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GENESIS AND COMPOSITION OF NORWEGIAN TILLS

ILLUSTRATED BY STUDIES FROM TWO AREAS IN SOUTHEASTERN NORWAY

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DISSERTATION FOR THE DEGREE
DOCTOR PHILOSOPHIAE

Agricultural University
of Norway
1981

PREFACE

The aim of this work has been to contribute to the understanding of till composition and its relation to source material and till genesis, with particular reference to the till matrix fractions. The thesis consists of an introductory chapter followed by nine papers concerning tills in Norway. The first two papers give a general description of the Norwegian tills and a review of previously published literature on tills in Norway. The remaining seven papers present results of detailed till studies from southeastern Norway.

The work has been performed at the Department of Geology, Agricultural University of Norway (NLH) where the basic data are stored. I want to thank my geologist colleagues at NLH for their inspiring discussions and valuable critism. I also wish to express my gratitude to Grete Bloch who carried out most of the laboratory work and assisted in the field, to Åslaug Borgan who drafted the figures, to Marie-Louise Falch for typing the manuscript and to Adrian Read for correcting the English text. The field work and laboratory analyses have been sponsored by the Norwegian Research Council for Science and the Humanities (NAVF).

The studies have been greatly stimulated by the work of the INQUA Commission on genesis and lithology of Quaternary deposits in which I have taken part during the last 5 years. I want to offer my special and most cordial thanks to the President of the Commission, Professor Aleksis Dreimanis, for his enthusiasm concerning every subject dealing with tills, for his valuable and wise advice and constructive critism as referee for several of the papers included in this thesis.

Last, but most of all, I want to thank my husband, Knut, who has accepted all the work and absence from home with great patience and a good sense of humour.

Ås, June 1981

Sylvi Haldorsen

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INTRODUCTION

Till is the dominant soil type in Norway as in most other countries which were covered by ice during the last glaciation. According to Goldthwait (1971 a; 4) "till has more variations than any other sediment with a single name". The composition and genesis of tills have therefore been described and discussed in numerous papers since the middle of the 18th century, when the glacial theory was generally accepted. Such subjects are also handled in special symposium volumes (Till/A Symposium (Goldthwait 1971b); The Uppsala Symposium on till and till stratigraphy (1973); Glacial till. An interdisciplinary study (Legget 1976); Till - its genesis and diagenesis (Stankowski 1976); Till Sweden (1977) and Moraines and Varves (Schlüchter 1979)). The genesis and composition of tills have been the main topic of studies by the INQUA-Commission on genesis and lithology of Quaternary deposits. The above mentioned symposium books and the work of the INQUA-Commission have clearly borne out Goldthwait's words. Till is certainly not the same everywhere: the great variations of tills because of variable bedrock lithologies, were realized already a long time ago (e.g. Granlund 1928, Krumbein 1933). The tills formed in the marginal parts of the large ice sheets are in many cases quite different from tills formed in the central part of the ice sheet. Results of till studies from the flat areas of the USA, Canada and Europe are not necessarily representative for tills from the topographically variable areas, such as Norway. Till formation associated with recent glaciers is not always representative for the conditions in connection with the former continental ice sheets, either during their maximum or during their deglaciation phase.

This, and the lack of detailed studies of Norwegian tills, are the main reasons why the Department of Geology, Agricultural University of Norway (NLH) in 1974 started a project called "Morenejords egenskaper og dannelse".

(The characteristics and genesis of tills). This was financed by the Norwegian Research Council for Science and the Humanities (NAVF). The main purpose was to study and explain some of the most typical characteristics of the Norwegian tills. Since considerable data already existed on the lithology of the coarse till fractions (gravel, cobbles and boulders) the main interest was focused on the till matrix. The work presented here gives the main results from this project. The study has chiefly concentrated on the following two subjects:

1. The relation between the till and the bedrock. This was initially the main purpose of the project. During the period 1970-1977 this was a popular topic for till studies both in America (see Goldthwait 1971b, Slatt 1971, Mills 1977, Shilts 1977) and in Scandinavia (Lindén 1975, Svantesson 1976, Melkerud 1977, Perttunen 1977). The results from long transported and homogeneous tills, such as are found in parts of America (e.g. Dreimanis & Vagners 1971, Gross & Moran 1971), were not necessarily applicable to Norwegian conditions (see Jørgensen 1977). The most representative works published before 1970 were the earlier Swedish studies (e.g.Hörner 1946;G.Lundqvist 1940, 1951; J.Lundqvist 1952, 1958, 1969a) However, even though these gave general information about the bedrock-till relationship, in none of these included studies of the total mineralogical composition of all till fractions and information on the sand, silt and clay mineralogy was generally sparse.

2. During 1975-1980 there was increasing interest about till genesis, an interest which has been greatly stimulated by studies of till formations from recent glaciers (see Boulton 1970, 1971, 1976, 1978; Shaw 1977a, 1977b). During the last several years a genetical classification system of tills has been thoroughly discussed in the INQUA-Commission on genesis and lithology of Quaternary deposits.

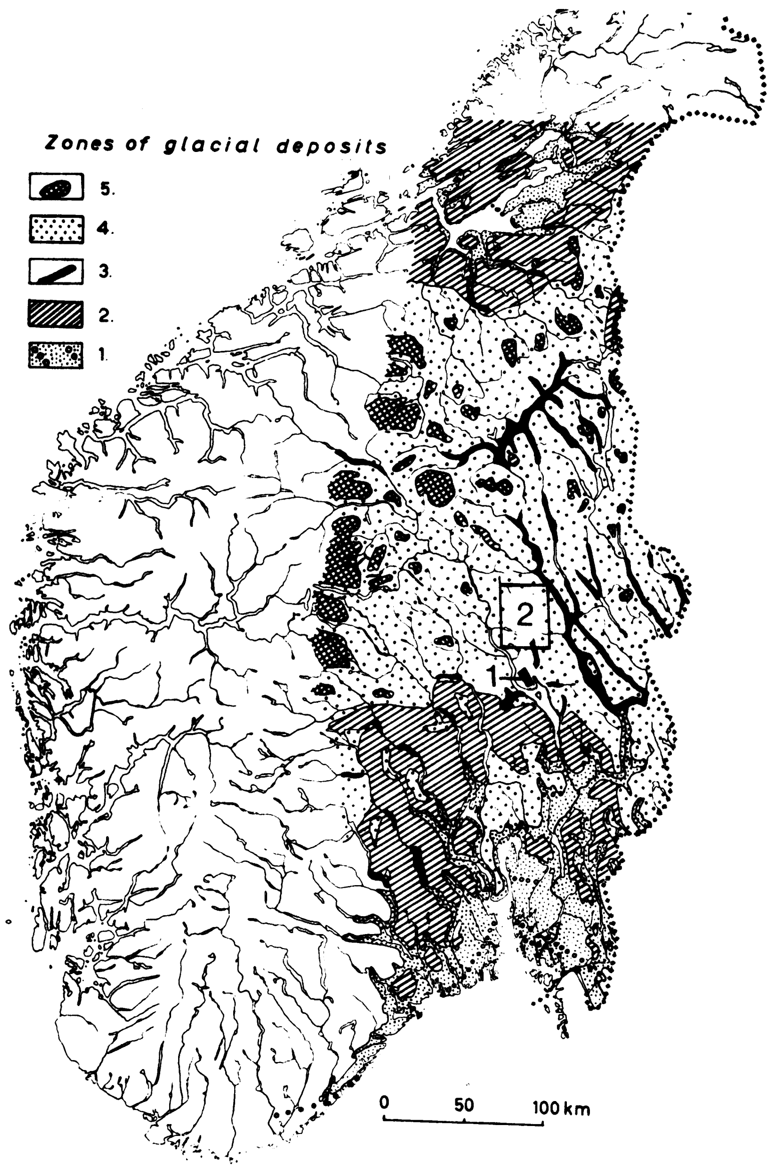

Fig.1 Map showing the zonal distribution of glacial sediments in southeastern Norway. (1) Uplifted marine sediments, including terminal moraines (2) Thin discontinuous till, chiefly ground moraine. (3) Glaciofluvial sediments and ablation drift in the valleys. (4) Dead-ice deposits on plateaus and along the ice divide. (5) Thin drift, marked by frost phenomena in mountain areas. After Holmsen (1963). The two areas considered in this present study are situated in zone (4) and are indicated by numbers 1 and 2 in the figure. Zone (4) is a zone of continuous till cover, as pointed out by Holmsen (1971).

In Norway information about till genesis has been very sparse. For a long time the tills were divided in two genetical groups; i.e. the basal till and the ablation till (see Holmsen 1934). This division is still used today, even though the Swedish works of Hoppe (1963), J.Lundqvist (1969a, 1969b) demonstrated that till genesis is much more complex. During the last three years the NAVF-project has also been concerned with the genesis of tills, where the purpose has been to give an adequate genetical classification of the tills and to study the relation between till genesis and till composition.

DESCRIPTION OF THE INVESTIGATED AREAS

Two areas from southeastern Norway were selected for detailed till investigations. Both areas are found in regions of continuous till covers (Fig.1).

1. The Nes peninsula, southern Ringsaker

The first area is located on the Nes peninsula in the district of lake Mjøsa, southeastern Norway (Fig. 2), in an area of variable bedrock. To the north there are Late Precambrian (Upper Proterozoic) sedimentary rocks, consisting mainly of sandstones with some shales and conglomerates. In the northern and southern part of the study area itself there are Cambro-Silurian limestones and shales. These Cambro-Silurian sediments are intersected by a Precambrian crystalline horst. This area was chosen for investigations of the bedrock - till relationship, with special reference to the matrix (<2mm) composition. It was found particularly suitable because:

a. The bedrock boundaries are roughly perpendicular to the previously determined directions of ice movements (see Fig. 2).

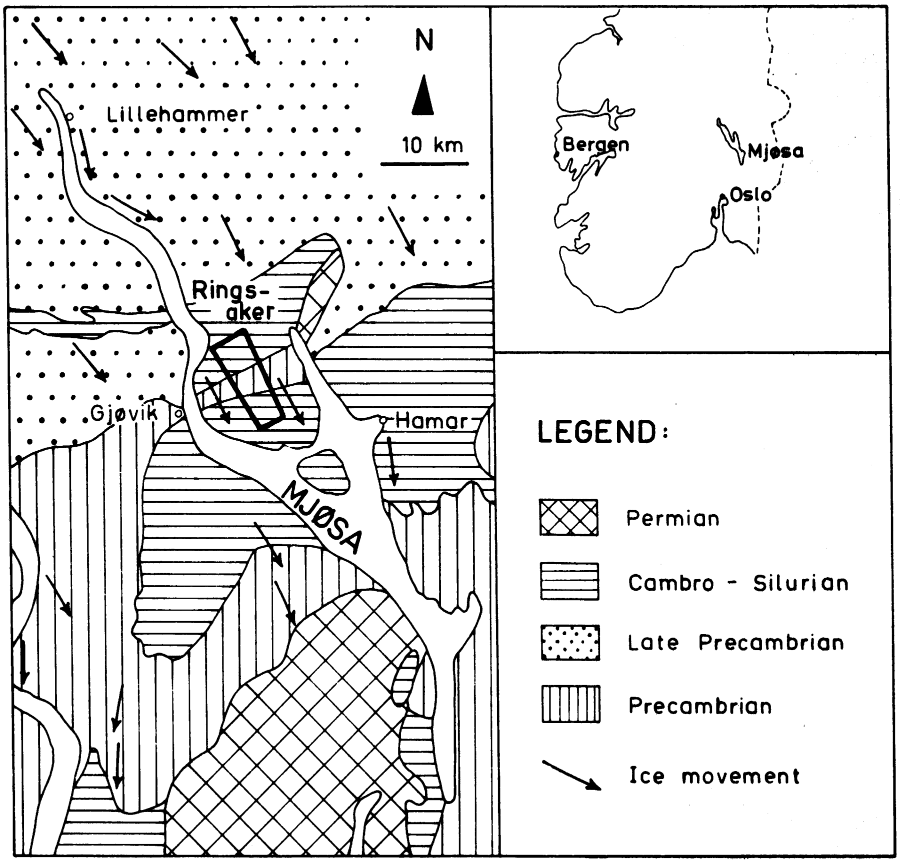

Fig.2 Simplified geological map of the Mjøsa district showing the situation of the investigated area 1.

b. There was abundant data available on the bedrock composition.

c. Till is the dominant sediment in the area and is only exceptionally overlain by other sediments. According to the traditional classification of tills in Norway the major part of the till in the area may clearly be interpreted as basal (=subglacial) till.

2. The Åstadalen area, Hedmark

The other selected area is the upper part of Åstadalen (Fig. 3). The bedrock in this area consists of Late Precambrian (Upper Proterozoic) sedimentary rocks belonging to the Brøttum Formation. The area can be divided in two according to the bedrock composition (Fig. 4). The northern part is dominated by sandstones (arkose and greywacke) which alternate with some layers of silty shale. The shale constitutes up to 5 - 10 % of the total bedrock volume. The southern part of the area consists of a rather homogeneous sandstone (arkose) with some conglomeratic horizons.

This area was chosen both for studies of the bedrock--till relationship and for studies of till genesis. The former mainly involved geochemical methods. The area was found to be particularly suitable for these studies because:

1. The southern homogeneous sandstone area gave favourable conditions for studies of till genesis and its effect on the till composition. This subject was particularly interesting because there are several genetically distinct till types in this area.

2. The close alternation of sandstones and shales made the northern part suitable for studies of the distribution of these bedrock components in the till matrix.

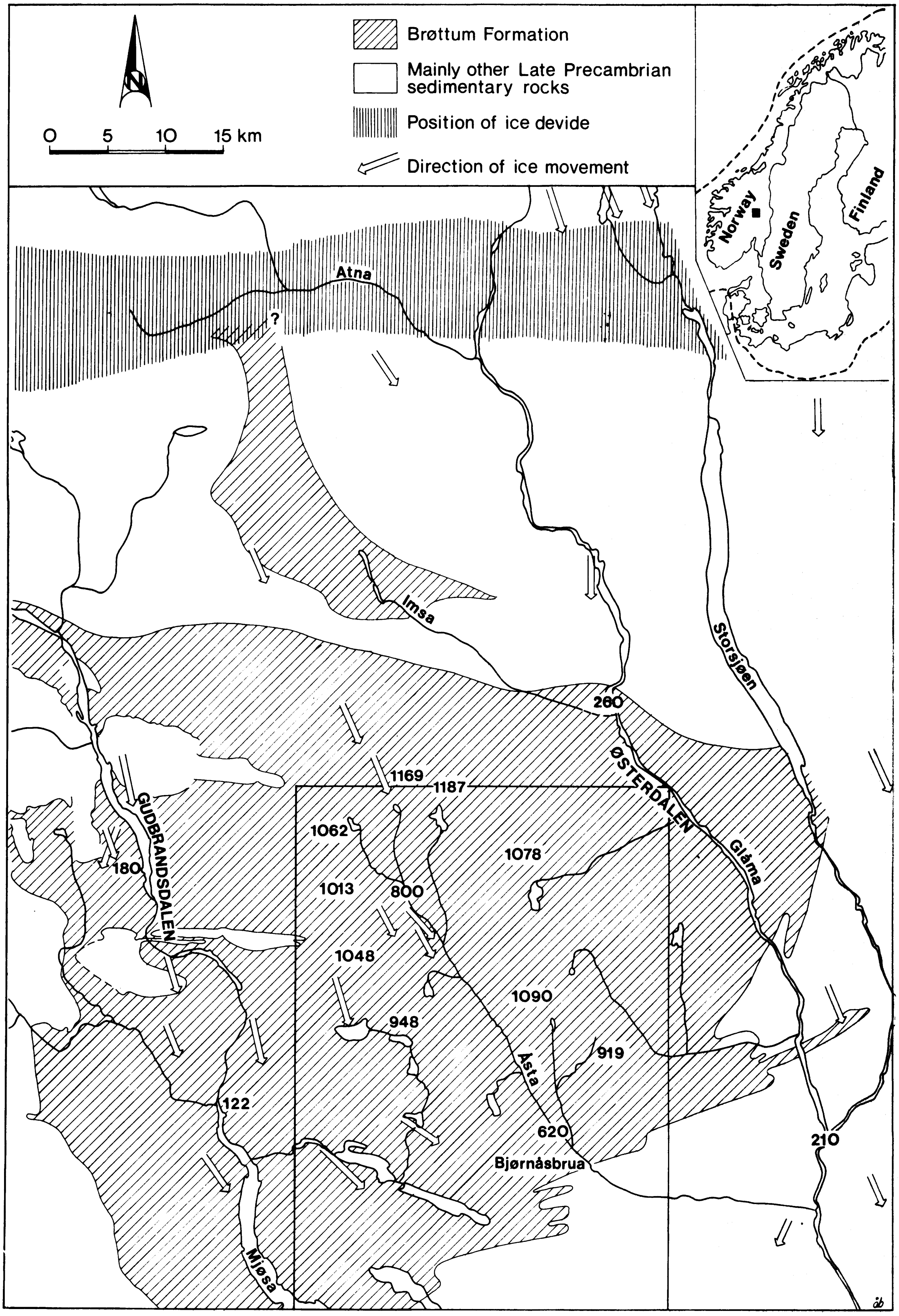

Fig.3 Keymap showing the position of the investigated area 2. Numbers give height abeve sea level in metres. The stipled line on inset map shows the maximum extension of the Weichselian ice sheet.

3: Detailed geochemical, mineralogical and structural data on the bedrock and detailed maps of the Quaternary geology were available.

4. The Åstadalen area represents an upland, relative to Gudbrandsdalen and Østerdalen. It is therefore believed to have been mainly a net erosion during the Quaternary. All previous studies of the Quaternary deposits indicated that there was one single till sheet deposited during the last glaciation.

COMMENTS ON PAPERS 1 - 9

Paper 1: Studies of tills and moraines in Norway - a historical review.

Paper 2: The characteristics and genesis of Norwegian tills.

Papers 1 and 2 are summary articles which mainly give the results from previous till studies in Norway. They may be regarded as an introduction to Papers 3 - 9.

Paper 1 gives a reviw of the papers on tills and moraines from 1824 to 1980. The literature was collected in connection with a Nordic analytical bibliography on tills and moraines. The work with this bibliography is now almost completed.

The conclusion from Paper 1 is that there are very few separate and general studies of Norwegian tills and their related morainic landforms. Most of the till descriptions form parts of studies where the main purpose has been another than to study the characteristics and genesis of just the tills. No single work gives all the most typical properties of Norwegian tills. However, several papers give valuable contributions to the understanding of Norwegian till, and together they give a picture of its most typical characteristics.

Based on such studies the characteristics of Norwegian tills are given in Paper 2. It is here pointed out that the Norwegian tills are strongly dependent on the steep

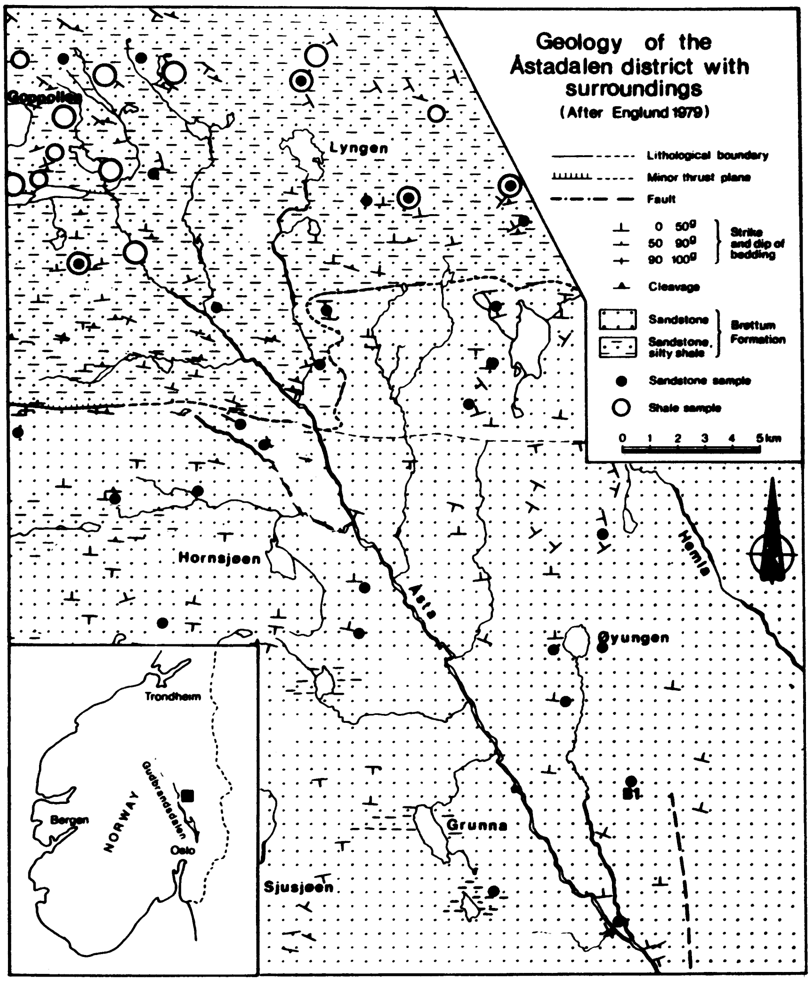

Fig.4 Bedrock geology in the Åstadalen area.

and variable topography with large mountainous areas, the resistant bedrock which dominate in most parts of Norway and the position of Norway beneath the central parts of the Scandinavian ice sheet. These factors define till provinces which are mainly characterized by small till thickness, short glacial transport and a coarse-grained texture. These are by far the most outstanding properties of Norwegian tills compared with till from the more marginal parts of the Scandinavian ice sheet.

