraines, or in abandoned bedrock basins, but probably the most extensive lakes form when an ice sheet is retreating from a watershed and blocking the normal drainage outlets. Such a lake is temporary; with further retreat of the ice outlets of successively lower elevation are uncovered, and the lake drains (e.g. McDonald, 1969).

Deltas

Deltas form where meltwater streams enter lakes. These deposits typically contain large-scale foreset stratification (e.g. Scott, 1971). The height of these sets is variable, depending on the depth of water into which the delta is prograding. Sorting is usually poor, with sand, gravel and clay included.

Quiet Water

In quiet water, varving is the distinctive feature of glacial lacustrine sediment. Such lakes may be bounded by a glacier, or ice sheet, or may simply be fed by glacial meltwater streams. Varves are annual deposits, consisting of a coarse summer layer and a fine winter layer.

Lacustrine varves show a sharp alternation between coarser (sand or silt) and finer (clay) layers. The beds of each grade are relatively well sorted, although there may be a considerable amount of clay in the coarse layer. These varves were termed diatactic by Sauramo (1923, p.78). As the source of sediment is approached there is a rapid increase in grain size and varve thickness (Sauramo, 1923, p.77, 95). As discussed by Latjai (1967), a bottomflow origin for varves was advocated by De Geer (1912), and later by Kuenen (1951). Antevs (1951) believed that transport took place in the upper water layers.

Density underflows in Lake Mead originating from the Colorado River have only slightly greater density than the lake water (Smith et al., 1960), suggesting that only a small density difference is required to form a well-defined density current.

Considering the thickness of most varves, (less than several cm), they must be deposited at very low rates of sedimentation. This could be caused by suspensions with a very low concentration of sediment, and low velocities. (The Lake Mead underflows average about 15 cm/s (Smith et al., 1960)). As pointed out by Latjai (1967), based on experiments by Kuenen and Menard (1952), a current with a continuous supply of sediment will not deposit a graded bed.

Thus, lacustrine varves, typically non-graded, and presumably having the coarse layer deposited during the melt season, and the fine layer falling out of suspension during the winter, are adequately explained by a slowly moving low density underflow. This is further supported by the presence of faint parallel lamination which is produced by short-term variations in the input of summer sediment (Latjai, 1967). Graded beds are more likely to be formed rapidly by the action of discrete turbidity currents.

Stratification of lake deposits may also be influenced by currents not controlled by density such as wind generated currents, and wave oscillation (see Sauramo, 1923, p.105-107, and fig. 5), which may produce ripple lamination.

In addition, ice-rafted particles depress and occasionally tear the underlying laminae and are conformably overlain by successive laminations forming "plomp-and-drape" structures. The structure may indicate the release of material from melting icebergs or an ice shelf, or from the melting of wind-blown shore ice.

D) Marine

The ideas set forth by Carey and Ahmed (1961) have influenced recent work concerning ancient glaciations (e.g. Reading and Walker, 1966; Casshyap, 1969; Lindsey, 1971). Carey and Ahmed (1961) considered the differences in sedimentation between the ice shelves developed by wet-based and dry-based glaciers. The wet-based glacier forms an ice shelf that deposits few erratics, but develops submarine slumps and turbidity currents (fig. 15). A shelf formed by a dry-based glacier drops many erratics in the outer zone where melting occurs, and forms dense brines in the inner zone where sea water freezes onto the base of the ice shelf. The brines, denser than normal sea water, sink and may form carbonates and sulphates.

Where ice shelves do not form, the environment may be dominated by rafting, the deposition of varves, or by the deposition of normal marine sediments. Deposits attributed to iceberg rafting in a marine environment are laminated and contain various erratics including clots of till which depress the lamination and are covered by succeeding lamination, and local concentrations of coarse sediment