Paper 3: The petrography of tills - a study from Ringsaker, south-eastern Norway

This paper gives the results of studies from the Nes peninsula, Ringsaker (Fig. 1). It concerns the relationship between till matrix lithology and the bedrock lithology.

Samples taken from sections along the main direction of ice movement were studied. The composition within each 1 Φ-unit of the matrix and also one part of the gravel fraction were studied. As far as I know, this is the only work published where all matrix fractions in a Norwegian till are considered in the same study.

The main conclusions from this study are the following:

1. There is a clear connection between the size-distribution of the minerals in the matrix and the properties their parent bedrock. Minerals from the clastic sedimentary rocks - both sandstones and shales, retained their primary size well during the glacial transport. This is because these rocks consist of mechanically resistant minerals. Minerals from the coarse-grained crystalline Precambrian horst rocks, on the other hand, were rapidly reduced in size during glacial transport and ended in the fine sand and silt fractions.

2. The matrix was dominantly of local origin. The main petrographical changes occurred just across the bedrock boundaries. This was most marked for the typical matrix

modes of the different rock types: For tills deposited in the Precambrian crystalline horst rock area it was the fine sand and coarse silt that was most closely related to the underlying rocks, while in the alum shale area it was the clay fraction.

3. As the components from different rocks were enriched in different matrix grades, it is difficult to charaterize the total till composition from this area by means of one or a few matrix grades.

Paper 4: Glacial comminution of mineral grains.

This paper presents the main conclusions from Paper 3, but also some other and more general aspects of the glacial comminution processes are included too. It represents a modification of the model of "terminal grades" presented by Dreimanis & Vagners (1969, 1973). They defined the "terminal grades" as the matrix modes which are the final product of the glacial comminution. Their work included a diagram showing the typical terminal grades of different minerals. The conclusion of Paper 2, however, is that it is difficult or even impossible to list particular "terminal grades" which are typical for one mineral. The same type may have modes in all fractions from clay to sand, depending on the properties of the parent rocks. This conclusion was based on the studies from Ringsaker and on general mineralogical aspects.

Paper 5: The genesis of tills from the central part of Scandinavia.

Paper 5 is concerned with the genesis of tills in Åstadalen. The traditional methods for such studies are applied: moraine morphology, boulder content and shape, gravel roundness, fabric measurements, grain-size distribution and sedimentary structures. The statistical calculations of the fabric data are based on the eigenvalue method. The eigenvalue may theoretically vary from 0 to 1 and values 0.6 indicate strong orientation of long axis.

Some data are based on the method described by Steinmetz (1962). The strength of orientation is then given by the value of R. The level of significance is dependent on the number of observations (see Watson 1956).

The main conclusions from Paper 5 are the following:

1. Till material which has traditionally been interpreted as basal (=subglacial) till forms a smooth morainic topography which I have referred to as cover moraine. This till can be divided into subglacial melt-out till and lodgement till. Compact homogenenous till with striated and abraded boulders indicates transport along the base of an active glacier. Probably this till is mainly a lodgement till, but locally the upper parts of it may be subglacial melt-out till. Coarse-grained till with angular clast material shows no signs of transport along the base of an actively sliding glacier and is therefore not to be interpreted as a lodgement till, in the way this term has been applied by for instance Boulton (1976). The deposition of such material was more likely by a passive melt-out from stagnant basal parts of the ice. It was concluded that it is more difficult to tell what is not a melt-out till than to tell what is not a lodgement till.

2. Much of the material which has traditionally been interpreted as ablation till form hummocks along the bottom of the valley. The source of this material was probably subglacial till which was secondarily transported by mass movement or water from ice-free parts of the valley side down on to the surface of the ice remnants in the valley. Other diamict sediments may have originated from supraglacially deposited fluvial material which slid or slumped down into crevasses and cavities in the ice or along the ice margin. During such movements the material became mixed and assumed a diamictic character. There is no evidence that the supraglacial sediments were originally englacial debris.

3. The complex sedimentary history of the tills and other sediments in Åstadalen illustrates how difficult it is both to classify tills by means of a rigid classification system and to distinguish between tills and other sediments. In some cases it is more valuable to describe the interpreted sedimentary history than to give the sediments a a spesific genetic name.

Paper 6: Melt-out till and the problem of recognising genetic varieties of till.

Paper 6 is written in co-operation with Prof.John Shaw, University of Alberta, Canada, who has for several years been actively studying till genesis. The first part of the paper gives a historical view of the melt-out concept. Much of our knowledge about the melt-out process relates to recent glaciers. Some observations from Omnsbreen, a rapidly retreating glacier in southern Norway are reported because they are illustrative for the melt-out process and the deposition of sorted, stratified sediments interbedded with till.

The criteria which provide evidence to support an interpretation of melt-out till are available. Any absolute proof is unrealistic. Fabric studies and stratigraphy are the most commonly used criteria. In most cases the regional relationship has to be considered too.

Based on the discussion in the first part of the paper, the ediments forming the transverse ridges in Åstadalen are discussed. At Åkerseter the till is interpreted as a melt-out till, while at Kvarstadseter both melt-out till and flow till are recognised.

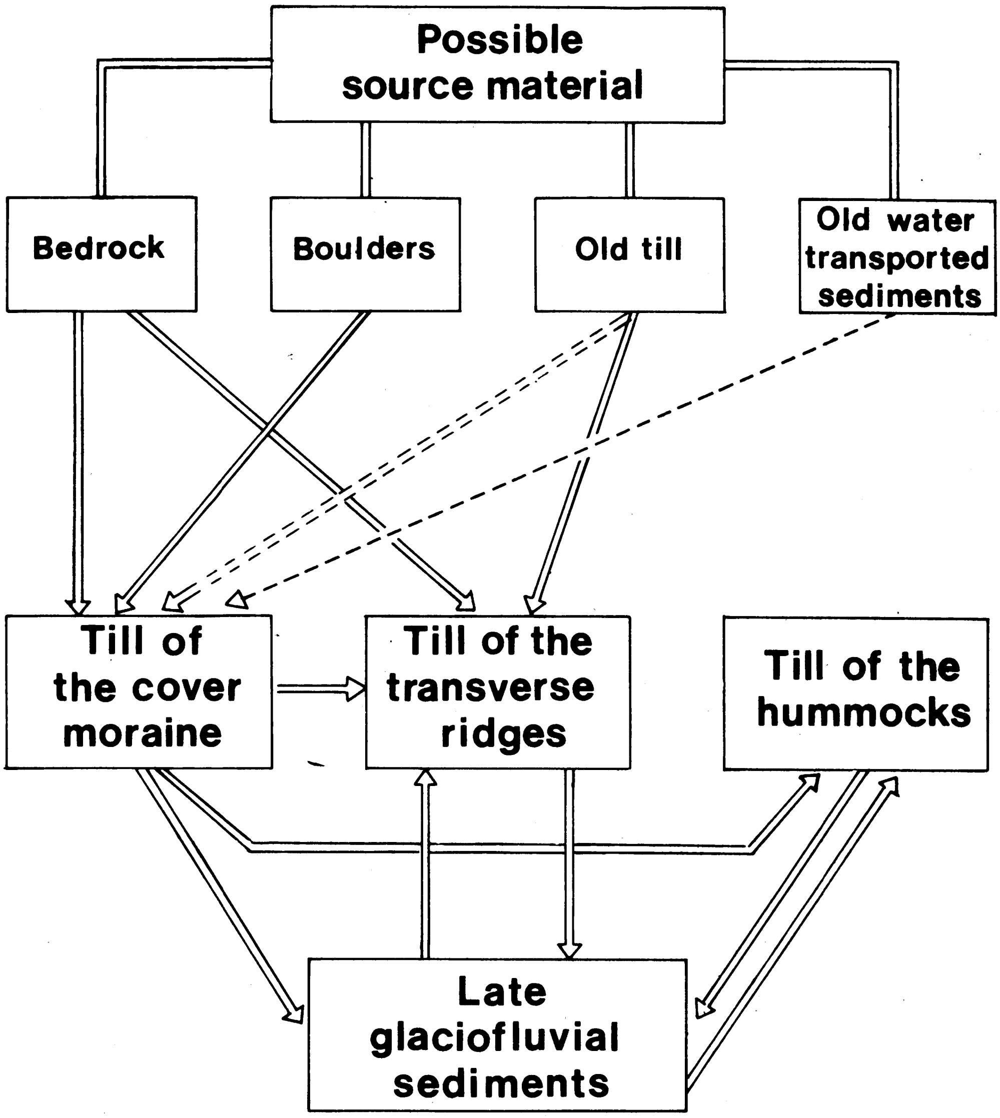

Fig.5 The supposed source materials of tills and other diamictons in Åstadalen.

Source material of tills in Åstadalen

From Paper 5 it can be concluded that the potential source materials of the tills in Åstadalen are glacially eroded bedrock, older till or other Quaternary sediments (Fig. 5). At mountain plateau and lee-side localities the till was most probably formed directly from comminution of local bedrock and boulders from the boulder fields. The till along the valley and western upland area cannot be traced back in the same way to its source area.

It is impossible to know how much old sediment is incorporated in the tills. Fine-grained silt and clay sediments have probably been unimportant since such sediments occur only locally in the valley today. There is no reason to believe that they were more abundant in an earlier ice-free phase. Other than tills, gravel-rich glaciofluvial and fluvial sediments are the dominant minerogenic sediments (Østeraas 1978). The gravel--sized material of these sediments is significantly more rounded than the gravel of the till (Paper 5, Figs. 8 & 18). Any great inclusion of such material would have been reflected by a certain amount of rounded gravel in the till. At some cover moraine localities a small component of rounded material is found in the upper 1 m of the till (Paper 5,Fig. 14) while the deeper parts of the tills does not usually contain such material. The rounded material has therefore been interpreted to result from incorporation of sediments from the deglaciation phase and not sediments from an old ice-free phase. The conclusion is, therefore, that the dominant parts of the tills from the cover moraine areas originate from the following sources: direct comminution of glacially eroded bedrock, comminution of boulders, or incorporation of older till (Fig. 5).

Also the rounded material found in parts of the transverse moraine ridges (Paper 5, Fig. 17) is believed to originate from the deglaciation phase. This is indicated at the localities where the ridges rest on a till with more angular gravel sized material. In most of the ridges the gravel material has the same degree of roundness as the gravel in the tills of the cover moraine. The source was then probably a basal drift of the same kind as that of the underlying till.

The diamictions forming the hummocks are assumed to be more influenced by redeposited material than any of the subglacial till types since they are either formed from redeposited till or from redeposited glaciofluvial sediments (Fig. 5). The degree of roundness and partly also the grain-size composition are, therefore, mainly inherited characteristics. Only the structure and fabric are totally the product of the supraglacial history.

Paper 7: Grain-size distribution of subglacial till and its relation to glacial crushing and abrasion

This is a work on the grain-size distribution of subglacial tills, illustrated by samples from Åstadalen. The samples were collected from the homogeneous sandstone area in the south (Fig. 4), outside the influence of the shale horizons which outcrop in the north. Only samples from the subglacial till forming the regular till sheet were included. The following conclusions were drawn from this work:

1. There is a close relation between the grain-size modes of the till matrix and the grain-size modes in the sandstone bedrock. This conclusion supports the ideas from Papers 3 and 4. Some artificial crushing and abrasion experiments showed that this mode was mainly the result of a crushing. If glacial abrasion was also involved, a considerably more fine-grained silt-rich material was formed, resulting in a fine-grained tail on the grain-size distribution curves. This shows that factors influencing the matrix modes for different minerals are even more complex than concluded in Papers 3 and 4.

2. Both the product of crushing (mainly sand) and the product of abrasion (mainly silt) are resistant parts of the till and may be regarded as the final products of

glacial comminution, but formed from different comminution processes.

3. The grain-size distribution of tills are in most cases complex distributions which deviate both from a Rosin-Rammler distribution and from a log-normal distribution.

4. Based on the conclusiona about glacial crushing and glacial abrasion two grain-size parameters are presented. The matrix index gives the ratio between the matrix component (material finer than 2 mm), which is rather resistant on glacial comminution, and the clast component (material coarser than 2 mm). The abrasion index gives the ratio between the resistant product of abrasion and the resistant product of crushing. Based on the conclusions from Paper 5 these two parameters differentiated well between genetically different tills of the cover moraine area.

Paper 8 Geochemistry of subglacial till matrix material

This is a paper of the geochemistry of the till matrix material in Åstadalen. Only samples from subglacial tills forming the cover moraine are included. The genetical aspects are based on the conclusions in Paper 5. The discussions and conclusions are supported by mineralogical analyses.

Till geochemistry is of importance for several areas of applied geology as for instance in agriculture, geomedicine and ore prospecting. However, in most cases such investigations are rather descriptive and very few studies give general information on the distribution of elements in tills. The investigations of paper 8 were carried out in the hope obtaining a better understanding of the distribution of the main elements. The conclusions of this work can be summarized in the following points:

1. There is a very distinct change in the chemical composition with decreasing grain-size, with a marked increase in the amounts of Al_2O_3, Fe_2O_3, MgO and K_2O. This reflects increasing content of sheet silicates and the decrease of quartz. Some artifical comminution experiments showed that the chemical composition of particular parts of the silt is very similar to that of the comminuted sandstone and comminuted shale. The difference in bulk composition therefore reflects different quantities of material within the various size grades for the two rock types. The comminuted sandstone is dominated by sand and coarse silt while the comminuted shale mainly consists of medium to fine silt. Also the tills have rather uniform chemical composition for the same fraction although, the bulk matrix composition varies with variable amounts of sandstone and shale components.

2. Simple geochemical parameters may give a quantitative estimate of the ratio between different bedrock components in the till matrix. Based on the results from fractionated samples the ratio of Al_2O_3/SiO_2 could be applied as a parameter for the ratio of sandstone and shale components in the bulk silt + clay. This ratio was shown to be dependent on both the bedrock characteristics and the genesis of the tills.

3. Within a homogeneous bedrock area the composition of the till matrix may vary depending upon the genesis of the till. In the southern uniform sandstone area, in Åstadalen glacial crushing mainly resulted in cracks along grain boundaries and each mineral type retained its original size well during glacial transport. This conclusion is supported by the studies of paper 7. Increased glacial comminution activity, mainly caused by an abrasive grinding, gave more cracks across minerals and resulted in a selective grinding of feldspars and sheet silicates compared to quartz. The result of this is that quartz mostly remained in the sand while feldspars and sheet

silicates were enriched in the silt.

4. In many previously published papers it has been suggested that elements in soils form either normal or log-normal distributions. However, a normal distribution of elements in tills can only be expected if the till was formed from a uniform source rocks and has a uniform genesis. Obviously, these requirements are only occasionally satisfied in most areas in Norway. The southern sandstone area in Åstadalen was selected for till investigations because of its uniform bedrock and smooth topography. In parts of this area where the till is dominantly of a lodgement type the distribution of the Al_2O_3/SiO_2-ratio may be approximately normal.

A log-normal distribution of elements may occur if till material from one bedrock area is transported into another bedrock area and the dilution can be described in the form of an exponential curve. This requirement may be satisfied in some parts of the Åstadalen area where till material from the northern shale/sandstone bedrock is transported towards the south and mixed with the local pure sandstone till. However, in Norway where the topography and consequently also the till genesis is so variable, the dilution will only occasionally occur in such a way. Normal or log-normal distribution of elements, or ratios of elements are therefore believed to form exceptions in Norwegian tills. Generally the distribution pattern is believed to be much more complex.

Paper 8 gives, up to the present, the most comprehensive study main elements in Norwegian tills. It is hoped that the most principle parts of the work may form a basis also for later interpretations of syngenetical geochemical variations in tills.

Paper 9 The enrichment of quartz in tills

This paper is concerned with the enrichment of quartz in tills. The conclusions are partly based on the results from Papers 6 and 8.

In a limited part of the homogeneous sandstone area in Astadalen there is an enrichment of quartz in the glaciofluvial material and in some of the tills, compared to the bedrock and the ordinary lodgement till. This enrichment of quartz is explained in the following way: Original till material was eroded by subglacial melt--water, and during the following glaciofluvial transport a significant abrasion occurred. This abrasion has formed a quartz-rich sand since the feldspar was ground down to silt size. Both the silt formed during this abrasion and the silt from the original till has been transported away from this local area by meltwater. Consequently the glaciofluvial material has become enriched in quartz in the sand fractions and also undergone a significant bulk relative enrichment of quartz in the matrix as a whole; the latter mainly on account of the loss of fines. In some places such glaciofluvial material has been incorporated in the glacier by a subglacial freezing on, and during the following glacial transport it was mixed with original till material. The latter subglacial deposited till has, because of the glaciofluvial component, a modest enrichment of quartz in the sand and a significant enrichment of quartz in the bulk matrix.

This study reflects the general principle that quartz is more resistant to mechanical comminution than most other main minerals. If the same processes, as described above, occurred in an area with texturally variable bedrocks one could expect an enrichment of quartz in different fractions. If the processes of fluvial activity and till formation were repeated several times the result would probably be a noticeable increase of quartz in both the sand and the silt.

An enrichment of quartz has been reported in several Scandinavian tills previously. It has been related to incorporation of pre-Quaternary weathering components.

The conclusion from Paper 9 is that a small, but significant quartz enrichment does not necessarily indicate any incorporation of preglacial weathering products, but may also be the result of pure mechanical processes.

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PAPERS 1 - 9

PAPER 1

STUDIES OF TILLS AND MORAINES IN NORWAY - A HISTORICAL REVIEW

SYLVI HALDORSEN

STUDIES OF TILLS AND MORAINES IN NORWAY - A HISTORICAL REVIEW

Haldorsen, Sylvi: Studies of tills and moraines in Norway - A historical review.

In Norway the literature dealing with tills and related moraines is fragmentary. Usually it forms minor sections of papers treating ice retreat chronology, ice divides and ice movements, stratigraphy and regional studies of Quaternary sediments. Before 1920 the most typical features of Norwegian basal till were described; its small thickness and coarse texture. Many of the most marked end moraines were mapped. In the years from 1920 to 1970 the most important topic was ice retreat chronology, including descriptions of marginal moraines. Investigations of the inland ice sheet were few and formed in most cases parts of regional studies by The Geological Survey. In the years from 1970 to 1980 several separate studies from the inland areas of Norway gave more knowledge about the formation and deposition of tills. There is still much work to be done before we have a full understanding of the typical Norwegian tills. Present knowledge about marginal moraines, supported by ^{14}C-datings, gives a rather complete picture of the ice front in Younger Dryas and in older and younger stadials. It is supposed that studies of till and moraines in the future will be dominated by investigations on the continental shelf and by sedimentological studies of the inland till sheet and tills composing the end moraines.

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CONTENTS

INTRODUCTION

The purpose of this study is to review till and moraine studies in Norway from the initiation of the glacial theory until the present. Since the literature is so fragmatic, not every publication touching on the subject will be referred, and some will be treated in greater detail due to special content or style. The references are grouped according to the main objective of the study and the period in which it was written. Authors residing, or who have had residence, in Norway are generally included, other Nordic authors being used only as comparatory references. Svalbard is not included due to the dissimilarity between it and mainland Norway, and the high degree of foreign participation in studies done there.

Till is the most common Quaternary sediment in Norway, but few separate studies of tills and related morainic landforms appear in the literature. Descriptions are usually minor sections of publications treating several topics, as on the following:

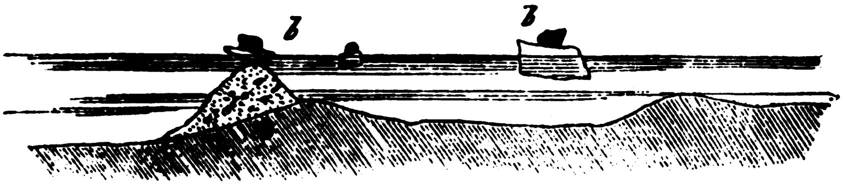
1. Ice retreat chronology by means of end moraines
2. Position of ice divides by means of erratics
3. The probable existence of a Skagerak glacier
4. Weichselian stratigraphy
5. Existence of ice-dammed lakes
6. Observations of tills and moraines included in the regional descriptions in soil surveys and by mapping the Quaternary geology.

INTRODUCTION OF THE GLACIAL THEORY

In 1824 Esmark concluded that the Norwegian land masses had once been covered by ice down to the sea, he was the first who presented such an idea in Norden, long before the glacial theory was generally accepted. His idea was based primarily on the occurrence of erratics and other glacial features such as striations and moraines, the most illustrative example being the very marked end moraine in front of Haukelivatn in southwestern Norway (Fig.1). This moraine is positioned near the coast and is far from recent glaciers. In 1826 his theory was published in English and he concluded, "I could give other proofs on the conclusion I have sought here to establish, but to persons judging the matter I considered this as sufficient". (see Holtedahl 1960, 358-359). At that time his idea was not generally accepted. According to Kjerulf (1871) this was mainly because his observations were too sketchy. The well reputed geologist Keilhau knew of Esmark's work and agreed

Vasryggen, den gamle morænе, der først erkjendtes som saadan i Nord-Europa.

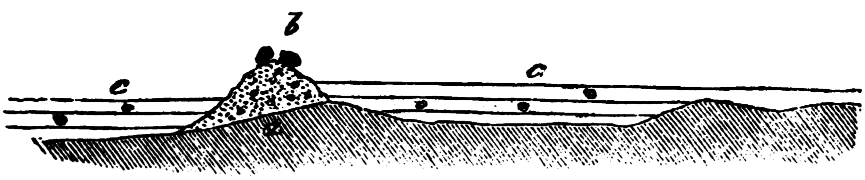
Fig.1 Vassryggen in Ryfylke, drafted by Reusch (1901 a). This was interpreted as an end moraine by Esmark already in 1824, long before the glacial theory was generally accepted.



Fjeldgrund med glacialbanke, bedækket af hav med seilende og transporterende isflag.

a) banken.

b) store og små seilende isflag, hvoraf nogle føres med strøm ned mod banken, hvorpå de strande og aflæsse deres byrde.



Samme fjeldgrund med glacialbanken og de transporterede blokke senere.

a) banken.

b) de på banken strandede blokke.

c) det under det forrige havdække afleiede ler o. s. v. med enkelte blokke hist og her.

Fig.2 Illustrations from Kjerulf (1860, p.14) showing the transportation of erratics by draft-ice.

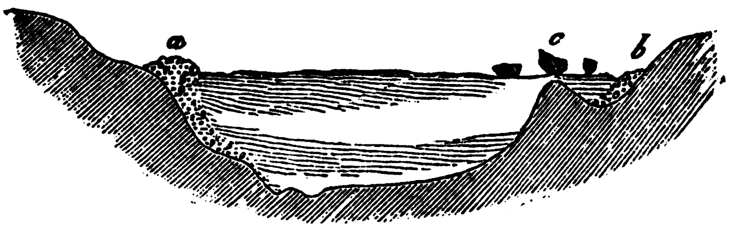
that glaciers had in some cases reached the sea (Keilhau 1838, 224) but did not believe in a total glaciation of Norway. Keilhau (1838, 1840) was still supporter of the "flood-theory". Esmark's theory, while not forgotten, did not play an important role in understanding the deposits we today know as glacigenic materials.

In the mid 19th century the theory of an extending post-Pliocene continental glaciation was accepted by most scientists, mainly as a result of the work of Charpentier, Agassiz and Torell (see discussions in Flint 1971). Kjerulf supported this idea and applied it in the interpretation of Norwegian soils (Kjerulf 1858). He was the first in the Nordic countries to apply the glacial theory for a total interpretation of till and morainic landforms (Figs. 2 & 3). Kjerulf (1865) gave the first descriptions of moraines and till in a Norwegian geology textbook (Fig.4). This book "Stenriget og Fjeldlæren" was written for use at the newly established Norges Landbrukshøgskole (The Agricultural University of Norway). Kjerulf further aided the introduction of the glacial theory when in 1858 he became the first director of the Geological Survey of Norway.

END MORAINE CHRONOLOGY

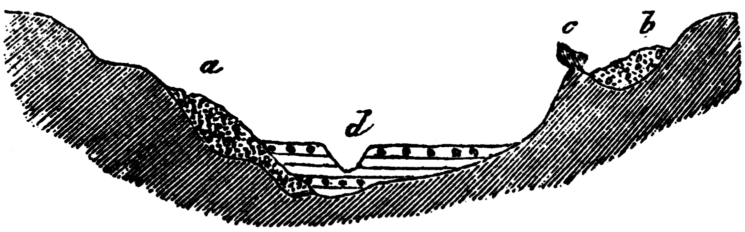
- 1900

Ice marginal deposits are mentioned in the early works of Kjerulf (1858, 1863) as he introduced the term glacial banks, (glacial banker) when describing end moraines formed beneath the marine limit (Fig.2). In 1958 he published a map of the



Gjennemsnit af en med gletscher fyldt dal.

a. og b) sidemorænér
c) blokke, som transporteres på gletscherens overflade, og hvoraf den ene vil blive liggende, om gletscheren afsmeltes lidt, på den fremspringende fjeldkant.



Gjennemsnit af samme dal senere.

a. og b) de tilbageblevne sidemorænér.
c) den gjenliggende blok.
d) sand, grus og rullesten afsat af vand i den gjennemstrømmede dal.

Fig.3 Illustrations from Kjerulf (1860, p.13) showing the formation of lateral moraines in a valley, and the later deposited proglacial glaciofluvial sediments.

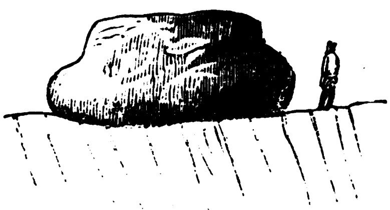
A

Moræner. Jøkel=Grus. Vandre=Blokke. Om disses almindelige Forholde er før talt pag. 98—101. De optræde i Norge ikke anderledes end andetsteds. De gamle Moræner findes liggende opefter alle Dale — ligefra Havets Bred ved Kristianiafjorden op i Høifjeldene til de Jøkelgjærder, som dannes den Dag i Dag for vore Øine — snart tværsover, snart langs-efter Vasdragets Retning. Den Første, der i Norge paaviste en saadan gammel Moræne var Esmark senior — ved Indgangen af Lysefjorden.

Grus eller Aur, som findes gjenliggende fra Istiden paa den skurede Fjeldoverflade, kan nævnes som Jøkel=Grus. Vandre=Blokke endelig store og smaa findes omstrøede overalt i Norge, baade høit og lavt. De findes liggende fast paa Toppen af høie Fjeld, men ikke paa de høieste — saaledes f. Ex. paa mangen Top i Jotunfjeldenes Udkanter mod Valders og Gudbrandsdal. De findes liggende øverst i de store Moræner som strække sig gjennem Smaalehnene og Grevskaberne paa hver sin Side af Kristianiafjorden. Og de findes ogsaa i og under Lerlagene, som i disse Egne dække Fjeldgrunden.

B

111.



Vandre=Blok (af Granit) paa fremmed Grund (af skraat stillede Lag).

Vandre=Blokke (erratiske Blokke) kaldes større Klippestykker (a), som vi finde liggende paa fremmed Grund (b) fordi de har vandret. Vi ser, Vandringen kan have foregaaet paa 2 Maader, enten bæres de paa selve Is=Bræens Ryg og bliver under Afsmeltningen ofte liggende ganske yderligt paa en Top eller en Kant, eller de seile paa Isflag og kan da gjøre større Vandring.

C

Nigaards=Bræen med dens Ende=Moræne.

Fig.4 The first descriptions of end moraines and till material in a Norwegian textbook for students (Kjerulf 1865)

A. Text describing moraines and till.
B. Description and illustration of erratics.
C. Nigaards-breen (Nigaards glacier), western Norway, with an end moraine in the front. This may be the moraine formed in 1850 or 1860 (see Fig.23).

Ra-moraines (Younger Dryas) located in the Oslofjord area (Fig.5). A significant part of the work having been executed previously by Keilhau (1838, 1840) who gave detailed, precise descriptions of end moraines in the Oslofjord and Sørlandet areas, but never completely accepted their glacigenic origin. In 1892 Vogt published a study correlating the Ra deposits with large ice marginal deposits in Sweden and Finland. He supported the idea that the large Scandinavian end moraines marked the outer limit of the last glaciation, while striations outside these were related to an earlier glaciation. Descriptions of end moraines in other areas of Norway appeared for example in an article by Reusch (1891) from Finnmark (Fig.6).

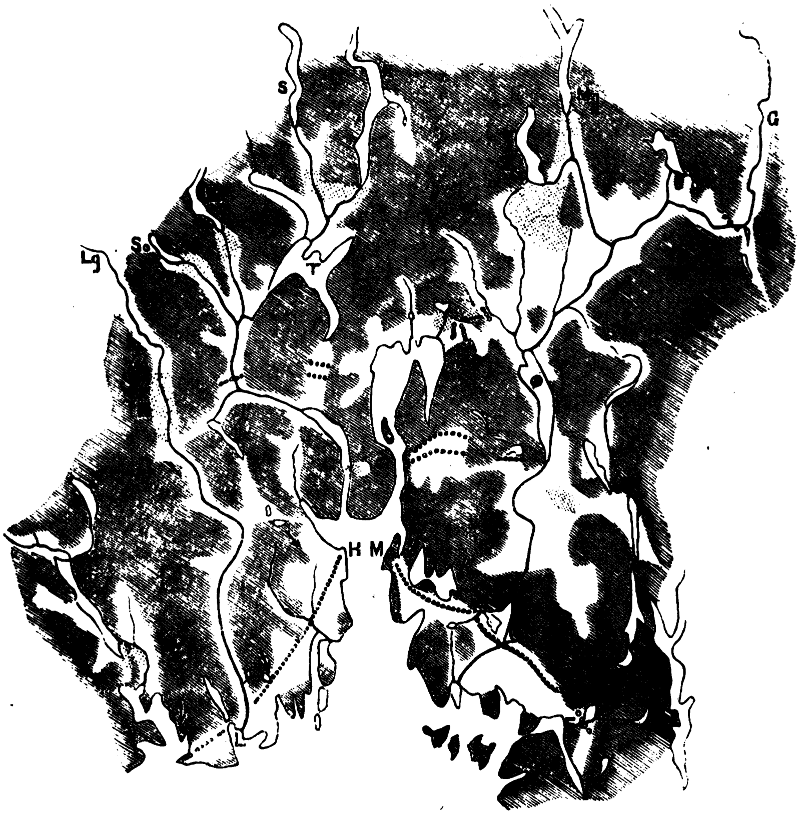
The sections in many end moraines indicated a complex formation. Reusch (1884) described several sections through tills and underlying stratified sediments with structures which he interpreted as glacitectonical (Fig.7). He concluded that a glacial oscillation had occurred with an overriding by the ice causing a disturbance of previously deposited sediments. K.O.Bjørlykke (1900) observed a disturbed marine clay with remnants of shell incorporated in the Ås moraine (Late Younger Dryas) and interpreted this as the result of a glacial advance.

<u>1901-1920</u>

The end moraine chronology form an important part of the papers during these years, too. Brøgger (1901) established a total chronology in the Oslofjord area which related the end moraines to the different marine clays and the respective characteristical mollusk faunas (Fig.8). Hansen (1910) published descriptions of the Ra moraine west of the Oslofjord, and at Sørlandet

Moræner og høitliggende sandflader ved Kristianiafjorden

(efter oversigtskart over den glaciale formation 1859 medfulgt Univ. Prg. 1860.)

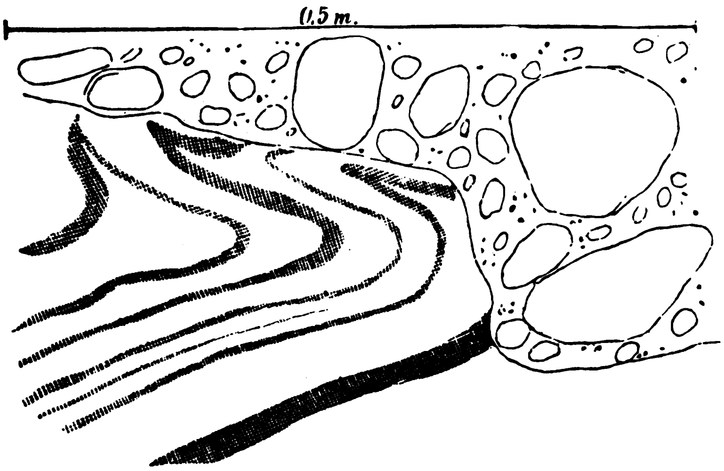


S Sperillen. *R* Randsfjord. *Mj* Mjøsen. *G* Glommen.
Lg Lougen. *So* Soneren. *Kr* Krøderen. *T* Tyrifjord. *Ø* Øiern.
K Kongsberg. *H* Horten. *M* Moss. *F* Fredrikshald. *L* Laurvig. *Kv* Kongsvinger.
streget betyder fjeldgrund,
prikket betyder høitliggende sandflader.
ustreget betyder ler og sandgrund,
små ringe betyder moræner,
pile betyder skuringsstribernes retning.

Fig.4 Position of the Ra terminal moraine (today correlated to the Younger Dryas) in the Oslofjord area. From Kjerulf (1871, p.30). Was also given in Kjerulf (1860).

Morænen foran Store-Vandet ved Hammerfest.

Fig.6 End moraine from Finnmark drafted by Reusch (1899, p.101).



Fra et andet sted i samme skjæring. Et stykke af grænsen mellem morænen og sandet, fremstillet i større detalj.

Fig.7 Section in glacial deposits from Dale, close to the city of Bergen (Reusch 1883, p.162). The disturbed stratification of the sorted sediments beneath the till was interpreted as a glacitectonical deformation.

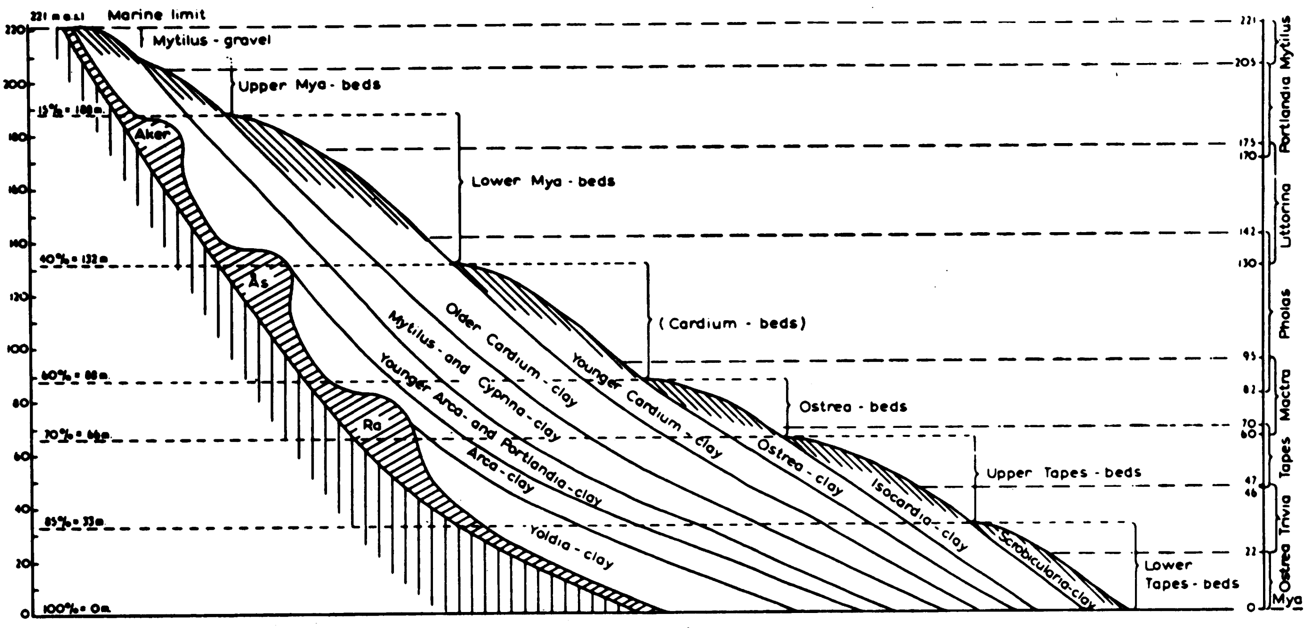


Fig.8 End moraines, sea level changes and marine clays in the Oslofjord area, based on Brøgger (1901). From O.Holtedahl 1960, p.383. This chronology has been applied until recently, but has now been revised.

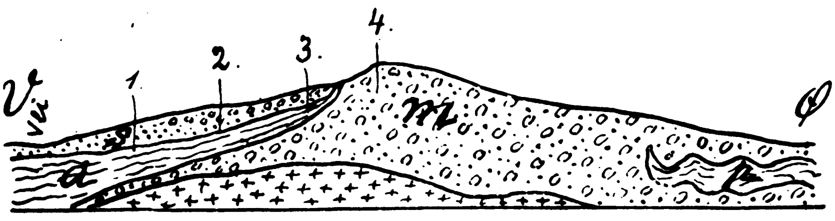


Fig. 1. Skematisk tversnit av Aasmorænen. ***m*** **moræne;** ***p*** **portlandialer tilsyneladende indesluttet i morænen,** ***a*** **arcaler;** ***s*** **strandgrus.**

Fig.9 Characteristic section through the Ås moraine (from K.O. Bjørlykke 1901, p.6), showing the till material (m) forming the ridge, and clay (a) capping the western side of the ridge (arca clay, see Fig. 8). A horizon of clay (p) was found within the eastern part of the ridge (portlandia clay, see Fig.8)

(Hansen 1913). Observations of end moraines at Sørlandet were also published by Danielsen (1910, 1912) and by Øyen (1911). After this any detailed and thorough studies of the end moraines at Sørlandet did not appear before about 50 years later (B.G. Andersen 1960).

C.F.Koldrup (1908) studied the end moraines in the Bergen area, in the same manner as Brøgger (1901) in the Oslo region. One important conclusion from this work was that the end moraines corresponding to the Ra in the Oslofjord area were in the Bergen area posited in the inner part of the fjords. It was clearly much more complicated to establish a total chronology of end moraines and clays in the Bergen area than in the Oslofjord area, due to the more irregular topography, which gave separate valley glaciers, and to the more complicated stratigraphy.

In northern Norway Vogt (1913) observed that there were usually two parallel end moraines, with a distance between them of some kilometres. He concluded that the outermost end moraines corresponded to the Ra in the Oslofjord area, and the innermost ones to the inner Ra (the Ås - Ski deposits). Much more recent investigations have shown that some of these correlations were correct even though the end moraine chronology in northern Norway is more complex than supposed by Vogt (1913) (B.G. Andersen 1968, 1975, Sollid et al 1973).

The internal structures of the ice marginal deposits were also a subject of interest. The detailed descriptions of K.O.Bjørlykke (1905, 1914) (Fig.9) are of importance today as they give valuable information about sections through the Ås moraine. Rekstad (1907) described a section in the Ra moraine at Halden and the occurence of shells beneath a till in

Østfold (Rekstad 1913). Descriptions of sections are also found in the regional work of C.F.Kolderup (1908) in the Bergen area.

1921-1940

The end moraine studies included those from the Bergen area (N.M.Kolderup 1938), the Sunnmøre (Kaldhol 1930), the Trondheim areas (O.Holtedahl 1929) and descriptions from northern Norway (Undås 1938). The studies were not as numerous as during the preceding years.

1941-1960

The ice marginal chronology was a subject of broad interest during these years. The position, extension, internal composition and fossil content of the Grefsen - moraine in the northern part of the city of Oslo were described in detail (Isachsen 1941, Gjessing & Fjellang 1956). Undås, who was deeply engaged in ice retreat problems, studied ice marginal deposits in the Møre - Trøndelag area (Undås 1942), in the Oslofjord area (Undås 1951) and in the Bergen area (Undås 1945, 1953).

The most extensive works on the deglaciation chronology are those by B.G.Andersen from south-westernmost part of Norway (B.G.Andersen 1954) and from Sørlandet (B.G.Andersen 1960). In the Ryfylke area Andersen (1954) related the end moraines to two stages, the Lysefjord stage (Younger Dryas) and the Trollgaren stage (Preboreal). The end moraines of the Lysefjord stage were usually high and steep-sided, indicating that the glaciers were very active. These moraines were partly interpreted as push moraines, formed by an oscillating ice front.

Fig.10 Moraine ridge on Storahei, Ryfylke, belonging to the Lysefjord stage (Younger Dryas) (B.G. Andersen 1954, Fig.12)

Fig.11 The Ra ridge (Younger Dryas) between Finsland and Øverbø, southern Norway (B.G. Andersen 1960, Fig.17).

Fig.12 The Ra ridge (Younger Dryas) at the Haslaodden, Fevik, southern Norway (B.G. Andersen 1960, Fig.4. Photo A/S Sørfly).

Estimations of the ice surface gradient were based on the position of the lateral moraines (Fig.10) which are very marked some places in the Ryfylke area.

Major parts of the Ra-deposits and older deposits at Sørlandet were described many years earlier (see descriptions for the years before 1920) but Andersen (1960) gave the first detailed description of the total extension of the Ra-deposit as well as older and younger stages in this part of Norway. He showed that parts of the Ra at Sørlandet consisted of two or three parallel moraine ridges. The till of the ridges was usually very rich in boulders. Andersen distinguished between marginal deposits formed by till and those formed by glacio-fluvial material. Four marked stages were distinguished: the Lista stage, the Spangereid stage, the Kristiansand stage and the Ra stage (Figs. 11 & 12). A rather new aspect to the work from Sørlandet was the inclusion of ^{14}C-datings which gave the absolute age of some deposits.

1961 - 1970

During these years the ice marginal chronology form the most important part of Quaternary studies in Norway and included large parts of the coastal Norway. There are detailed descriptions of end moraines and lateral moraines from the area around the Hardangerfjord (Liestøl 1963; Anundsen & Simonsen 1967) (Fig.13). The latter includes particularly detailed description and illustrative photos of lateral moraines. Undås (1963), who had a continuing enthusiasm about ice marginal chronology, published his voluminous work about the

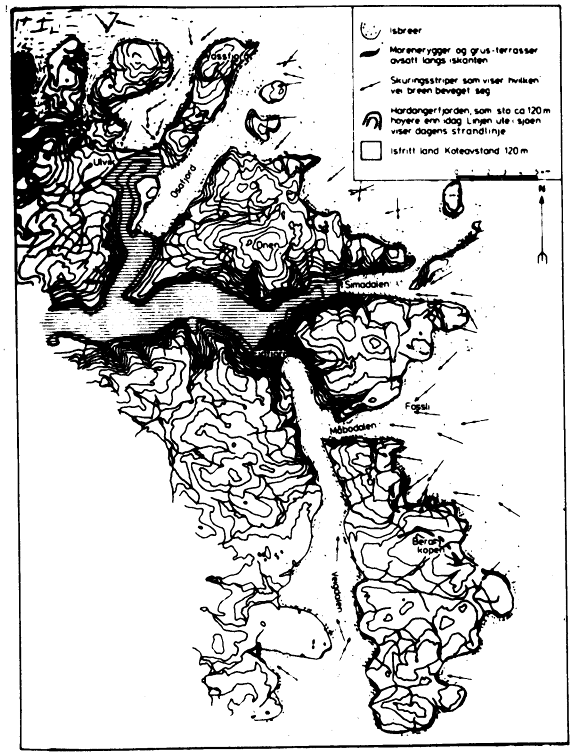


Fig.13 The position of the ice front in the Hardangerfjord area in Preboreal. Based on end moraines and lateral moraines. From Anundsen & Simonsen 1967.