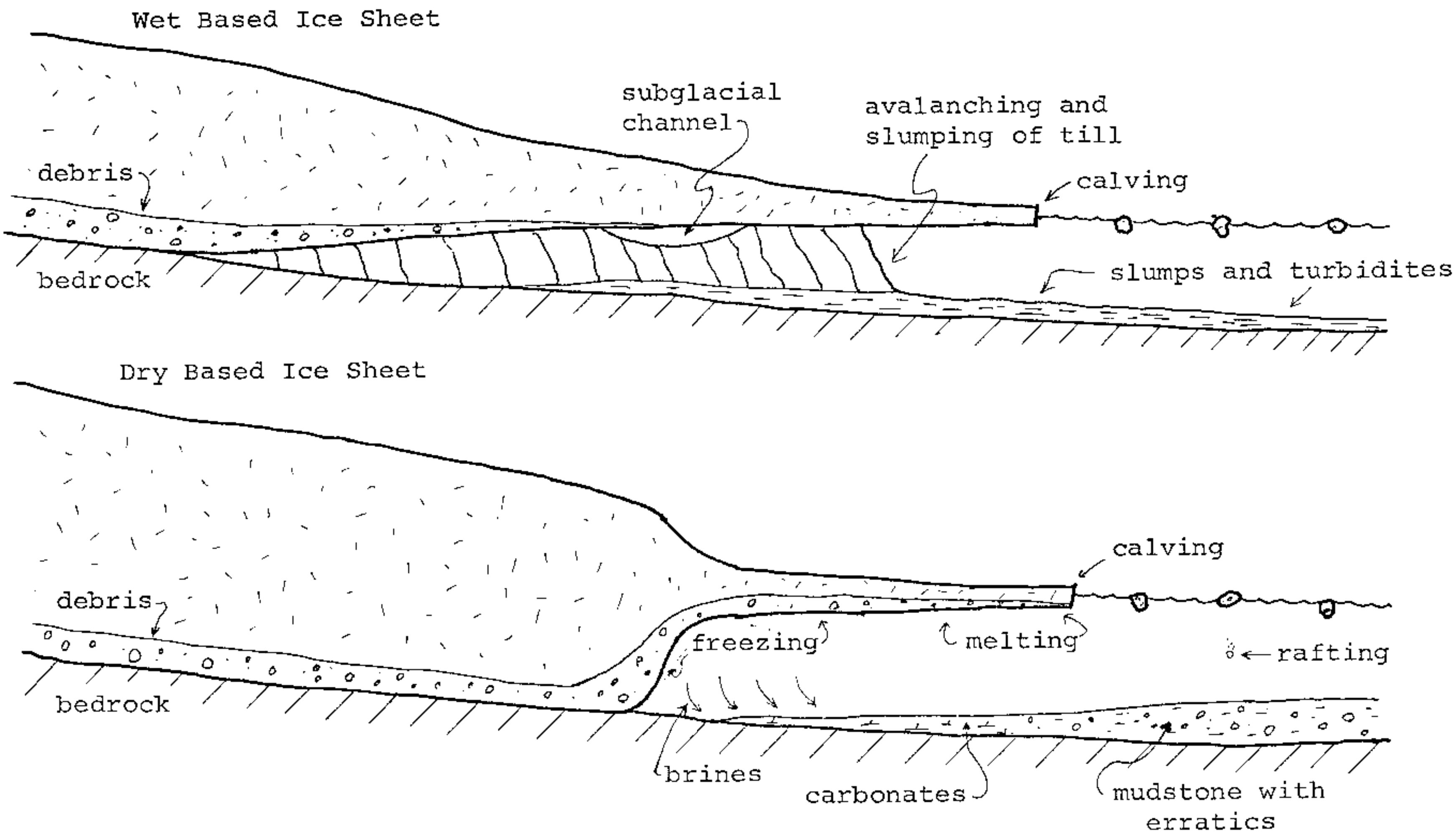

Figure 15 . Sedimentary processes and products in a shelf-type marine proglacial zone. (modified from Carey and Ahmed, 1961).

which may form when icebergs suddenly turn over (Ovenshine, 1970).

According to Reading and Walker (1966) where iceberg distribution is controlled by the presence or absence of pack ice, periods of rafting (summer) would alternate with periods of non-rafting (winter) so that a laminated sediment would result. Such a mechanism could form bedding planes rich in clasts. However, weak currents seem, to the present author, a more likely explanation for fine parallel lamination. In contrast, where rafting is from land-supplied ice, i.e. an ice shelf, deposition would be continuous, and the resultant sediment would be massive. The preservation of the massive structure would require the complete absence of currents capable of transporting clay or fine silt. Such quiet conditions may exist beneath an ice shelf, but the shelf bottom profile and the presence of a fauna beneath the Ross Ice Shelf (Zumberge and Swithinbank, 1962) suggest that at least some currents are present there.

Marine varves differ from lacustrine ones. Salts in sea water cause the flocculation of clays which then fall out of suspension relatively rapidly and become mixed with the coarser component of the suspension. These were termed <u>symmict</u> by Sauramo (1923, p.82). Varves would be preserved only in a quiet marine environment, and such an area could grade laterally into an active marine environment where waves and currents are important in reworking and grading the bottom. Scattered dropstones are all that might remain of a glacial influence in such conditions.

Shore ice, transported by winds and currents may carry debris into offshore areas (Pelletier, 1968).

In conclusion, we may quote Lindsey (1971) "the true distribution of facies, especially with regard to sedimentary structures is largely unknown in modern glacial marine environments; hence correlation between ancient glacial marine deposits and modern deposits is nearly impossible".

3.2.4. The Periglacial Environment

Deposits of the periglacial zone are formed by two main processes: wind activity, and freeze-and-thaw (see West, 1968).

Winds which blow outward from a continental ice sheet deflate and sort the marginal unfrozen sediments, mainly outwash, and deposit silt grade material called loess (see Smalley, 1966). Near the source it may accumulate in sheets up to 20 m thick (West, 1968, p.65). Wind blown fines abrade and polish pebbles into ventifacts. The formation of loess is related to the presence of available material, especially silt, and to continental conditions providing the appropriate climate (West, 1968).

Freeze-and-thaw is important in causing solifluction (mass flow), and deformation, such as involution, polygons, and ice-wedges (see West, 1968). A further effect is the rotation of the long axes of stones into a vertical position. Several periglacial features are often found together (e.g. Westgate and Bayrock, 1964).

In Siberia, the maximum depth of the active freeze-and-thaw layer is about 4 m (see West, 1968, p.71).

3.3. Tillite, Its Description and Genesis

3.3.1 Definition and Scope

Till is an unsorted, or poorly sorted deposit of glaciers. It includes the direct deposits of the glacier (e.g. ground moraine), as well as remobilised till on the glacier and in the proglacial zone (e.g. flow tills, see Hartshorn, 1968). Tills may be resedimented a considerable distance from the original sites of deposition, away from the glacial and proglacial zones, where they may finally come to rest amongst non-glacial deposits. Such resedimented deposits have been referred to genetically as mass-flow deposits, tilloids, etc. These sediments and tills are both included in the descriptive term diamictite (Flint *et al*. 1960) which refers to poorly sorted sediments with a wide range of grain sizes. The use of the term tillite for the diamictites of Finnmark is justified by their interpretation as glacial deposits. The evidence for this interpretation is presented in Chapters 4, 5 and 7.

Because this study concerns lithified tills, many standard features of tills, recorded by geologists of the Pleistocene and Recent, could not be determined. These include: 1) an accurate determination of the grain size distribution, 2) composition of the tillite according to size grade, 3) heavy mineral analysis, 4) clay mineral analysis, 5) strength, and 6) porosity and other features described by Scott and St. Onge (1969). The features which can be used to describe the Finnmark tillites are those obvious in the field, polished specimens and thin sections. They are described below.

3.3.2 Description and Genesis of Selected Features of Tillites

Colour

Within the Smalfjord and Mortensnes Tillite Formation there is a considerable, and striking variation in colour. It was deemed sufficient to describe the colour subjectively in the field. In general, the weathering colour was considered to be more important for field recognition of units, but ordinarily both the fresh and weathering colours were recorded.

In most cases the colours reflect the primary composition of the tillite. For example, at sedimentary contacts the contrasting colours of two tills glacially sheared together are retained. Only along Varangerfjord in the Mortensnes Tillite are apparent diagenetic changes seen where masses of green tillite are surrounded by purple tillite. A buff or brown weathering indicates the presence of dolomite dispersed in the matrix. This colour often masks the blue or green tints of the fresh rock. Weathering was not found to alter strongly the colour of rocks with little dolomite.

Clasts

Clasts are arbitrarily defined as those grains in the tillite greater than 2 mm in diameter. There is usually a clear distinction between clasts and matrix in most tillites.

Clast Concentration: This is a visual estimate of the area, on a representative exposure of tillite, covered by clasts, expressed as a percentage of the total area examined. In most cases this ranges from 1 - 60%.

Clast Composition: The composition of clasts in the Finnmark tillites falls into three groups. Depending on circumstances any group may be of local or exotic derivation.

1) Clastic sediment: Both tillite formations rest unconformably on sedimentary successions containing mostly sandstone and mudstone, with little carbonate. In many cases the sedimentary fragments in the tillite can be related to one of the underlying stratigraphic units.