Fig.14 Parts of the moraine ridges at Somarskardet, the Narvik-Skjomen area, Nordland. (Dahl 1967, Fig.5)

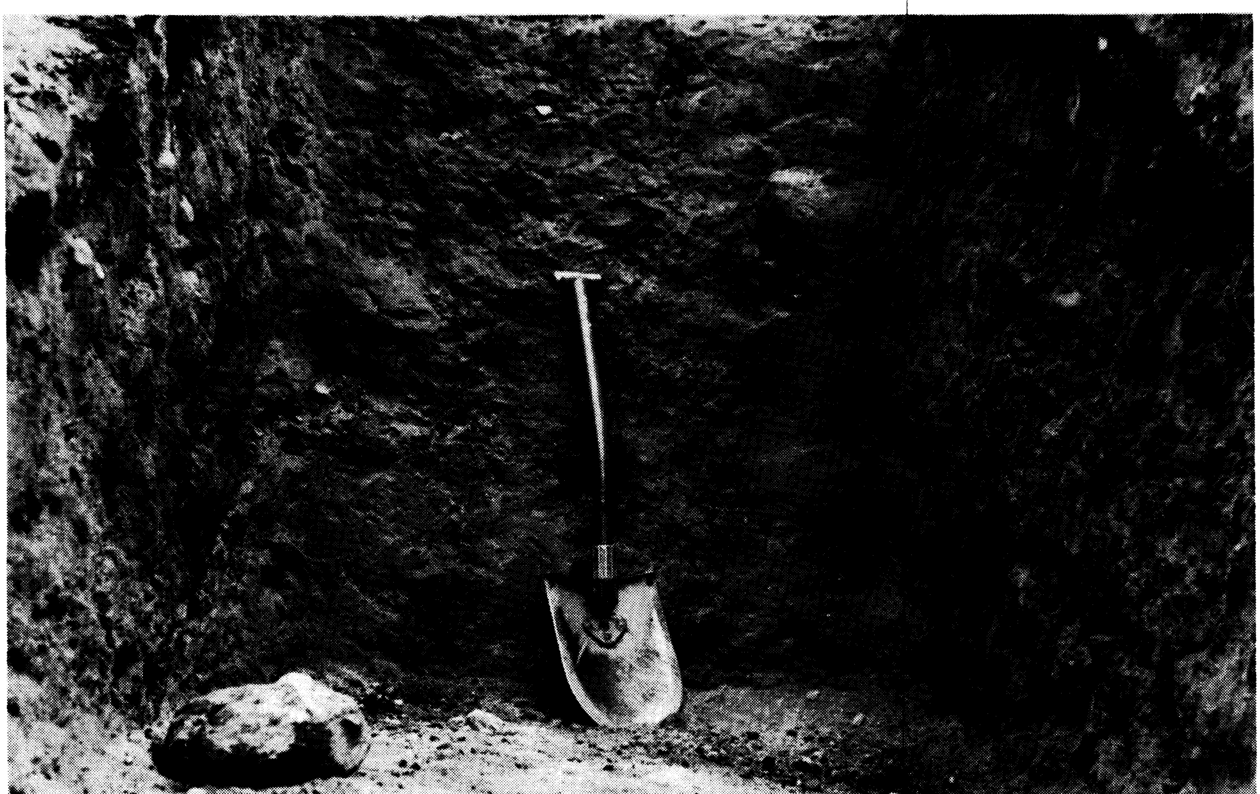


Fig.15 Squeezed moraine material with only a few small boulders. 2 - 3 m depth in the central part of the largest moraine ridge at Somarskardet (Dahl 1967, Fig.6. Photo B. Dahl.)

Fig.16 Air photo of Strandvik, Hordaland, western Norway. The course of the Younger Dryas end moraine is indicated (dotted). Nunatak moraine is marked in the upper right (m). Direction of glacier flow is indicated by arrow. (Aarseth & Mangerud 1974, Fig.4. Photo: Fjellanger Wideröe A/S.)

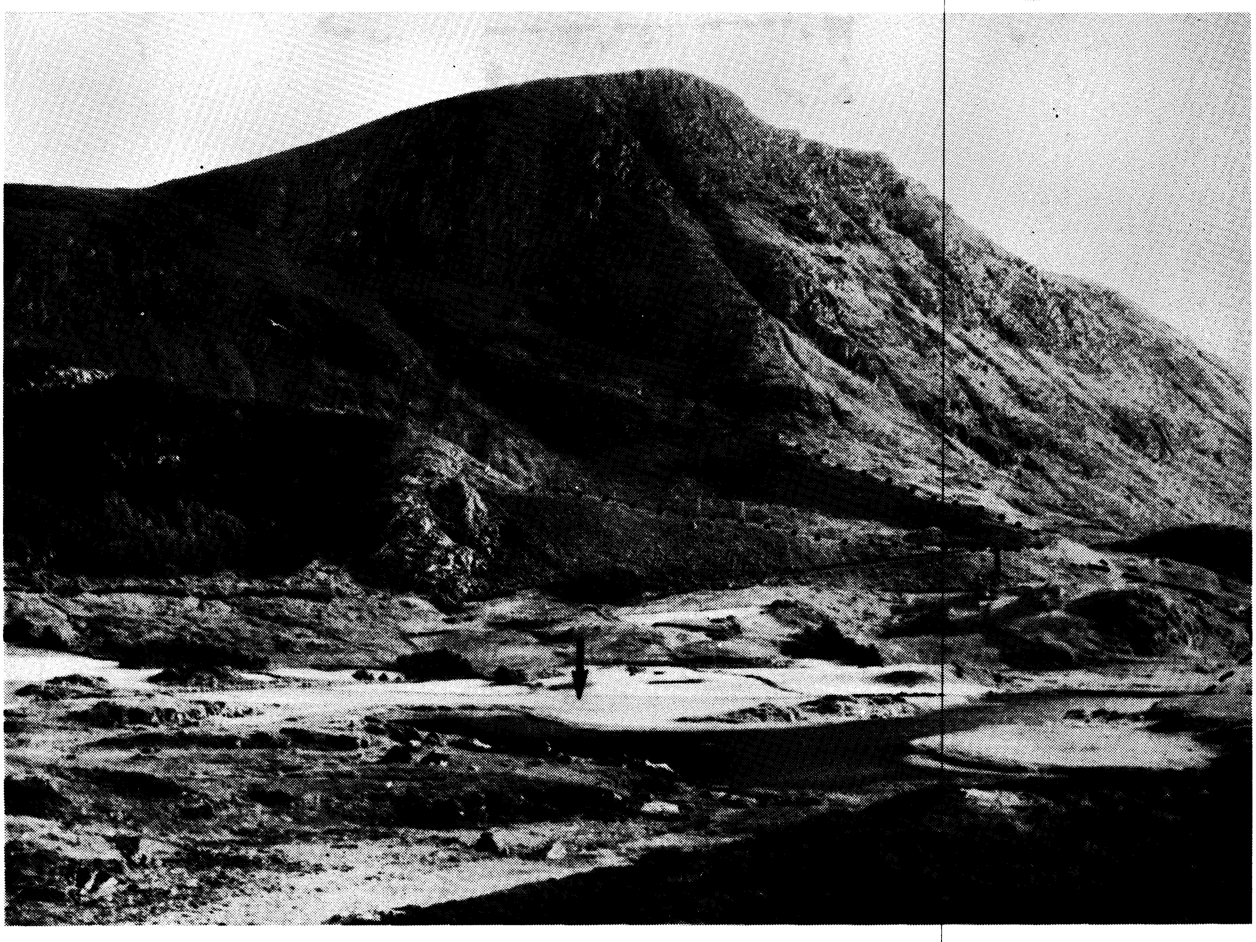


Fig.17 The lake, the end moraine (dotted) and the cirque at Kråkenes, northwestern Norway. Arrow indicate the site of the ^{14}C dated core. (Mangerud et al 1979, Fig.8).

Ra-moraine in western Norway. A summary article on the ice retreat in the Bergen area was later given by Mangerud (1970 a). Based on ^{14}C-datings and end-moraine chronology, Mangerud presented a figure showing the oscillations of the ice front from the Oldest Dryas to the Preboreal time. At Sunnmøre, Reite (1967) described the end moraines from local glaciations and correlated them to the Younger Dryas age.

In Nordland, Dahl (1967, 1968) studied the glacial accumulations and ice retreat by means of end moraines and other morainic deposits, for example drumlins. His work included many detailed descriptions of the internal structures of moraine ridges, and an important part of it concerns the genesis of the ridges. The moraine ridges generally consisted of very compact till with pressure structures, interpreted as basal till (Figs. 14 & 15). The ridges were, according to Dahl, formations from active oscillating glaciers.

The work of B.G.Andersen (1968) done in Troms gave additional details about the marginal morainic deposits, including descriptions of sections. By means of end moraines, Andersen distinguished between different stages: The Egga moraines (Middle Weichselian), the Island moraines, the Skarpnes moraines (Older Dryas), the very marked Tromsø - Lyngen moraines (Younger Dryas) and the Stordal moraines (Preboreal or Boreal). From Finnmark, Marthiniussen (1961) published a study concerning shore line determinations but the position of the ice front determined by means of the end moraines is also included.

1971 - 1975

Quantitatively, the deglaciation cronology partly based on the end moraines, form the main part of the studies during the period 1971 - 1975, too (Western Norway south of Bergen: Anundsen 1972, Follestad 1972, the Bergen area: Aarseth & Mangerud 1974 (Fig.16), the Sognefjord area: Vorren 1973, the Trøndelag: Sollid & Sørbel 1975, Nordland: Møller & Sollid 1972, Finnmark: Sollid et al. 1973, Marthiniussen 1974). It was now concluded that the Younger Dryas end moraines were not necessarily syncronous with the Ra in the Oslofjord area, this was particularly well pointed out by Aarseth & Mangerud (1974) in their work from Hordaland . This conclusion was based on better datings and more continuous studies of the end moraines which linked together the earlier more fragmentary studies.

The study by Vorren (1973) in Sogn is a good example of a detailed moraine chronological work. Based on end moraines, lateral moraines and on ^{14}C-datings he distinguished between two different Preboreal stages; the Gaupne stadial and the Høgemo stadial. In this area no systematic investigations of the end moraines had previously been carried out.

B.G.Andersen (1975) continued his studies in northern Norway, and in northern Nordland he described the marked end moraines belonging to the Tromsø - Lyngen stage. In Nordland these were usually found at the mouth of fjords.

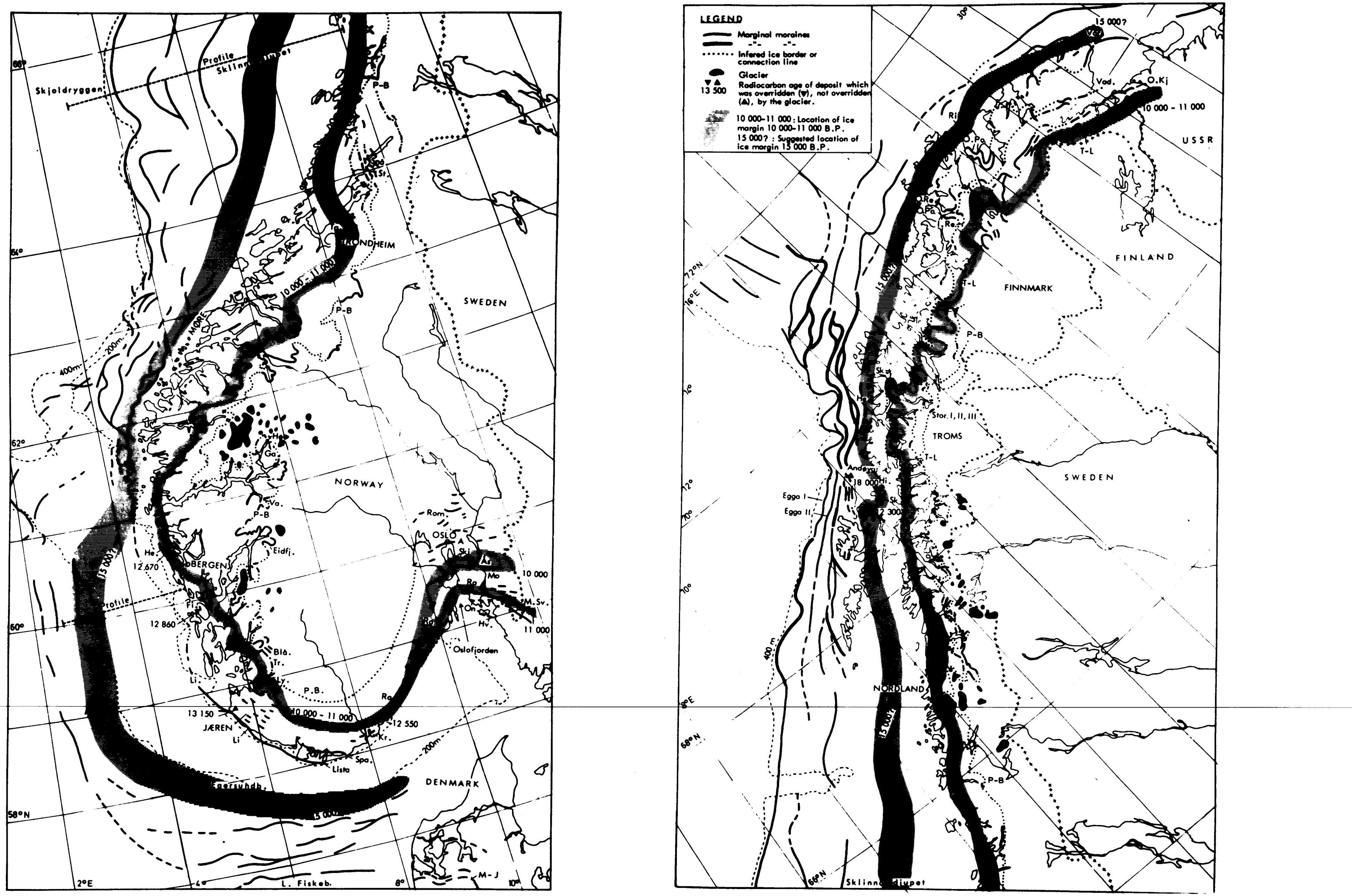


Fig.18. Map showing the ice marginal chronology in Norway. according to our present knowledge (B.G. Andersen 1979, Fig.1)

1975 - 1980

The stratigraphic work of Mangerud et al. (1979) from northwestern Norway, included till descriptions. From a glaciological point of view the most important part of their work was calculation of the erosion rate of a cirque during Younger Dryas. The calculation was based on the amount of material accumulated in the end moraine in the front of the cirque (Fig.17), the amount of material accumulated in a lake and ^{14}C-datings of the lake sediments.

Conclusions from the most important literature on end moraine chronology, was summarized by B.G.Andersen (1979) and presented on the IGCP deglaciation symposium in Uppsala in 1978. This showed that all fragments which have been contributed during 100 years are now linked together and give a rather complete picture of the retreat of the Weichelian ice front (Fig.18) in Norway.

ERRATICS

Data on the distribution of erratics is found in several small, separate studies. It has been regarded as an important activity to trace their distribution, and the purposes of the studies were manysided. The distribution of erratics was partly known from the detailed work of Hörbye (1855, 1859). As late as 1859 (p.232-233) Hörbye concluded that theories concerning the origin of erratics were still at speculative stages. After the glacial theory was generally accepted the distribution of erratics, partly based on Hörbye's work, became important parameters in studies of ice movements and ice divides. Examples of this are the studies by Schiøtz (1895 a) from Rendalen, southeastern Norway and Rekstad (1895, 1896, 1898) from Gudbrandsdalen.

The studies of stones in the end moraines have been applied for calculations of transport lengths. Based on petrographical investigations of 500 stones from the Ås moraine, Øyen (1900) concluded that less than 20 % were derived from the local bedrock while more than 70 % were transported more than 30 km. Similar studies of an end moraine from Asker (Øyen 1906) showed that more than 50 % was transported a distance exceeding 30 km. These studies clearly reflected the generally long transport distance for the coarse material in end moraines in the Oslofjord region.

P.Holmsen (1951) like many before him applied the distribution of erratics for more exact localizations of the main ice divide in southeastern Norway. In another study (P.Holmsen 1964) he applied the distribution of erratics to interprete the position of the ice divides during the last active glacial phase. Oftedahl (1957, 1958) mapped the boulder train from the Joma ore deposit and from this he discussed the ice movements. His study illustrates the applicability of glacial erratics for ore prospecting, a method which for a long time had been widely used in Finland.

The "Skagerak glacier"

Helland (1885) studied the glacial deposits in Jæren and concluded that they were more comparable with deposits in Denmark than with deposits from other parts of Norway. The similarity with Denmark was reflected both in the great thicknesses and in the composition of the sediments. In a clay-rich till there was a great abundance of far transported material from the Oslo region and flint and chalk from Denmark. (The occurrence of such boulders at Jæren were reported also earlier by Kjerulf (1879)). Helland (1885) concluded that this was deposited by a Skagerak-glacier which was supposed to have originated in southern Sweden and Norway, and to have flowed through the Skagerak and overidden northern Denmark, Lista (southernmost Norway) and Jæren. The theory of the Skagerak glacier was supported by most geologists during the subsequent 75 years.

Horn & Isachsen (1943) and Isachsen (1954, 1960) studied some pieces of mesozoic coal in the Skagerak till and Horn suggested that these might originate from Bornholm or Skagerak. From erratics Isachsen tried to outline the eastern and northern extension of the supposed Skagerak glacier and theorized that it had reached Karmøy, northwest of Jæren. Undås (1949) found pieces of flint on the island of Utsira, west of Karmøy, and suggested that these had been deposited by the Skagerak glacier.

Discussion of the Skagerak glacier heated up again during the years 1960-1965. By means of grain-size analyses, petrography and fabric analyses of tills, and studies of drumlins, Ringen (1964) argued that any Skagerak-glacier had not reached Karmøy, north of Jæren. In 1964 B.G.Andersen and Feyling-Hansen in separate articles concluded that there was no evidence of a Skagerak glacier in Jæren. They argued that the erratics from the Oslo area were ice-rafted material and that the clayey "Skagerak till" was more likely a glaciomarine clay. After that time discussion about the Skagerak till ended. It is odd that it took 75 years to disprove the theory of the Skagerak glacier, but this proves that the idea was good, even though it was not correct.

OTHER STRATIGRAPHICAL AND CHRONOLOGICAL WORKS

After the glacial theory was accepted, discussions soon concerned whether the glacial deposits in Norway originated from one or more glaciations. The theory that some of the Quaternary deposits in Norway are older than the last glaciation is not new.

Jæren

Helland (1885) suggested that a glacier from the east had overidden Jæren after the deposition of the Skagerak till. The till deposited by this glacier was coarser and of more local origin than the Skagerak till. Helland (1885) also described a disturbed clay with shell at Sandnes, Jæren. The disturbance was interpreted as glacitectonic and the shells were therefore related to an interglacial time. It seems Helland used the term "interglacial" synonymously with "an ice-free period". Sections from Jæren showing disturbed sediments with fossils beneath a till were also described by Reusch (1890).

K.O.Bjørlykke (1908) supported the idea of Helland (1885) concerning the Skagerak-glacier. He concluded that three different glaciations were represented by three different tills with intervening interglacial periods. The oldest till and interglacial sediments were uncertain. The Skagerak till was related to the second glaciation. Material from the supposed last interglacial was found as remnants of clay with shell incorporated in a till at Reve, southern Jæren. The shells indicated a mild climate and was thus interpreted as inter-glacial locality. The youngest till was the same as that observed by Helland (1885), deposited by a glacier from the east. Quite recent studies from Jæren B.G. Andersen et al. (1981). support the early ideas that the Pleistocene deposits at Jæren are complex. The recent conclusions are elsewise different from the early ones, and the studies have hitherto shown deposits from the Weichselian only.

The Bergen area

In the city of Bergen Rekstad (1900) found shell beneath a till and related the shells to an interglacial time. C.F.Kolderup (1908) discussed this and several other localities with the same type of stratigraphy and concluded that the shells did not necessarily relate to an interglacial time, as most of them belonged to an arctic fauna. If they were interglacial, Kolderup supposed that they related to the beginning or the end of the interglacial. Several localities with tills and sub-till clays or till with incorporated clay and shells, have later been described from Bergen (Holtedahl 1964, Undås 1953, Mangerud 1970 a). ^{14}C-datings indicates that some shell localities are of Bølling age, others are related to Allerød.

The first description of a till containing "safe" interglacial material was given by Mangerud (1970 b). This was a clayey till containing pollen from an interglacial time from the Fjøsanger locality near Bergen. The till also contained sealbones. (Later this locality has been excavated and showed a complete Eemian sequence and an underlying till, probably from the Saalian (Mangerud et al. 1981)).

Gudbrandsdalen

Weichselian stratigraphy and deglaciation chronology in the Norwegian inland has particularly been studied in Gudbrandsdalen and has included important descriptions of till and related morainic landforms.