2) Dolomite and Chert: Dolomite, and associated chert and partially silicified dolomite makes up a large part of the Grasdal Formation and Porsanger Dolomite Formation (see Chapter 2). These units

contain stromatolites, pisolites, micrites, and other carbonate rocks which are readily identified in the field.

3) Crystalline: This includes a wide variety of igneous and metamorphic types such as: red and grey gneiss and granite, granodiorite, quartz diorite, and greenstones (Føyn, 1937, pp. 124-131). Over most of the area crystalline clasts cannot be directly related to lithologies in the shield to the south (Føyn, 1937, pp. 129-131). However, along Varangerfjord the Mortensnes and Smalfjord Tillites contain rocks similar to those occurring on the other side of the fjord.

Locally derived clasts come from the immediately underlying strata, while exotic clasts have undergone considerable lateral transport.

Clast Size Distribution: This has been determined by a visual estimation of the average clast diameter, and of their maximum diameter of the largest clast observed.

Clast Shape Rounding and Surface: Clast shape was designated as equant or tabular, other types being less frequent. The degree of rounding was also estimated. Aspects of the clasts surface are described when facetting, striations, or polishing were observed. About a dozen striated and facetted clasts were observed in the Finnmark tillites.

Fabric: At a few suitable localities the long axis orientations of up to 75 clasts were recorded. These were taken on surfaces parallel to the regional bedding, and the local cleavage was recorded as well to determine the extent, if any, of tectonic clast rotation. These are presented in 15° classes on circular graph paper.

Regarding the development of the above features, little in the way of detailed, rigorous, quantitative treatment of the problem is known to the author. Gillberg has documented the downflow decrease in grain size for Cambro-Silurian sedimentary rocks in southern Sweden (1965). The relative amounts of different materials in the till would be a function of the area of the lithology exposed to erosion, the erodibility of the material, the rate at which the material is ground into the matrix population, and the distance of transport for each component material. This applies not only to preglacial rocks, but also to earlier proglacial deposits which may strongly influence till composition (Krumbein, 1933).

The development of an idealized glacial clast shape has been described by Von Engeln (1930), who found that the internal properties of the material are very important, as well as glacial activity. The ideal form of such a clast (Von Engeln, 1930, Wentworth, 1936a) is a flat iron, with a pentagonal outline, one pointed end, and one slightly scoured flat end. Subparallel striations are the most common, but on lateral facets the striations are directed diagonally downward towards the point. While in motion, the clast is probably orientated with respect to the direction of glacier flow as a roche moutonnee would be, the flat side downstream, and the point upstream.

Clast fabric has been utilised in many studies of Pleistocene deposits to determine glacial flow directions. The long axes are usually orientated in modes longitudinal or transverse to glacier flow, and clasts may be imbricated, dipping upstream. As to the development of clast fabric, Holmes (1941) supported a lodgement origin, Harrison (1957) favoured melting out of englacial fabrics at the base of stagnant portions of the glacier, Lindsey (1970) suggested that englacial shear domains can form both longitudinal and transverse fabrics, which could be partially modified by subglacial shear during deposition, and Andrews and Smith (1970) argued that the fabric forms by the subglacial flowage of the till after deposition, caused by the movements of the overlying glacier. Hydrostatic pressure prevents the compaction of the till. At any rate, the presence of transverse as well as longitudinal fabrics indicates that two-dimensional fabric alone cannot reveal what the palaeoflow direction was. However a modal orientation of clasts can be used to argue against an origin by ice rafting (Spencer, 1971).

Matrix

Grain Size: This was estimated in the field as to the relative proportions of sand, silt and clay. These observations were, in some cases, supplemented by thin section study.

Carbonate Content: Carbonate content, mainly dolomite, was estimated by noting the weathering colour, and the grain size of the matrix. A fine matrix was often found to be associated with a high dolomite content. This was further determined with thin section study.

The development of matrix in till is controlled by the same factors that control clast development, except where considerable amounts of winnowing take place, for example in ablation tills. Also, chemical processes may be important where the carbonate content of the debris in the glacier is high. Changes in temperature and pressure within the glacier system may result in chemical precipitation. The influence of pressure on the dissolved ion concentrations in glacial meltwaters has been suggested by Page (1971) who cited calcite deposition on the lee side, and solution on the stoss side of subglacial obstacles as examples of this effect.

Gross Attributes

Thickness: The lateral spacing of thickness measurements was controlled by the lenticularity of the unit, the degree of exposure, and the amount of time available.

The thickness of till deposited at a given point is a function of many complexly interrelated variables, some of which are: thermal regime, amount of load, rate of melting, rate of flow of the glacier, which are related to climate,bedrock geology, gradients, etc., subglacial topography which may have an important local as well as large scale effect on glacial deposition (Gillberg, 1965; Oldale and Uchupi, 1970, observations of the glaciated shelf off northeastern North America), tectonic subsidence as suggested by the extremely thick tillites in

Australia (Mawson, 1949), Scotland (Spencer, 1971), and western United States (Crittenden, 1971) and subsequent erosion. Other factors such as isostatic depression and duration of glaciation may also be important.

Contacts: The contacts of tillite units are described with much attention. Subglacial erosion may incorporate such large quantities of the substrate into the basal parts of the tillite that a deeply erosive surface may appear gradational. The nature of a basal contact is useful in interpreting the overlying tillite, as ground moraines tend to lie on erosion surfaces, while aqueous tillites may grade up from an underlying ground moraine.

Structures: The wide variety of structures observed in the tillites and closely related sediments are the basis for a descriptive-genetic classification. Whether or not this scheme can be successfully applied to tillites outside of Finnmark remains to be seen. The various types of tillite (fig. 16) are as follows:

Massive: lacking in any internal discontinuities, such as bedding or lamination, and texturally and compositionally homogenous. This is the most common variety of tillite in Finnmark, composing perhaps 3/4 of all tillite. Its occurrence above an erosive base, and other features (Chapters 4, 5 and 7) suggest that it is largely of ground moraine origin.

Heterogeneous: contains internal discontinuities and/or textural and compositional variations. There are two main kinds of heterogeneous facies:

Ghost Clast: these are clasts of tillite which weather a different colour from the enclosing tillite, but are otherwise similar in texture and composition. The structure was observed only in the thick middle member of the Mortensnes Tillite, and its possible origin is discussed there.

Layered: sheet-like, usually subhorizontal discontinuities and/or changes in composition and texture. This is intended as a descriptive term which includes two genetically contrasting