The work of Tollan (1963) in northern Gudbrandsdalen gives one of the few detailed discussions of drumlins in Norway. The ratio of length to width was related to the velocity of the glacier, according to the existing theory of drumlin formation. The drumlins were by Tollan regarded as accumulation forms.

In middle and southern Gudbrandsdalen Mangerud (1963) and Bergersen (1964) studied grain-size composition and petrography of clasts in the till, and Bergersen applied the result from roundness analyses for the characterization of tills. Particularly interesting is the work of Mangerud (1965). He described the large accumulations of tills in some of the tributary valleys of Gudbrandsdalen. Based on tills and sub--till sediments he proposed a Weichselian stratigraphy and related parts of the till to an early part of the Weichselian, a conclusion which has been supported by more recent investigations. The work included studies of the till matrix mineralogy and Mangerud showed that the quartzite bedrock by a glacial comminution was rapidly crushed down to separate minerals.

A facinating till phenomena is the Kvitskriuprestinn, the remarkable earth pillars in Gudbrandsdalen which are formed in a compact till. Strøm (1943) concluded that the till was deposited during the second to the last glaciation. Also Mangerud (1965) discussed the formation of the Kvitskriuprestinn (Fig.19) and concluded that their exictence was dependent on the grain-size distribution, particularly the high content of clay, and the overconsolidation of the till. Mangerud theorized that they were formed during the Weichselian, and not during any preceding glaciation.

Bergersen & Garnes (1972) and Garnes (1973) carried out very detailed studies of till stratigraphy in Gudbrandsdalen, based on the huge sections found in the main valley and its tributaries. Analysis of fabric,roundness,grain-size distributions of clast petrography combined with studies of striations and sub-till sediments, gave the following Weichselian stratigraphy:

1. The sub-till sediments were related to an interstadial time (the Gudbrandsdalen Interstadial).
2. Four glacial phases were recognized and most of the tills were correlated to the second oldest of these. During this phase the ice divide was supposed to lie northwest of Gudbrandsdalen. The tills were deposited as thick lee-side deposits in many tributary valleys.

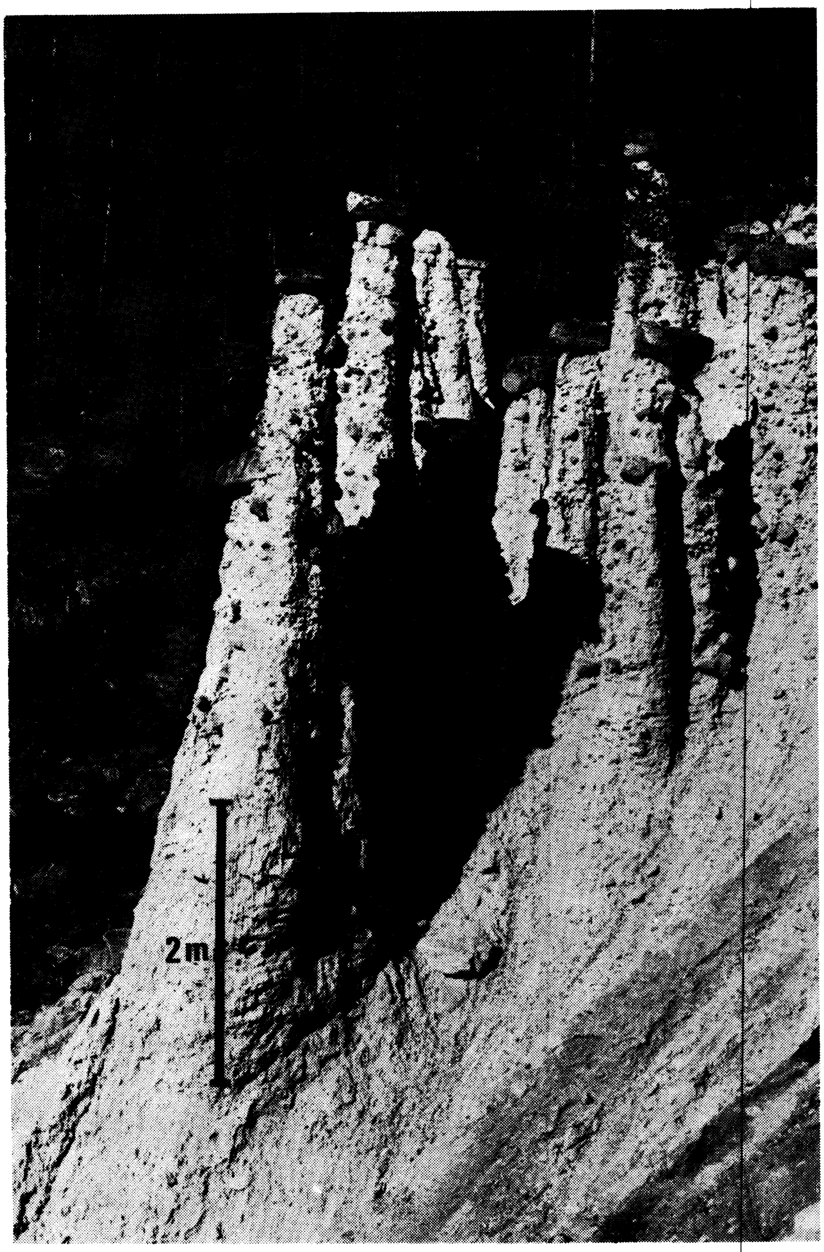


Fig.19 The earth pillars Kvitskriuprestinn in Urddalen, a tributary valley to Gudbrandsdalen. (Mangerud 1965, Fig.10)

Fig.20 Section in the thick till deposits at the Stenseng gully in lower Sjoa valley, Gudbrandsdalen. The boulder pavement in the upper part of the exposure represents the upper surface of the thick till deposited by glaciers flowing towards southeast. The overlying tills are deposited by glaciers flowing towards east and towards northeast respectively (Garnes & Bergersen 1977, Fig.6.)

Their theories were verified by more recent works (Garnes 1978, 1979, Garnes & Bergersen 1977, 1980). In a large till section at Stenseng, Sjoadalen (Fig.20) tills deposited during four different glacial phases are represented (Garnes & Bergersen 1977). The tills from the two or three earliest phases were related to the time before the Weichselian maximum. The efforts by Garnes & Bergersen represent up to the present some of the most detailed studies of till stratigraphy in Norway.

Hardangervidda

The comprehensive study by Vorren (1979) from Hardangervidda demonstrates clearly how the morainic landforms and the till material may form important parameters in chronological and stratigraphical studies. The direction of ice movements was interpreted by means of drumlinoid forms and fluted surface.

The till material was described by several parameters; lithology, fabric, grain-size composition and structures. The tills were divided into four groups based on the internal structures: Massive till, tills with inclusions, fissile tills and layered tills.

Based on the tills, sub-till and inter-till sediments and other parameters, Vorren (1979) postulated a rather complete Weichselian stratigraphy for Hardangervidda, including four different phases.

Other parts of Norway

A new aspect of till studies was established by the finding of a musk ox vertebra at Dovre in a gravel beneath a till.

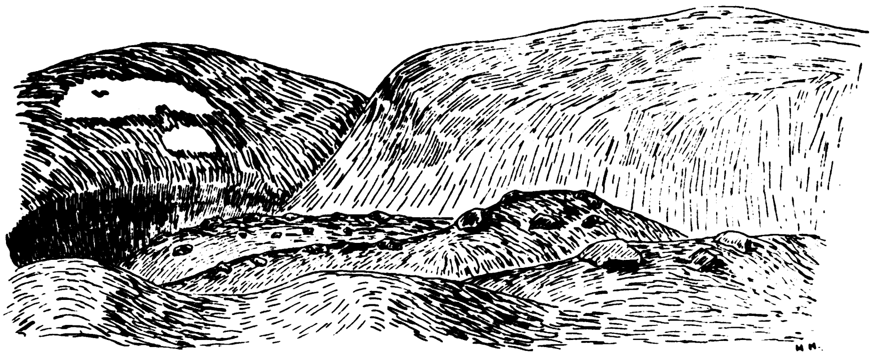


Fig.21 Ablation moraines southeast of Kråkvassbotn, north-western Norway (H.Holtedahl 1950, Fig.22).

Fig.22 Glacial features from the area Bugøyfjorden - Gandvik, Finnmark. 1. Terminal moraines. 2. De Geer moraines and other forms similar to 1 and 3. 3. Lee side moraines. 4. Boulders. 5. Hummocky moraines. 6. Fluted surfaces. 7. Glacial striae. 8. Meltwater channel. 9. Major meltwater channel. 10. Meltwater canyon. 11. Washed rock surfaces. 12. Sorted deposits. 13. Terrace. 14. Kettle hole. (Sollid et al. 1973, Fig.50).

The vertebra and the site where it was found were described by K.O.Bjørlykke (1913a, Øyen (1913) and Reusch (1913). The vertebra was related to an interglacial time.

From the inland part of Norway the work of Sund (1943) gave a regional interpretation of the deglaciation in the Hallingdal - Hemsedal area, southern Norway and it included descriptions of moraine ridges and particularly of the dead-ice landscape.

The deglaciation study by H.Holtedahl (1950) from north-western Norway gave descriptions of the dead-ice morphology and ablation moraines (Fig.21) and sections through hummocks and ridges with till resting on stratified sediments. Sollid (1964) described the morainic landforms, including drumlins, in the Dovre - Hjerkinn area.

The work of Sollid et al. (1973) from Finnmark gives a classification of the different moraine types, as end moraines, de Geer moraines, fluted surface and drumlins (Fig.22).

ICE-DAMMED LAKES

The studies of moraines in Gudbrandsdalen were not only concerning stratigraphy, ice movements and ice divides. At the end of the 19th century there was an intensive debate about the existence of ice-dammed lakes. The main problem was whether the 'setes' which are marked benches along the valley, were lateral moraines (Schiøtz 1892, 1895 b, Reusch 1894, Øyen 1898) or shore lines formed in ice-dammed lakes (Hansen 1890, 1892 1895). This was of importance for understanding the deglaciation history of the inland part of Norway.

Discussion of the ice-dammed lakes was also concerned with Østerdalen (G.Holmsen 1915). In 1910 Reusch still regarded the 'setes' in Gudbrandsdalen as lateral moraines. He also critized Holmsen's interpretations in Østerdalen (Reusch 1917). In 1918 Holmsen gave a clear description of the 'setes' and interpreted them as shore lines. After this the most intensive debate about the 'setes' ended.

A detailed discussion of this problem is given by Garnes & Bergersen (1980).

RECENT GLACIERS

The Norwegian glaciers and the related moraines have been visited by numerous scientists (example: see Fig.3) but have quantitatively formed only a minor part of Norwegian till and moraine studies.

The early studies by Rekstad (1902, 1905, 1912) connected the advances of recent glaciers with end moraines, and Fægri (1934) related the botany in the front of Jostedalsbreen to the oscillations of the glaciers. Ahlmann (1935) and Werenskiold (1937) gave descriptions of several end moraines in Jotunheimen.

Major studies of ice-cored moraines and recent end moraine chronology were published by Østrem (1959, 1961, 1962, 1964, 1965). He applied, in addition to drillings, different geophysical methods to measure the thickness of morainic layers in ice-cored moraines. Layers containing wind-blown organic material were dated by the ^{14}C-method and this was compared with results from tritium-datings (Østrem 1965). It gave "a new approach to the end moraine chronology", as Østrem pointed out in his works from 1961 and 1962.

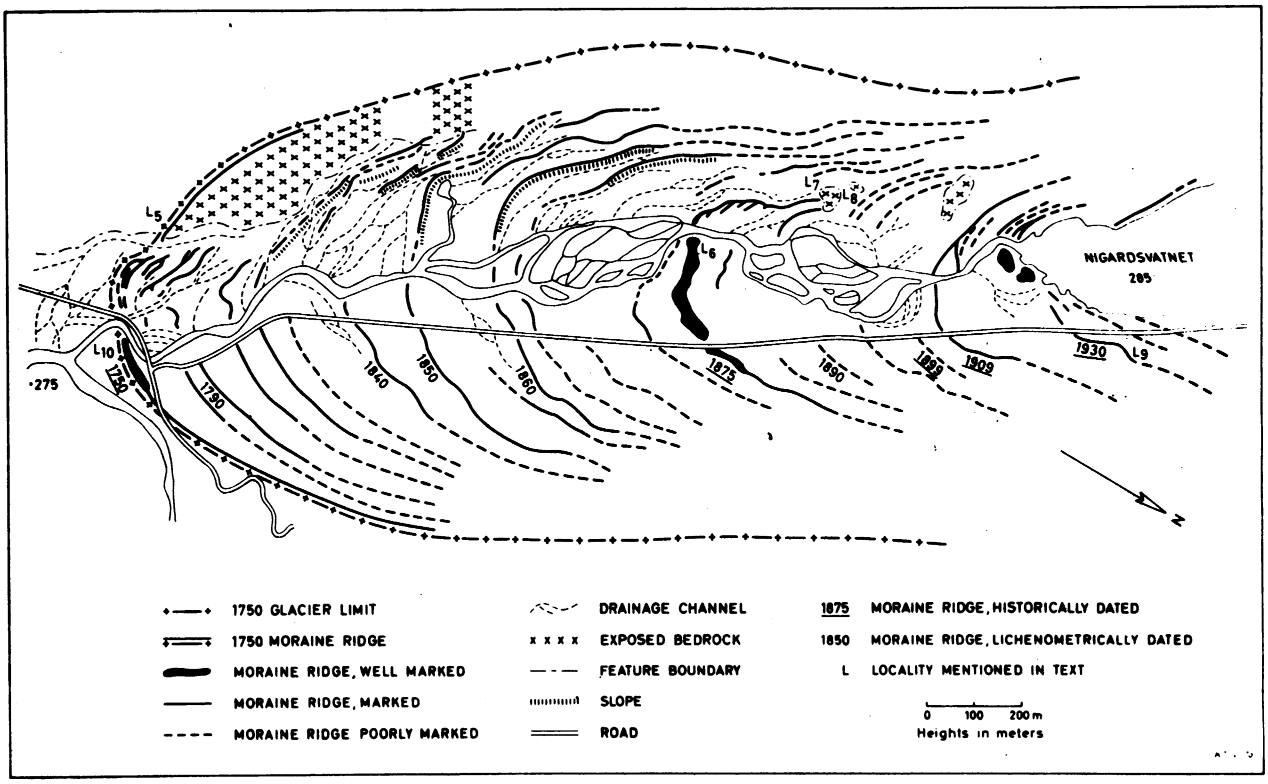


Fig.23 Map of Nigardsdalen drawn from aerial photographs taken by Wideröe's Flyveselskap A/S. Details have been added from field studies. (J.L.Andersen & Sollid 1971).

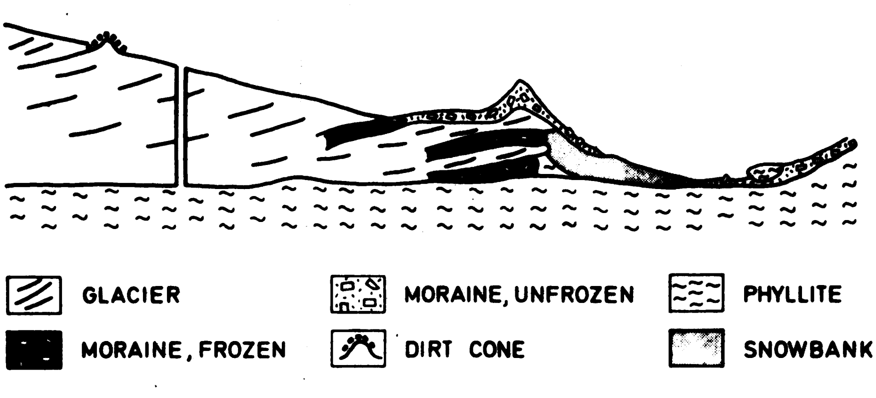


Fig.24 Formation of shear plane moraines in the front of Midtdalsbreen (J.L.Andersen & Sollid 1971).

In front of two recent glaciers (Nigardsbreen and Midtdalsbreen) J.L.Andersen & Sollid (1971) made detailed maps of different morainic landforms (Fig.23) and included lichenometric datings of end moraines. They described the formations of end moraines by the process of basal freezing followed by a transportation along shear planes up to the surface of the ice (Fig.24). Such studies have otherwise been uncommon among Norwegian glacial geologists.

REGIONAL STUDIES OF THE QUATERNARY DEPOSITS

- 1900

After the introduction of the glacial theory regional descriptions of tills and moraines were published by geologists employed by the Geological Survey (Helland 1885, 1893, 1894, 1895, Kjerulf 1863, 1871, 1879, Kjerulf & Dahll 1858-1865, Sars & Kjerulf 1860, Reusch 1891, Münster 1900). Early publications dealt with the most typical and conspisious characteristics of Norwegian tills; their coarse texture and normally small thickness (see for instance Reusch 1891, p.80-81). Publications from he Geological Survey appeared regularly from 1891 and continue to be the most important source of regional till descriptions.

1901 - 1920

During these years a large number of publications of Quaternary geology appeared - and included descriptions of tills and moraines. The most important general contribution was the work of K.O.Bjørlykke (1913 b): Norges kvartærgeologi (The Quaternary geology of Norway). This study gave a thorough review of earlier published papers, and contained new information, partly collected by the author himself. It presented end-moraine chronology known at that time and included rather detailed descriptions of the regional till distribution in Norway. This work is recommended to those desiring detailed information concerning the oldest Norwegian literature on tills and moraines.

In addition to Bjørlykke's work, the regional descriptions from The Geological Survey partly accompanying the geological maps, form the main part of the till litterature during the first part of the 20th century. Reusch (1901 b) studied parts of the Valdres (middle southern Norway) and observed that there was many places a lack of end moraines. He concluded that the glaciers had not been active in such areas during the deglaciation. He postulated a regional stagnation of the ice sheet, a model which was much later assumed for many inland parts of Scandinavia (Mannerfelt 1945). Reusch (1901 b) also observed that till thickness is decreasing with increasing height in the mountain areas. This is a characteristic which is typical for Norway. As far as I know, Reusch (1901 b) gave the first description of a drumlin in Norway (Fig.25). Rekstad (1903) pointed out another typical regional variation in till thickness; east of the watershed in southern Norway he found that the till cover was rather continuous; while west of the watershed it was thin and large parts of the bedrocks were exposed. Both Rekstad and Reusch were interested in the end moraines in the inland areas which they regarded as

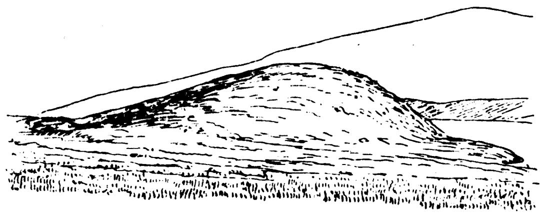


Fig.25 The first drumlin described from Norway (Reusch 1901 b, p.81) The drumlin was observed during a journey in Valdres, southern central Norway.

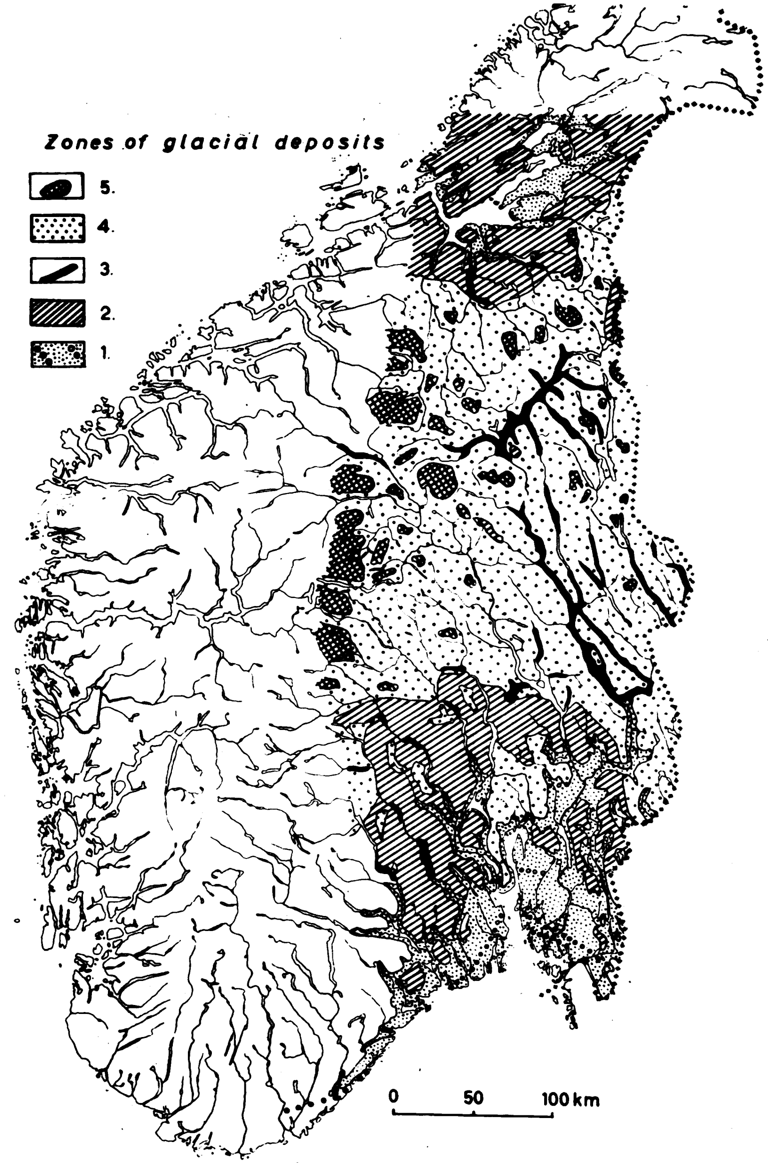


Fig. 2. Map showing zonal distribution of glacial sediments in southeastern Norway. (1) Uplifted marine sediments, including terminal moraines (shown by lines of circles). (2) Thin discontinuous till, chiefly ground moraine. (3) Glaciofluvial sediments and ablation drift in valleys. (4) Dead-ice deposits on plateaus and along the ice divide. (5) Thin drift, marked by frost phenomena in mountain areas.

Fig.26 Soil regions in Norway (G.Holmsen 1963).

important for understanding the glaciation.

Jæren was an area of great interest for geologists, because if its agricultural importance, and its thick and complex Quaternary deposits which are quite untypical for Norway. Two years after K.O.Bjørlykke (1908) published his work from Jæren another voluminous work was published by Grimnes (1910). This was written mainly for agricultural purposes. Grimnes studied a great number of sections, especially from southern Jæren, and gave detailed descriptions of the sediment composition. His descriptions of the regular till sheet are even more important. The Skagerak till was, as in earlier works, described as a clayey till with large and small, more or less rounded stones (Grimnes 1910, p.50). Grimnes pointed out that the matrix of this till was particularly rich in calcium, which gave favourable conditions for agriculture. Till material overlying the Skagerak till (i.e.the till from the last glaciation, described by Helland 1885 and K.O.Bjørlykke 1908) was by Grimnes (1910, p.52) described as coarse and far less favourable from an agricultural point of view. In the central area of Jæren the basal till was the dominating soil type (Grimnes 1910, p.56). This was partly found as typical stoss- and lee-side tills with the greatest thicknesses at stoss sides.

1921 - 1940

During these years the regional studies mainly in connection with regional mapping, formed the major part of the till literature (Rekstad 1921, 1922, Reusch 1923 and Streitlien 1935). The last part of this period was dominated by the works of G.Holmsen (1932, 1935, 1937). In his descriptions a distinction between regular till and ablation till or "dead - - ice till" was introduced. Holmsen (1924) contributed to general understanding of Norwegian tills in his work; 'Hvordan Norges jord ble til' (How the surface deposits in Norway were formed). He here pointed out that the Norwegian basal till sheet is usually not more than 1 - 2 m thick, and that there is a clear relation between the till and the underlying bedrock.

1941 - 1960

The regional studies of G.Holmsen (1950, 1951, 1952, 1954, 1955, 1956 a, 1958, 1960) primarily from southeastern Norway, form an important part of the till literature during the middle of the 20th century. The map from Oslo (Holmsen 1951) in scale 1: 250 000 was the first separate map of the Quaternary deposits. The Quaternary maps with descriptions made a distinction between areas with continuous till covers and areas with thin and discontinuous tills and included descriptions of the morainic morphology. The systematic descriptions of the regional till variations were partly based on the interpretations of the deglaciation history. G.Holmsen distinguished between the rather smooth morainic surface formed by the basal till and the more hummocky surface formed by the accumulation of ablation till from stagnant ice remnants. He applied the term "bregrus" (glacial gravel) to the till material, a term which had long traditions in Norway as Kjerulf (1965) (see Fig.2) had earlier introduced the term "jøkulgrus" in his textbook. Holmsen's descriptions gave a particularly clear picture of the dead-ice topography which is so typical for the north-eastern parts of Southern Norway, especially along the Swedish border. Here he described the hummocky landscape formed by coarse, unsorted ablation till and pointed out how these occur along with sorted glaciofluvial material. His descriptions have formed the foundation for the present classification of moraine types in Norway.

G. Holmsen had extended contact with his colleague G.Lundqvist in Sweden who gave several detailed descriptions of tills (Lundqvist 1940, 1943, 1951). These Swedish studies constitute, in my opinion, some of the most valuable papers on till composition that have ever been published. In Sweden, The Geological Survey gave very early preference to the mapping of Quaternary deposits. In Norway it was given a low priority; until recently the bedrock mapping has been dominant. As G.Holmsen at that time was the only state geologist working dominantly with Quaternary deposits, he had to base his mapping partially on work done by students. Most of the descriptions include only visual observations. Even though G.Holmsen had more restricted economic resources than his Swedish colleagues, his soil maps with descriptions have been of great importance, and they form some of the most systematic regional descriptions of till in Norway.

Another general description of tills was included in the work of Holmsen (1956 b), where the soils were grouped into five regions:

1. The area left by active glaciers shows:
   a. A region of submarine end-moraines and intermediate marine deposits, i.e. a region below the late glacial

marine limit.

b. A region sparsely covered by morainic drift.

2. The area of the stagnating ice-sheet shows:

c. A region of glaciofluvial and ablation morainic deposits in the valleys.

d. A region of dead ice traces on the mountain plains and along the ice-shed area.

e. A mountainous region showing frost-split rocks, solifluction phenomena and structural ground.

This soil classification was later published in English (see G.Holmsen 1963) (Fig.26).

In 1953 O.Holtedahl published his general description of the Quaternary geology in Norway (Norges Geologi, Bind II), which gives important information about the tills and moraines. Parts of this, including more recent data, were published in English in 1960 in connection with the International Geological Congress. It is difficult to refer particular descriptions from these books in a few words. They give up to now the only regional description of tills and moraines from the whole of Norway and have formed the basis of several detailed investigations of glacial deposits.

1971 - 1975

After 1970 The Geological Survey paid more attention to mapping of the Quaternary deposits than previously. This is primarily because the Norwegian government during the last years has given priority to the mapping of natural resources in a broad sence, and not only to the ore minerals.

The new series of Quaternary geological maps in scale 1: 50 000 have formed an important part of the till literature. Follestad (1973, 1974) published the first two maps from the Mjøsa area. Till is there the predominating soil type, and information about the tills form major parts of the descriptions. These descriptions seem to have been inspired by the modern Swedish descriptions, and include some of the same parameters like till gravel petrography and grain-size distribution (Fig.27). They also include heavy metal studies (Bølviken & Follestad 1973). There are discussion on the distribution and genesis of tills. The same type of maps and descriptions are presently published by The Geological Survey.

1976 - 1980

Three descriptions accompanying the maps of the Quaternary deposits were published during the period 1976-1980. Follestad (1977) and Sveian (1979) described the areas west of lake Mjøsa. Of particular interest is the discussions of the Mjøsa till, a till with a clay content which in some cases exceeds 25 %. This has been explained as an incorporation of lacustrine clay from the Mjøsa basin. Sørensen (1979) described transverse moraine ridges of the Rogen type from Elvdal, close to the Swedish border.

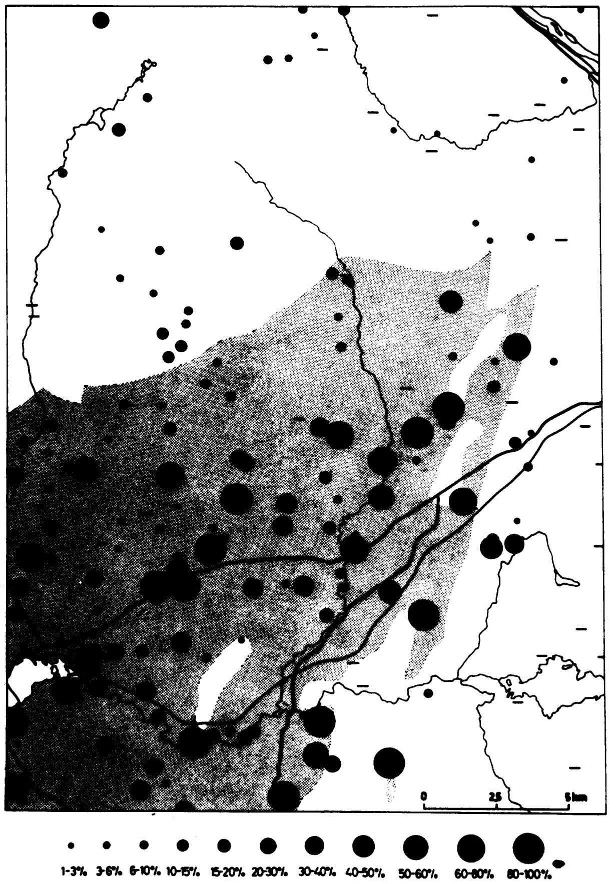


Fig.27 Example of gravel petrographical studies in the description to a modern Norwegian Quaternary geological map (Follestad 1973, p.11). This example shows the percentage of Cambro-Silurian rocks in the till fraction 4.8 - 8 mm. The extension of Cambro-Silurian bedrocks is indicated by the shaded area. The investigation is from Løten, east of the lake Mjøsa.

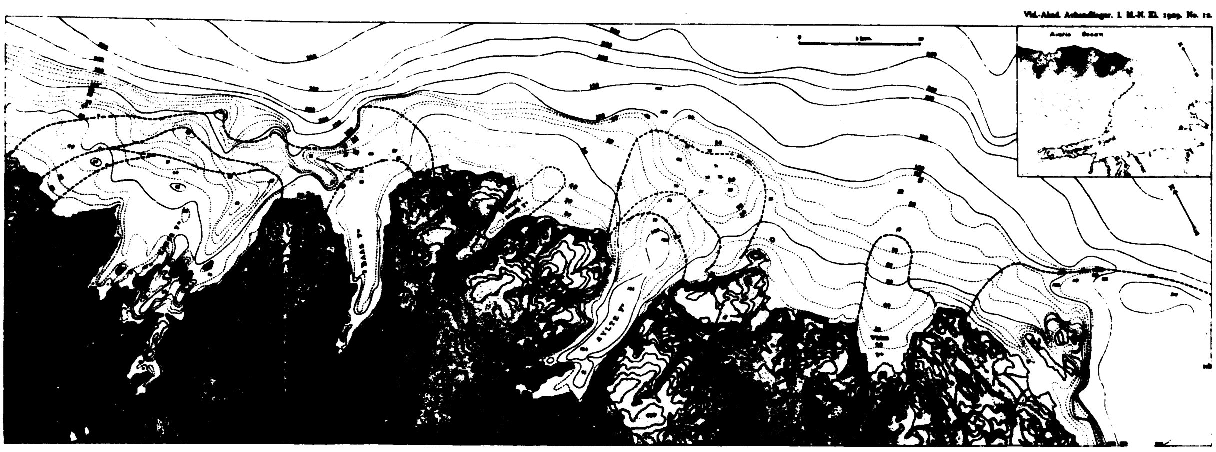


Fig.28 Map from the work of O.Holtedahl (1930) showing the supposed submarine moraine ridges (stipled) outside the coast of northeastern Finnmark.

MARINE GEOLOGICAL STUDIES

Helland (1875) observed and discussed a feature which is very characteristic of Norway: The end moraines are usually found in the front of glacially eroded lakes. Helland concluded that the end moraines reflected the marginal deposition, while the lakes with troughformed profiles behind the moraines reflected the glacial erosion. He interpreted the fishing banks outside the coast of Norway as end moraines and suggested that a landscape similar to that on the mainland, with lakes and end moraines, would have formed outside the present coast if the sea level was lowered, so that the fjords became lakes. This was a new and important aspect of the glacial theory. (According to K.O.Bjørlykke (1913 b) this was a controversial idea which was not supported by Kjerulf).

Some ideas about the extension and retreat of the Weichselian ice cap outside the coast of Norway were published by O.Holtedahl (1930). Based on information about the bottom topography outside Finnmark he theorized that some of the ridges were end moraines (Fig.28). O.Holtedahl continued these studies and in 1940 he published a work on supposed end moraines outside other areas of the Norwegian coast.

In 1951 and 1955 the first regional investigations of the sediments on the continental shelf outside Norway were published by H.Holtedahl. The studies included soundings and sampling by dredging and cores. The grain-size distribution and petrography of large number of samples taken both from tills and other sediments were studied. The conclusion was that most of the sediments were transported out from the mainland by glaciers. This was a logical conclusion from these data, though we today know that this is valid only for the coarsest material.

During the last few years the continental shelf has become an important area for till investigations and moraine chronology. Detailed investigations of the sediments and morainic morphology are based on cores, surface samples and seismic profiles (Rokoengen et al. 1977, 1979, Bugge et al. 1978, 1980, Vorren & Elvsborg 1979). These have given new information about the extension and deglaciation of the Weichselian ice sheet. Such studies, which are of great importance for the understanding of the Pleistocene in Norway, will be continued.

SOIL SURVEY AND HEAVY METAL STUDIES

K.O.Bjørlykke was professor of the Department of Geology and Soil Science at the Agricultural University from 1898 to 1931. He was both a highly qualified geologist and a proficient soil scientist, what is clearly demonstrated in his many publications. He recognized the very vital connection between soil genesis and quality for agricultural use. At that time this relation was probably more important than today, as modern agriculture seems to be more and more independent of the primary composition of the soils. K.O.Bjørlykke pointed out that soil descriptions should include soil maps, descriptions of sections, information about the genesis, grain-size distribution, petrographical composition and content of plant nutrients (K.O.Bjørlykke & Løddesøl 1930, p.1).

Accordingly several detailed soil descriptions were published by the Department of Geology and Soil Science (Fig.29) (Hundseid 1911, Kaldhol 1915. Glømme 1921, 1926, Sørlie 1925, Streitlien 1928, H.Bjørlykke 1929, K.O.Bjørlykke & Løddesøl 1930, Gyland 1935, Vigerust 1936).Among these the work by K.O.Bjørlykke & Løddesøl (1930) from Ås gives us the most comprehensive descriptions of tills. The soil descriptions were of particular importance because they gave quantitative information about the composition of tills. The regional studies from the Geological Survey were during these years mainly based on visual descriptions.

The works of Selsjord & Låg (1953) from Hordaland and Semb (1954) from Klepp, Rogaland gave detailed information on the till petrography, grain-size distribution and chemistry. Skadsheim (1956) studied the content of boulders and cobbles in tills from an agricultural point of view. Låg (1948, 1960) studied "the parent material of the morainic cover of the south-eastern part of Norway". The investigation included stone petrography, grain-size distribution and content of plant nutrients in tills from different bedrock areas. The till material was divided in three main groups:

1. Coarse-grained tills with a stone petrography which reflected the underlying bedrock (autochthonic till),
2. Coarse-grained till with dominantly long transported stones (allochthonic till)
3. Clayey till

Låg discussed how the till material was formed, described the crushing of bedrock material and tried to interprete the

4. *Profilet er tatt i det sydøstre hjørne av planteskolen, nogen meter fra landeveien, ca. 105 m. o. h.*

Den øvre del av profilet bestod av en mørkgrå matjord, som strakk sig til ca. 40 cm.'s dyp; derunder kom en lysegrå undergrunnsjord.

Undergrunnsjorden (C) inneholder 11,8 % leirholdige deler og de øvre jordlag noget mere. Jordarten må derefter betegnes som *et leirrikt morénegrus.*

Kjemisk analyse (Kj. Kontrollst., Trondhjem):

	A (0-25 cm.)	B (25-40 cm.)	C (40-60 cm.)
Kvelstoff (N)	0,16 %	0,14 %	0,02 %
Fosforsyre (P_2O_5)	0,20 »	0,16 »	0,12 »
Kali (K_2O)	0,08 »	0,04 »	0,05 »
Kalk (CaO)	0,59 »	0,33 »	0,19 »
Jernoksyd (Fe_2O_3)	3,01 »	3,12 »	3,49 »
Glødetap	6,47 »	5,52 »	2,46 »
Reaksjon (pH)	6,7	6,4	6,3

Efter glødetapet kan matjordens humusinnhold settes til ca. 4 %. Både A- og B-skiktet er forholdsvis rike på fosforsyre og kalk, men noget fattigere på kali. Nogen utlutning legger man ikke merke til; den er forresten vanskeligere å konstatere efter de foreliggende analyser, da matjorden er så dyp at den omfatter både A- og B-skiktet.

Reaksjonen er svakt sur.

Fig.29 Table showing the chemical composition of soils from the Ås moraine. Such chemical analysis formed standard parts of the soil surveys by the Department of Geology and Soil Science from the beginning of the 19th century (K.O. Bjørlykke & Løddesøl 1930, p.39).

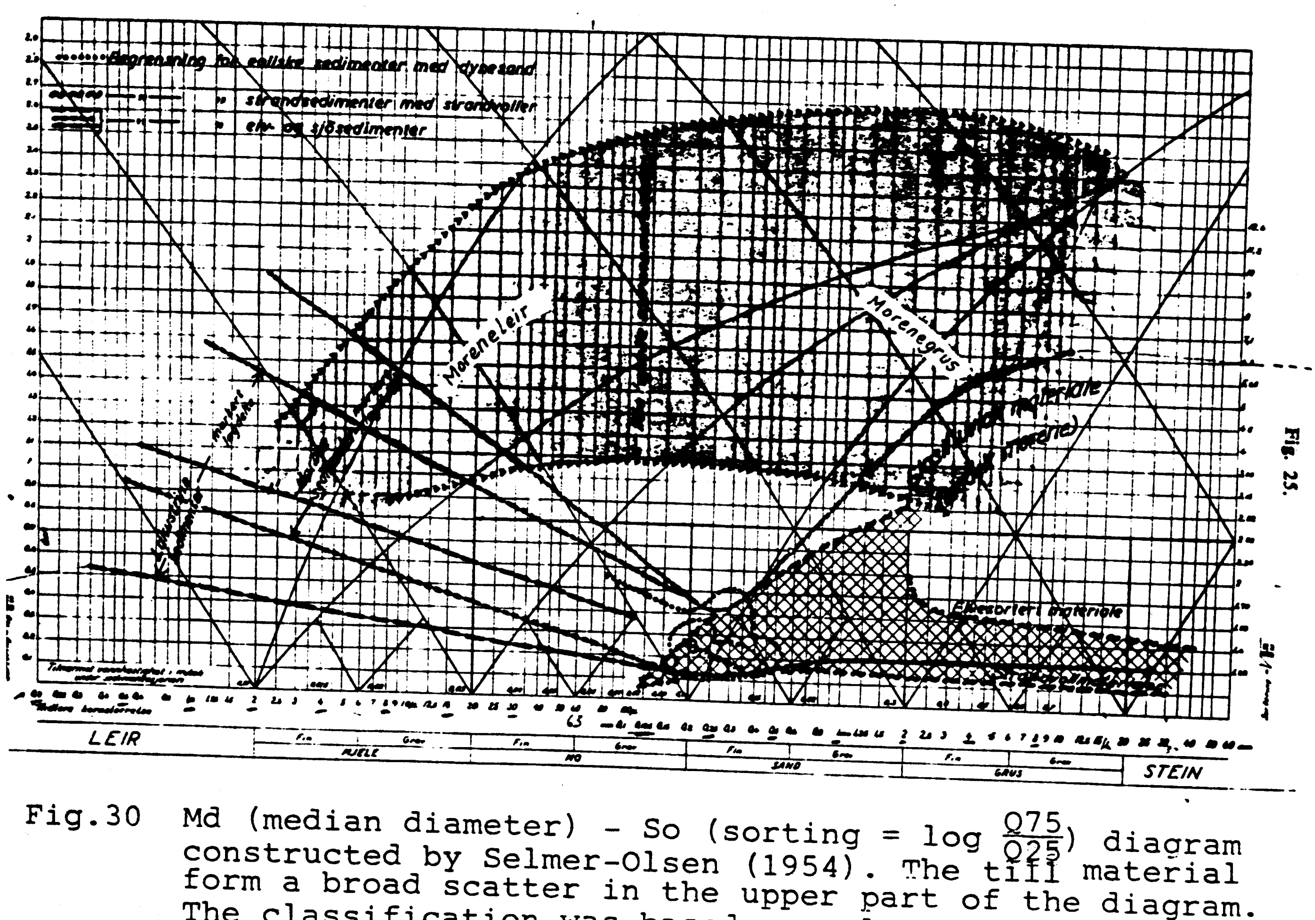


Fig.30 Md (median diameter) - So (sorting = log $\frac{Q75}{Q25}$) diagram constructed by Selmer-Olsen (1954). The till material form a broad scatter in the upper part of the diagram. The classification was based on a large number of samples from all parts of Norway.

behaviour of the ice.

Semb (1962) gave the hitherto most detailed soil description in Norway. The paper which concerned Jæren is accompanied by a soil map worked out in accordance with international standards. The paper very clearly points out the close connection between the soil profile type and geology. The investigation included the petrography of the fine sand, in addition to stone countings. This is important since the coarse fractions are not necessarily representative for the total till.

Some heavy metal data on soils, including till, were published by Bølviken (1967) and by Låg et al. (1970). The purpose was to demonstrate the use of geochemical studies in ore prospecting and documentation of naturally poisoned soils. The use of geochemical parameters for ore prospecting has been subordinate in Norway compared with the studies in Finland and in Sweden (see e.g. Hyvärinen et al. 1973).

The work of Bølviken & Gleeson (1979) on heavy metals in tills and other soil types should also be mentioned. This is the first work of its kind in Norway which applies the results of modern till studies to explain the distribution pattern of elements in tills. This work illustrates that detailed information about the genesis and composition of tills may be of value in applied geology.