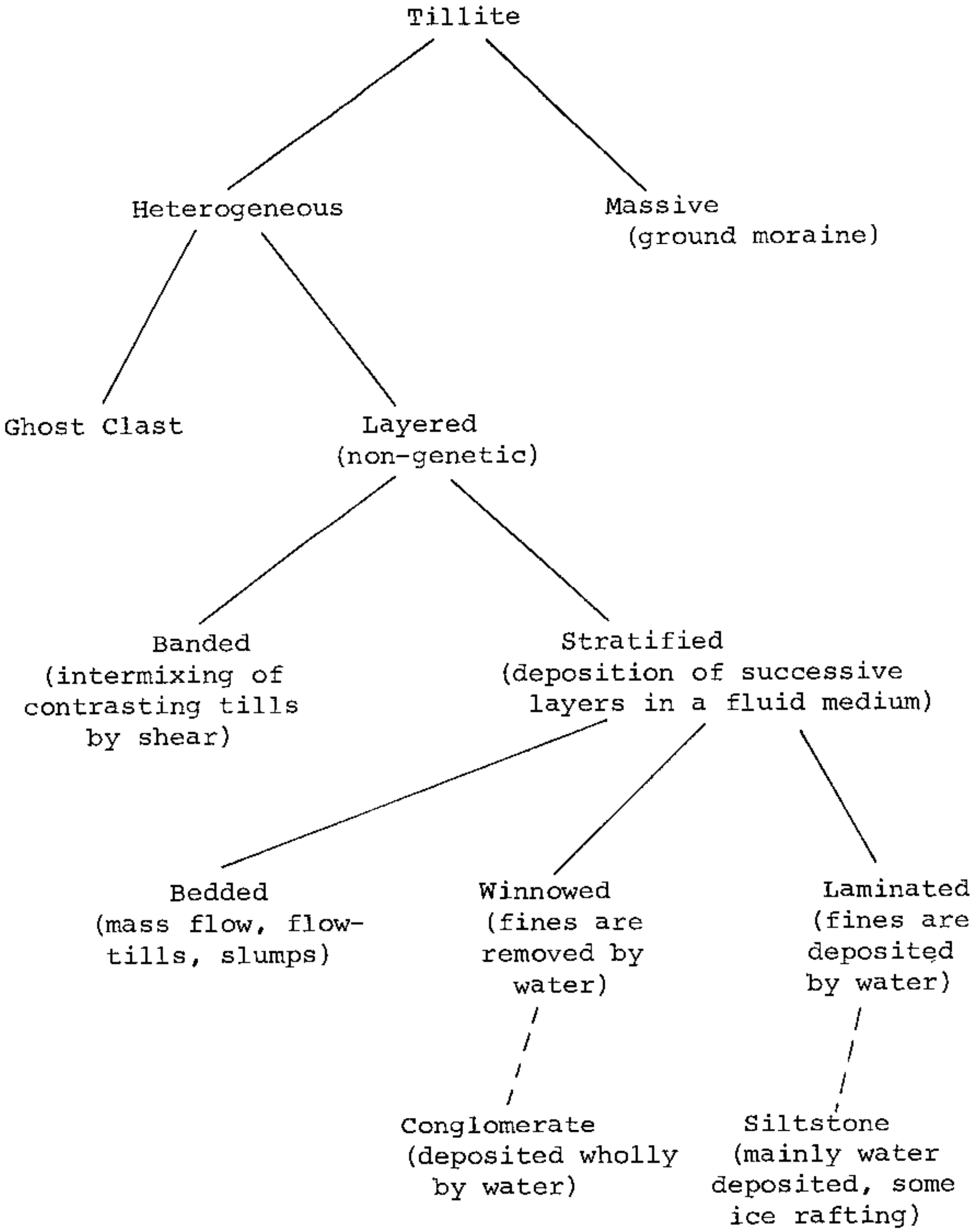

Figure 16. Structural Classification of Tillite. Suggested environments of deposition are determined from the evidence presented in Chapters 4,5 and 7.

varieties of tillite: banded and stratified.

Banded: adjacent layers composed of tillite differing in composition and/or texture. Deformation structures, particularly isoclinal folding may be prominent, while primary sedimentary structures such as cross-lamination and parallel lamination are absent. Individual bands can often be seen to die out laterally.

Three glacial processes are invoked to explain banding in tillite: 1) subglacial regelation freezes basal sediment into the glacier forming banded ice (Boulton, 1970a). It is not certain how such banding could be recognized in a tillite, but the adjacent bands might differ in texture, while having a similar composition. 2) Englacial shearing may form banding by segregating out different grain sizes so that the coarse grains are entrained in shear planes and the intervening ice contains the finer debris (Chamberlin described a similar structure in some Greenland glaciers (1894)). The resulting bands would have the same composition, but differ texturally. 3) Alternatively, englacial shearing may be associated with the mixing together of two texturally and/or compositionally contrasting debris populations, so that adjacent bands are different in either or both respects. As mechanism (1) would appear to be associated with an overall erosional regime, it would probably not be important for the deposition of till beneath an active ice sheet. Thus, banding with textural changes only, could form by mechanisms (2) or (3), while banding with both textural and compositional changes could form by mechanism (3) only. The latter type of banding is the most frequent in the Finnmark tillites.

Stratified: tillite which occurs in beds, or which contains stratification such as sorted lenses of gravel, parallel lamination and so forth. Three types of stratified tillite are recognized: bedded, winnowed and laminated. All three are attributed to deposition in a fluid medium.

Bedded: division of the tillite by bedding planes.

The beds may or may not contain other structures, or be similar in composition or texture. There is evidence in some cases of a slump origin for the tillite beds. Bedding planes are not observed between the layers in banded tillite.

Winnowed: grain supported sandstone or conglomerate, often with stratification such as bedding, cross-bedding, or lamination. Removal of part or all of the tillite matrix is attributed to current activity. There is a gradation between winnowed tillite and well sorted conglomerate and sandstone as the sorting improves due to the increasing importance of current activity.

Laminated: tillite with fine, very continuous parallel lamination. Associated primary sedimentary structures such as cross-lamination, grading, loading, and plomp-and-drape (see below) indicate subaqueous deposition and distinguish this facies from banded tillite. In addition, the laminae, which consist of mud and silt, are much better sorted than banded tillite layers. The delicate nature of the lamination and the fine grain size indicate weak currents and require that clasts which may occur in the sediment were dropped into place, probably by floating ice. Graded units closely repeated in a siltstone or mudstone are termed varves, even though the unit cannot be proven to relate to an annual cycle.

Plomp-and-drape: refers to the depressed laminae below, and the raised laminae above dropped in, outsized clasts. It is a common feature of many of the siltstones.

In addition to the above facies, deformation structures such as folds, faults and breccias are instrumental in determining the mode of origin of tillite units. These structures are described in the context of the tillite units in which they occur.