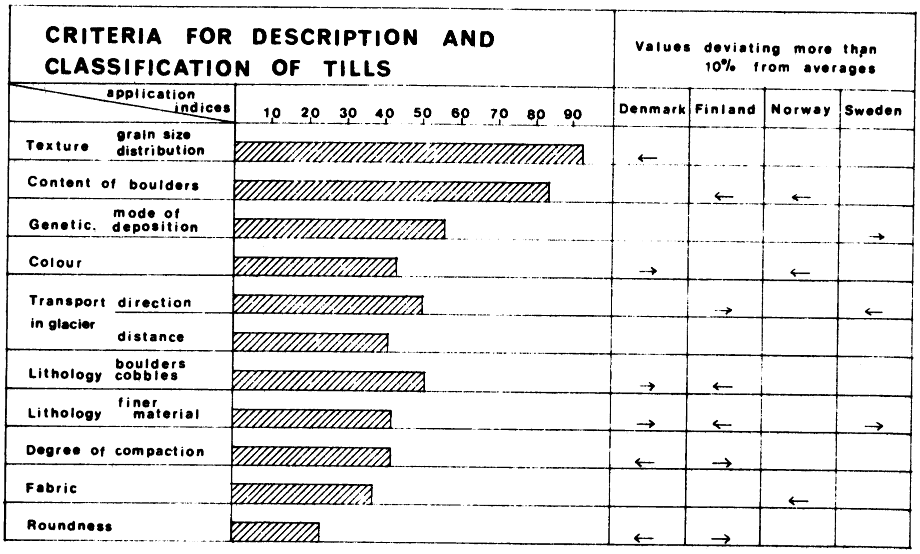
TILL MATERIAL AND TILL GENESIS - SEPARATE STUDIES

Few Norwegian papers present separate studies of till composition and till genesis.

In 1954 Selmer-Olsen published a study of the plasticity and grain-size distribution of Norwegian sediments. based on about 2000 samples. The grain-size data was presented in a median-sorting diagram which distinguished well between genetically different soil types. The tills constituted a broad zone in the upper part of the diagram, indicating poor sorting (high Selmer-Olsen's sorting value (Fig.30)). This diagram has later been widely applied by Norwegian Quaternary geologists.

In 1968, the Numedal project, which involved detailed studies of the till matrix composition, was initiated, with Prof. I.Th.Rosenqvist as the coordinator. Mineralogical and geochemical studies of the sand, silt and clay were carried out. Much of the data from the project is still not published, but are available as cand.real.theses at the Univ.of Oslo. One conclusion from the project was that all the sediments, in Numedal, and particularly the till, were significantly influenced by pre-Quaternary (Tertiary) weathering products (Roaldset & Rosenqvist 1971, Korbøl & Jørgensen 1973, Rosenqvist 1975 a, 1975 b). Roaldset (1972, 1973 a, 1973 b) published data on the clay mineralogy and geochemistry of tills including analyses of rare earth elements, a parameter which was not previously studied in detail in any Norwegian soil.

In connection with the work of the INQUA-Commission on Genesis and Lithology of Quaternary deposits, Haldorsen (1975) distributed a questionnaire among Nordic geologists on methods of till investigation. The replies revealed that the Norwegian till investigations, like in other Nordic countries were dominated by visual observation and grain-size data. But other parameters were also considered in a large number



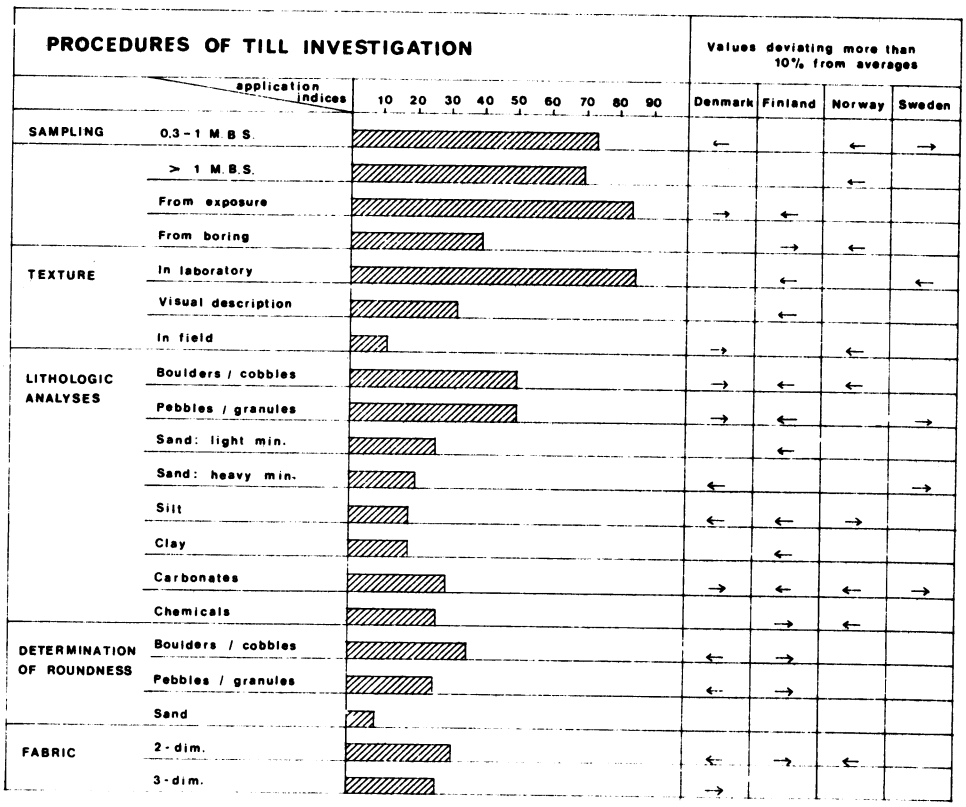


Fig.31. Diagrams showing the criteria of till classification and methods of till studies in Norden (Haldorsen 1975, p.7 & 8). Based on a questionnaire replied by till investigators from 38 Nordic institutions representing 146 till investigators. Numbers 10 - 90 indicate the percentage of studies in which the different parameters are applied. Arrows show deviation from the average, towards right: higher than the average, towards left: lower than the average.

of the studies (Fig.31). The results were presented at the Commission's meeting in Poland in 1975 where it proved that the same parameters dominate in till studies in other parts of the world.

Separate studies on the roundness of gravels in till was published by Bergersen (1970, 1973). He concluded that the roundness values were valuable parameters for the interpretation of till genesis.

During the years 1970 - 1980 there has been increasing interest in the composition of Norwegian tills. It was recognized that the results of till studies from the marginal parts of the Scandinavian ice sheet and from America were not always representative for Norwegian tills. Jørgensen (1977) gave a summary article on the grain-size distribution of Norwegian tills based on data from 3000 till samples. The till could only be divided in two main groups by means of the three-component system: gravel, sand, silt/clay. The first group was samples from Cambro - Silurian bedrock areas, the second was tills from all other bedrock types, (Fig.32). Based on the three-component system: sand, silt, clay, not even these two groups could be distinguished, since both groups have a low clay content. Jørgensen (1978) also described the compaction and permeability of homogenized and packed tills, and showed how the grain-size distribution could be used to estimate permeability after packing.

For tills from Hardangervidda, Vorren (1977) used the grain--size parameters of Folk & Ward to distinguish between basal till and ablation till and between tills formed from phyllitic and granitic rocks.

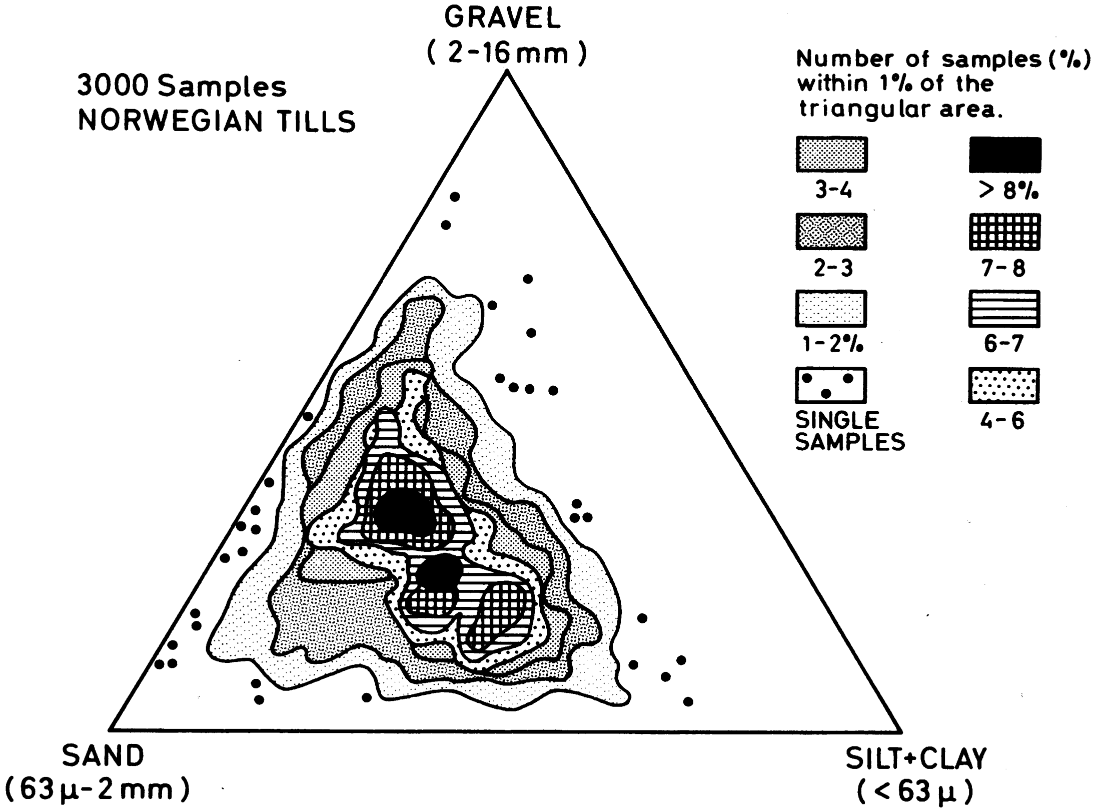


Fig.32 Mechanical composition of 3000 till samples (<16 mm). Two distinct maximum concentrations are observed due to tills from areas with Cambro-Silurian sedimentary rocks (lower maximum) and tills from Precambrian rocks (upper maximum) respectively. (After Jørgensen 1977, p.152).

A detailed study from the Mjøsa region, of all till matrix fractions was carried out by Haldorsen (1977). The study was based on X-ray diffractograms and thin sections. This is the only work published in Norway which includes studies of the total clay, silt and sand. The study was concerned with transport length, the dilution of rock component during the glacial transport, the mechanism of glacial comminution of different rock types and the size distribution of different rock components in the till. The conclusions were further discussed in a small separate paper (Haldorsen 1978).

Garnes (1976) published a separate paper on drumlins from Eigerøya in southwestern Norway, and concluded that these most probably were erosional forms.

FINAL REMARKS

It is surprising how quickly understanding about the genesis of tills and moraines were established after the introduction of the glacial theory. Many of the works which were published before 1900 were detailed and multifarious, several of them represent orinal contributions which are still of interest today not only from a historical point of view. These studies were actually focused on many of the problems which have been discussed up to the present among Norwegian glacial geologists. The studies before 1920 outlined the most typical characteristics of the Norwegian tills and the position and features of the most marked end moraines.

The studies from the period 1921 - 1950 are not as numerous and varied as during the preceding twenty years, as The

Geological Survey gave greater preference to bedrock mapping.

From 1950 to 1970 studies of the ice retreat by means of end moraines and regional descriptions accompanying the Quaternary geological maps were totally dominating. From 1970 attension was paid to studies of till from the inland Norway which gave more knowledge about the formation of Norwegian tills. There is still much to be done before we have a full understanding of the Norwegian till sheet.

During the last few years the Norwegian Continental Shelf Institute and the Norwegian Geotechnical Institute as well as the Universities of Bergen, Oslo and Tromsø have been increasingly involved in studies of the Quaternary sequence in the North Sea and in other parts of the continental shelf. Such studies will certainly be of increasing importance in the future. They will probably give information about the pre-Weichselian tills which have only been found at isolated localities on the Norwegian mainland.

The glacial geologists seem to be gradually more involved in sedimentological problems which also include the tills. The result of till studies from recent glaciers have initiated detailed sedimentological studies of Pleistocene tills in many countries. The genetic classification of tills based on their sedimentological properties forms an important part of the work of INQUA-Commission on Genesis and Lithology of Quaternary deposits. The sedimentology of Norwegian tills, both the regular inland till sheet and the complex facies variations of the marginal deposits, should be an interesting subject for Norwegian sedimentologists in the future. This is already today clearly indicated by the studies of the ice marginal deposits belonging to the Ås - Ski stage which were recently begun at the Agricultural University.

Aknowledgements. This work has been initiated by a Nordic cooperation and will form the basis for the Norwegian part of a Nordic analytical bibliography on tills and moraines. The criteria of a till bibliography and the choice of relevant literature have in particular been discussed with Hans G. Johansson and Ib Marcussen. The selection of literature in Norway has been commented by Kari Garnes. The manuscript has been commented by Per Holmsen and Per Jørgensen. Eldri Jørgensen has taken photos of illustrations and several colleagues have placed photos at my disposal. Barbara Kvalvåg kindly corrected the text of the English manuscript and Marie-Louise Falch has type-written the manuscript. To all these persons I tender my sincere thanks.

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PAPER 2

THE CHARACTERISTICS AND GENESIS OF NORWEGIAN TILLS

SYLVI HALDORSEN

THE CHARACTERISTICS AND GENESIS OF NORWEGIAN TILLS

S. HALDORSEN

Till is the dominating Quaternary sediment in Norway; only along some valley bottoms and below the marine limit is the till commonly covered by younger sediments.

The properties of Norwegian tills are controlled by the following factors:

1. Elevation: Large parts of Norway are either mountainous or upland areas higher than 700 metres a.s.l. (Fig.1 A).
2. Relief: There is a variable topography with mountain areas intersected by deep valleys and fjords.
3. Bedrock: The bedrock concists mainly of resistant Precambrian rocks or of Cambro-Silurian sedimentary rocks (Fig.1 B).
4. Ice: Generally the country was situated far inside the ice margin during the maximum of the Scandinavian ice sheet.

Thickness

Till covers of large extension and a thickness of many metres as they occur in the marginal areas of the Scandinavian glaciation are quite uncommon in Norway. The only two regions where such till covers may occur are at Jæren in southwestern Norway and at parts of Finnmarksvidda in northern Norway. The characteristics of tills from Jæren may be considered as comparable with those of the Danish tills (HELLAND 1885), while tills on Finnmarksvidda in many ways are similar to those from the adjacent Finnish areas (A.READ, pers.comm.1981). The following generalized descriptions of the Norwegian tills therefore do not apply to these two regions.

Over great areas the till cover is discontinuous (Fig. 1 C). Its thickness here only locally exceeds 1-2 m (Fig.2). Even in areas with a continous till cover (Fig.3) the average thickness is usually not more than 5 m.

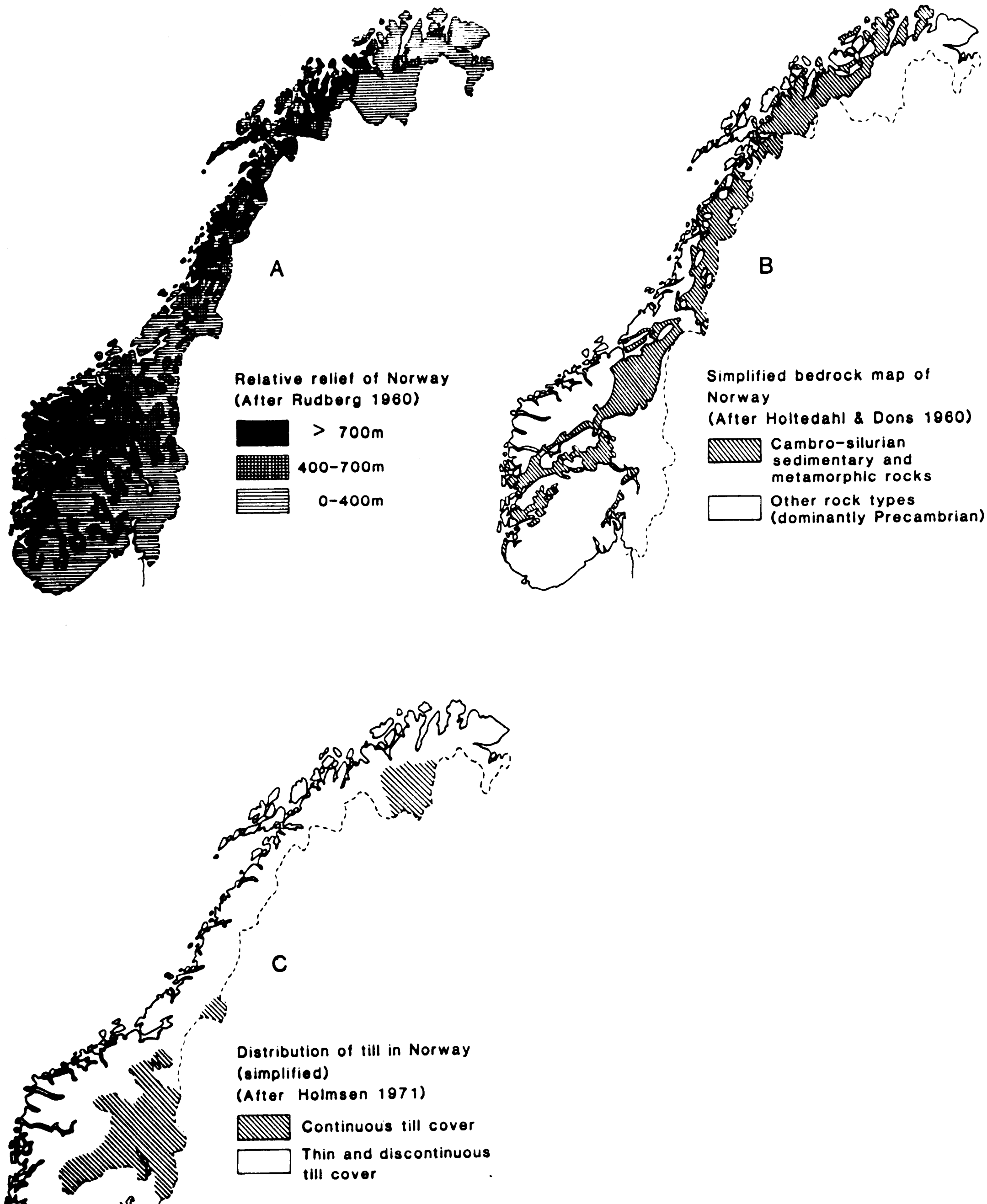

Fig.1 Relief, bedrock composition and till distribution in Norway.

Fig.2 Characteristicly discontinuous till sheet from Øyungenfjellet mountain area, southeastern Norway. Note the great frequency of angular boulders.

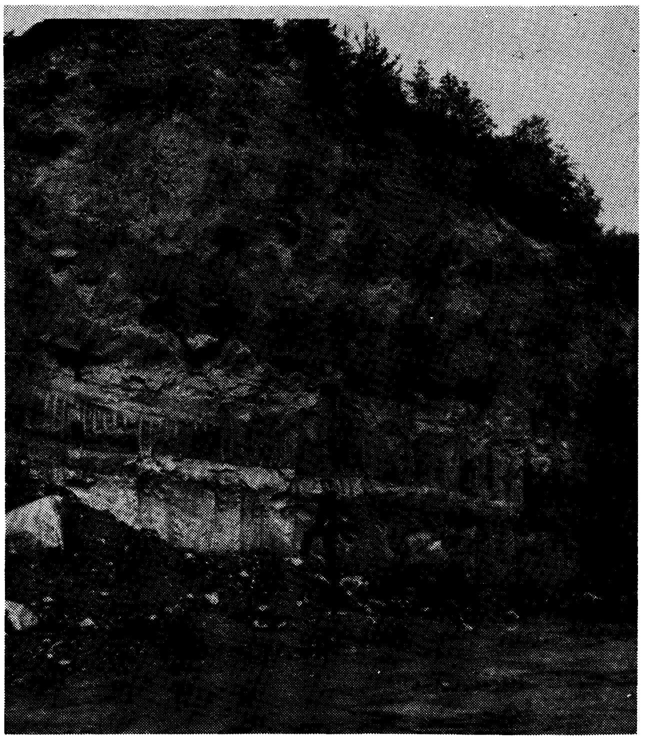

Fig.3 Exposure in a thick valley deposit from Numedal, southeastern Norway. The upper part consists of lodgement till, the lower part of sub-till sediments which have been related to an early Weichselian interstadial (ROALDSET 1973) (Photo: P.Jørgensen).

The small till thickness is mainly a result of the relief. The Norwegian upland areas were regions of net erosion during the Pleistocene. Vertical glacial erosion was particularly strong in areas with steep topography. In accordance with this the till is most discontinuous along the western parts of Norway where the mountainous areas are intersected by deep fjords and valleys, while it is somewhat more continuous in the east in areas which were situated close to the ice divide. The removal of material was also promoted by the central position beneath the ice sheet. The transport of material was directed out from the area towards the ice margins all the time. Large amounts of material from the land areas are therefore found on the continental shelf.

During the glacial maximum the activity at the base may have been rather small in the central part of Scandinavia. A smaller amount of till was therefore formed here than in the marginal areas where there was a more continual accumulation of till. This may be an additional explanation of the small till thicknesses in Norway.

Another reason for the thin till cover can be seen in the dominance of resistant bedrock types (Fig.1 B). Continuous tills are thus found in some Cambro-Silurian areas, where neighbouring areas with Precambrian rocks only bear a sparse cover of till (see FOLLESTAD 1973, 1974).

Transport Length

The bulk of the present till material has not travelled further than 5 km. In most cases it reflects strongly the immediately underlying rock types (see LÅG 1948). This applies not only to the coarse material but to all grain sizes. A transport of 20-30 km is already considered as "long" in Norway.

In general the upland areas are covered by the most local material (see LÅG 1948, BERGERSEN 1964). In the valleys which acted as drainage channels for the ice the glaciers were active until the complete deglaciation and they therefore contain more far travelled till material than the uplands. The valley floors may in cases be covered by multicyclic material which has been

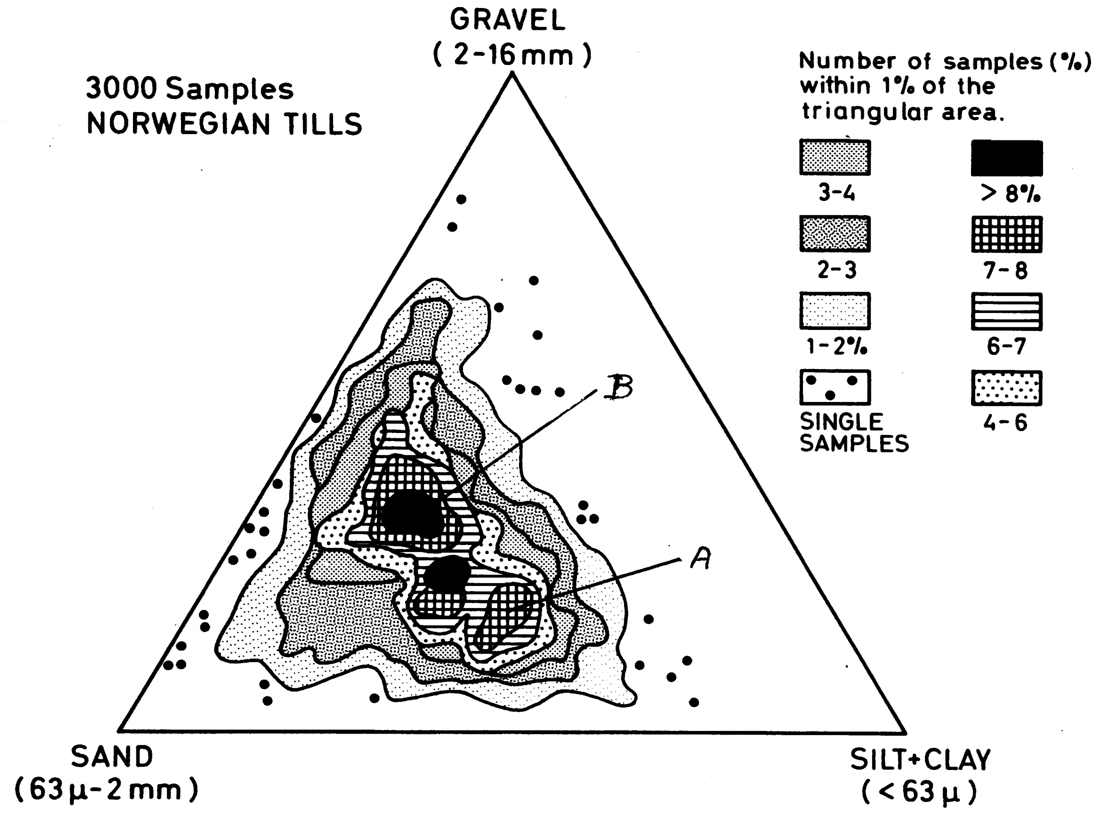

Fig.4 Grain-size distribution of Norwegian tills shown in a triangular diagram (After JØRGENSEN 1977).

A: Maximum of tills from Cambro-Silurian bedrocks.

B: Maximum of tills from other bedrock types.

picked up and retransported during several glacial phases (KORBØL / JØRGENSEN 1973).

Another long transported till component is the erratics. Typical erratics in Norway are the Late Precambrian sedimentary rocks from the area north of the Lake Mjøsa and the Permian vulcanic rocks from the Oslo area. They are found within and south of their source area. Such erratics may have undergone glacial reworking and redeposition during several glaciations. It should be emphasized that in Norway such long transported components usually form only minor parts of the tills.

Grain-Size distribution

The Norwegian tills are generally coarse-grained (Fig.4). JØRGENSEN (1977) showed that the clay in most cases constitutes less than 10 % of the material finer than 16 mm. This applies to tills from most bedrock areas. A higher clay content is found locally in Cambro-Silurian areas (FOLLESTAD 1973, 1974, HALDORSEN 1977) and in the places on land where the glacier has incorporated older marine clays (e.g. H.HOLTEDAHL 1964, MANGERUD et al.1981, GJESSING / FJELLANG 1956).

The Norwegian tills commonly have a gravel content (fraction 2 - 16 mm) of 20 - 40 % (Fig.4). The proportion is considerably higher if the total gravel fraction 2 - 64 mm is taken.

Boulders and cobbles are abundant in most tills in Norway. These large fractions usually make 30 - 70 % of the total till (Fig.5). The content is dependent on the bedrock types and on the topography. Steep and variable topography together with intensely jointed bedrock in many places have promoted a considerable glacial plucking and contributed great amounts of coarse clasts to the till (Fig.6).

The Norwegian tills can be divided into two groups according to their grain-size distribution (Fig.4) (JØRGENSEN 1977). The main difference between them is found in the content of silt + clay and in the content of gravel (see Fig.5). The most silt-rich group is composed by tills from Cambro-Silurian bedrocks, and

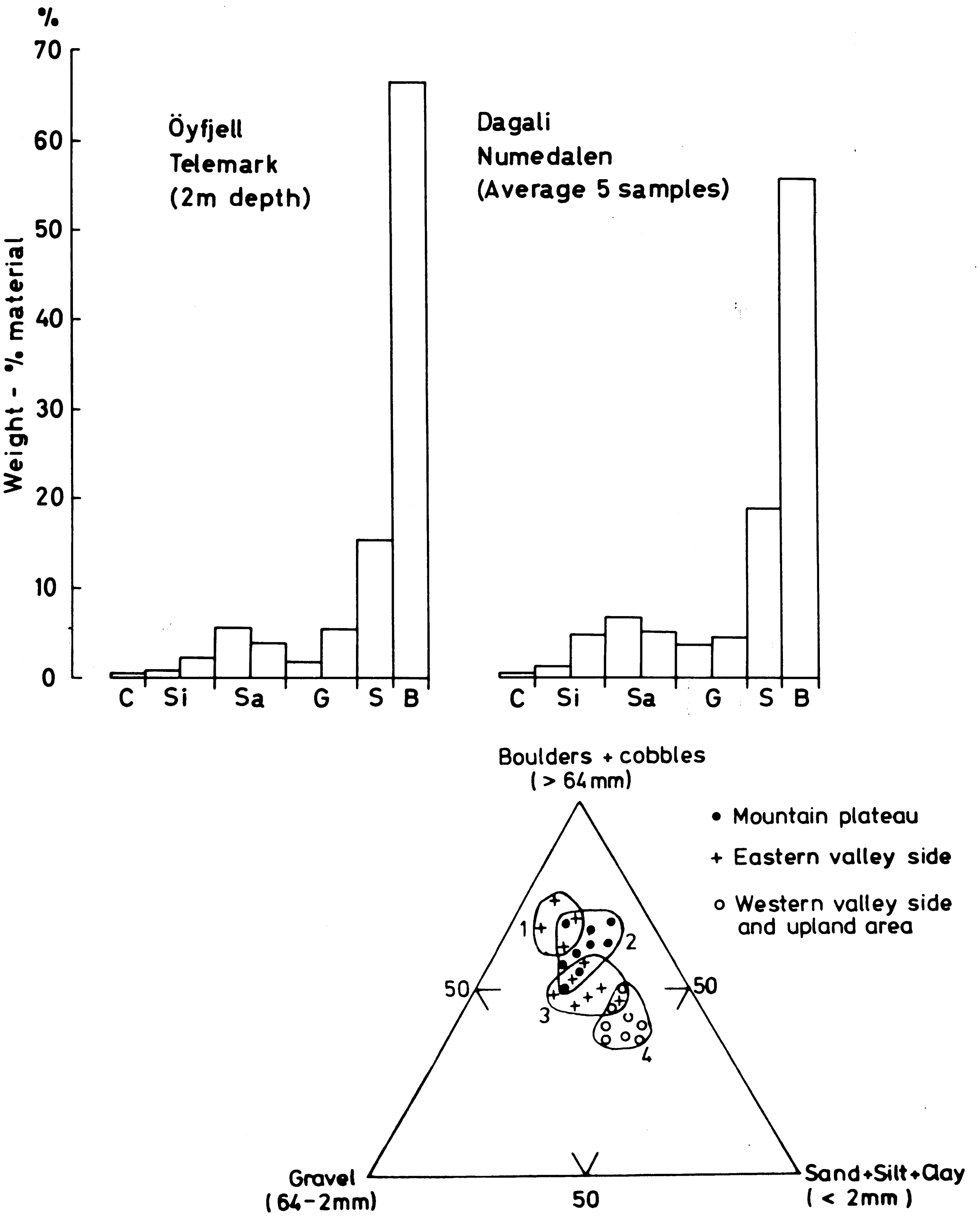

Fig.5 Total grain-size distribution of some tills from Norway.

A. Tills from Precambrian bedrock areas (JØRGENSEN 1977). C=clay, Si=silt, Sa=sand, G=gravel, S=stones and B=boulders.

B. Tills from Åstadalen, souteastern Norway.
1: subglacial melt-out till, lee-side localities
2: subglacial melt-out till, mountain areas
3: genetically composite till
4: dominantly lodgement till

Fig.6 Boulder-rich till surface at a lee-side locality in Åstadalen, southeastern Norway. The till is interpreted as a subglacial melt-out till.

the most gravel-rich group is composed by tills from all other bedrock types.

Time of till deposition

Pre-Weichselian Quaternary tills have rarely been identified in Norway. Safe examples can only be given from the Bergen area (Fig.7) (MANGERUD et al. 1981) and from Voss, west of Bergen (SINDRE 1979). Locally the basal parts of the present till sheet may have been deposited before the Weichselian maximum. Tills of presumably early Weichselian age are described by BERGERSEN / GARNES (1972, 1981), VORREN (1979), HELLE et al (1981) MANGERUD et al. (1981).

However, in most areas there is only one single till unit. The major part of this till was probably deposited after the Weichselian maximum when the ice sheet became thinner and - due to the high basal melting - an active basal sliding occurred.

Minor proportions of the till material may have been formed in pre-Weichselian times. ROSENQVIST (1975 a, 1975 b) proposed that tills in Numedal, southern Norway, even contained a pre-Quaternary component. However, both within and outside the valley areas most of the till material presently found may be considered as fresh bedrock material which was glacially comminuted during the Weichselian.

Till Genesis

Only a few studies of Norwegian Pleistocene tills have involved detailed interpretations of till genesis. The classical division of tills; basal tills and ablation tills, has been applied for a long time (HOLMSEN 1954, 1955, 1960).

The first group refers to material transported at the glacier base. It is characterized by its compactness, relatively fine-grained texture and its smooth surface morphology. The second group refers to material which is believed to originate from

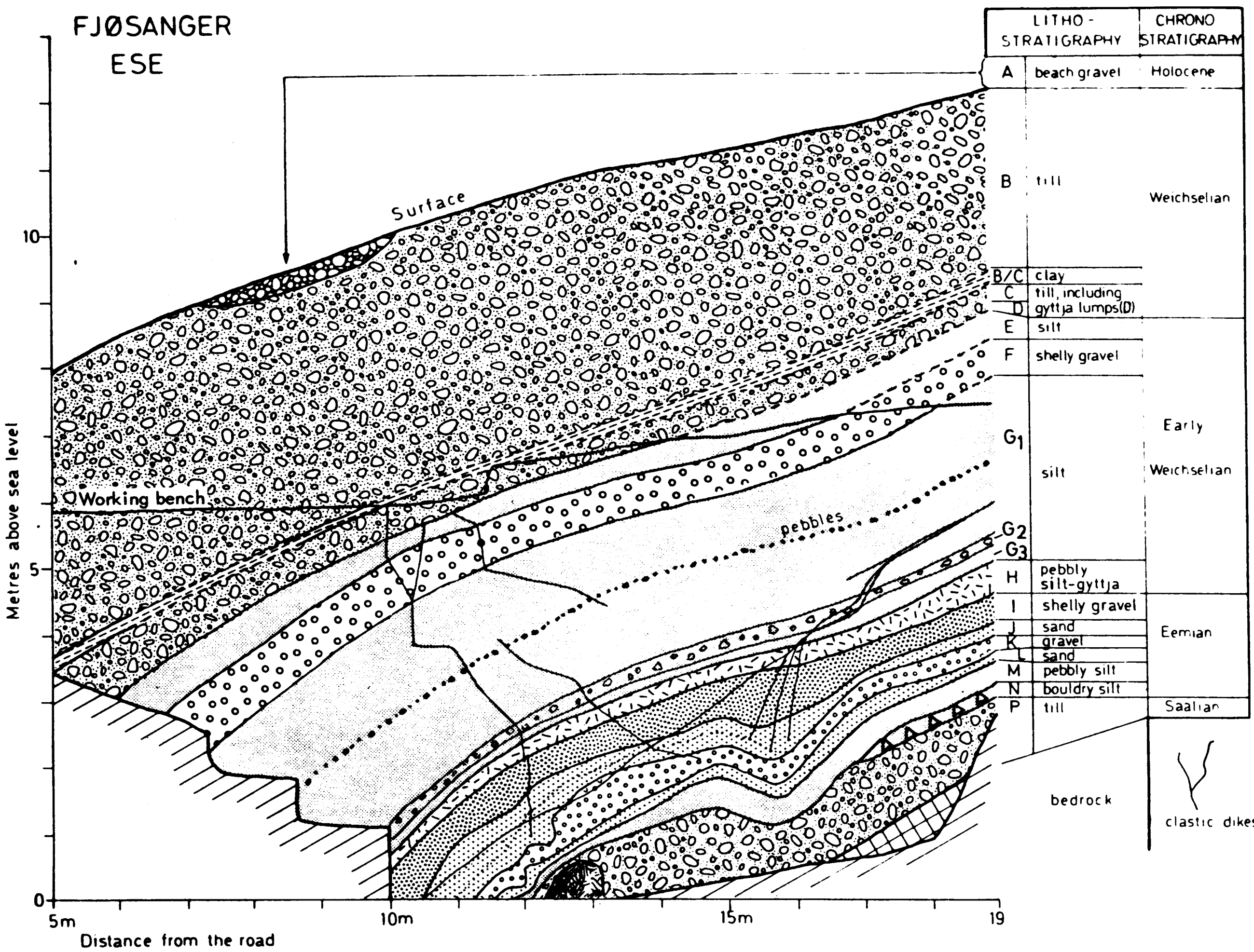

Fig.7 Saalian till (P) beneath an Eemian (I-N) and Weichselian (B-G) sequence at the Fjøsanger locality, Bergen MANGERUD et al. 1981).

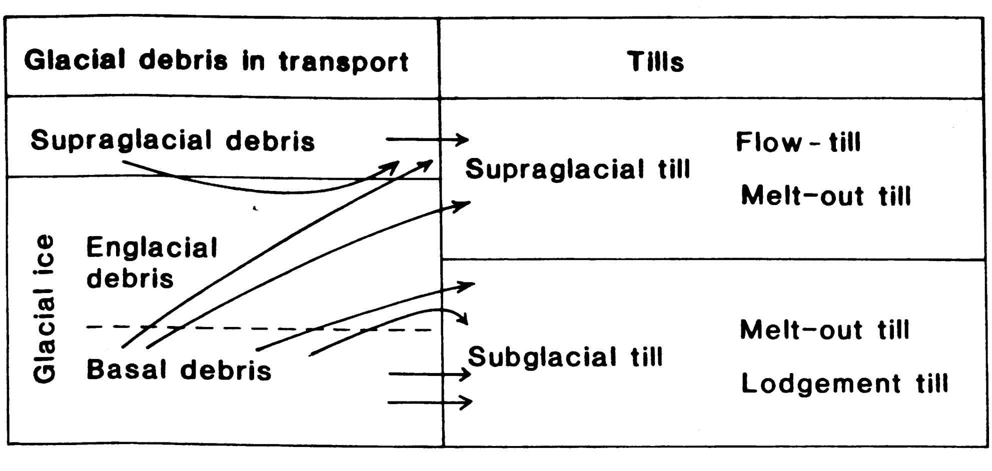

Fig.8 Genetic classification of Norwegian tills. (Modified after DREIMANIS 1976).

supraglacial drift. It is identified by its sandy matrix and its low degree of compaction and by a hummocky and ridge-shaped surface morphology. VORREN (1979) studied tills from Hardangervidda and found that these criteria in many cases distingquished well between the two till groups.

However, VORREN (1979: 41) also pointed out that it is many cases difficult to distinquish between the two till groups. This is also shown by the studies from recent glaciers (BOULTON 1976, SHAW 1977, LAWSON 1979) and from till studies in Sweden (G.LUNDQVIST 1940: 36-41, 1951; 55, J.LUNDQVIST 1969 a: HOPPE 1963). HALDORSEN (in prep) tried to interprete the till genesis in Åstadalen, southeastern Norway. The results may be representative for some other areas with the same characteristics.

The general criteria for interpretations of till genesis and the results from Åstadalen led to the following classification (Fig.8).

Subglacial Tills

By far the most common types of till were formed by basal accumulation of debris. These subglacial tills (Fig.8) can be divided into two subgroups: lodgement tills and subglacial melt-out tills.

Lodgement tills as described by BOULTON (1976) and DREIMANIS (1976) are characterized by high degree of compaction, a silt-rich matrix and by abraded, striated clasts. They were formed at the base of active, sliding glaciers. Tills with these characteristics are found many places in Norway (Fig.9). This applies to tills described from Jæren (GRIMNES 1910: 54-73), Hardangervidda (VORREN 1979) the Mjøsa district (HALDORSEN 1977), Åstadalen (HALDORSEN 1981) and parts of Finnmarksvidda (HOLTEDAHL 1960: 429-431). Along most valleys and in areas where a gently undulating topography promoted a uniform, basal sliding, lodgement till should be the main till type. Therefore, much of the previously described basal till in Norway is probably lodgement till.

Where basal stagnation occurred, a subglacial melt-out till was locally deposited. This may have happened where friction against the bed caused isolated parts of the basal ice to stagnate, or where topographical obstacles forced the movement to slow down. The deposition of till material was a process of "passive" melt-out (Fig.8).

Some subglacial melt-out till was probably also formed from the debris which remained in the ice until the deglaciation was completed. Such till would form the uppermost part of a till sheet which dominantly consists of lodgement till.

One type of subglacial melt-out till has been described from Åstadalen, southeastern Norway by HALDORSEN / SHAW (in prep). This has accumulated in ridges transverse to the direction of ice movement (Fig.10), like the Rogen moraines in Sweden which have been described and discussed by J.LUNDQVIST (1969) and SHAW (1979). The ridges in Åstadalen are composed of abraded clasts in a sandy matrix. The long-axis orientation of the clasts is consistently parallel to the direction of ice movement. These ridges were probably formed in zones where basal ice with a high debris content was stacked or folded. The described moraine ridges are concentrated in areas upstream of valley narrowings. Their formation is related to the deglaciation phase. The material was probably formed by basal drift of the same kind as the lodgement till. The low content of fines is mainly the result of water activity during the melt-out process.

Transverse moraine ridges have been described also from other parts of central Norway (SØRENSEN 1979, CARLSON et.al. 1979, SOLLID / SØRBEL 1979, SOLLID et al. 1980). They have partly been interpreted as accumulations of supraglacial material (SØRENSEN 1979: 23-24). Their genesis, however, has not been studied in detail. Therefore one can not exclude the possibility that also some of these ridges may originate from a melting out of basal drift.

Quite a different type of subglacial melt-out till has been identified in the mountainous areas surrounding Åstadalen. It was formed in areas where the activity at the glacier base

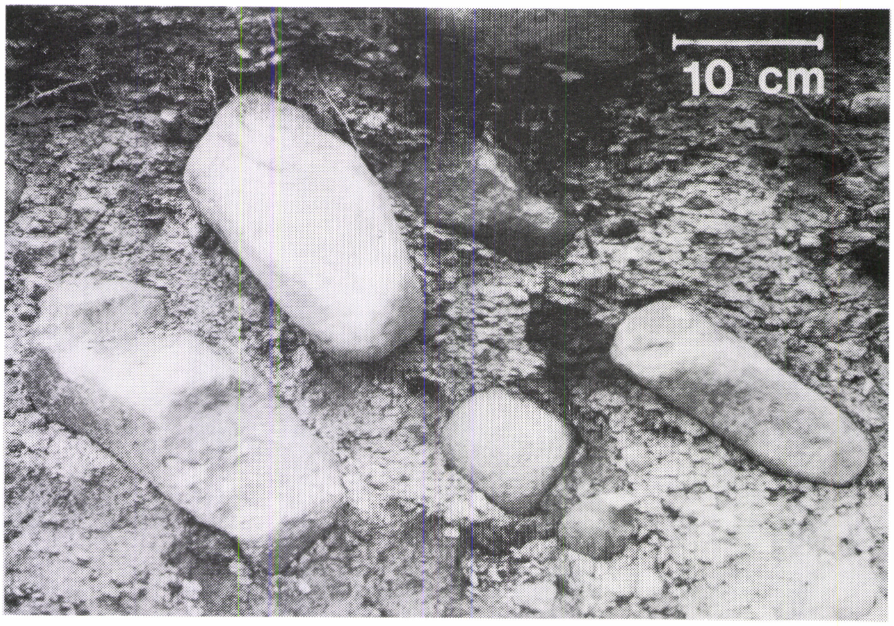

Fig.9 Lodgement till in Åstadalen, southeastern Norway, with a characteristic long-axis dip of the clasts in an up-glacier direction.

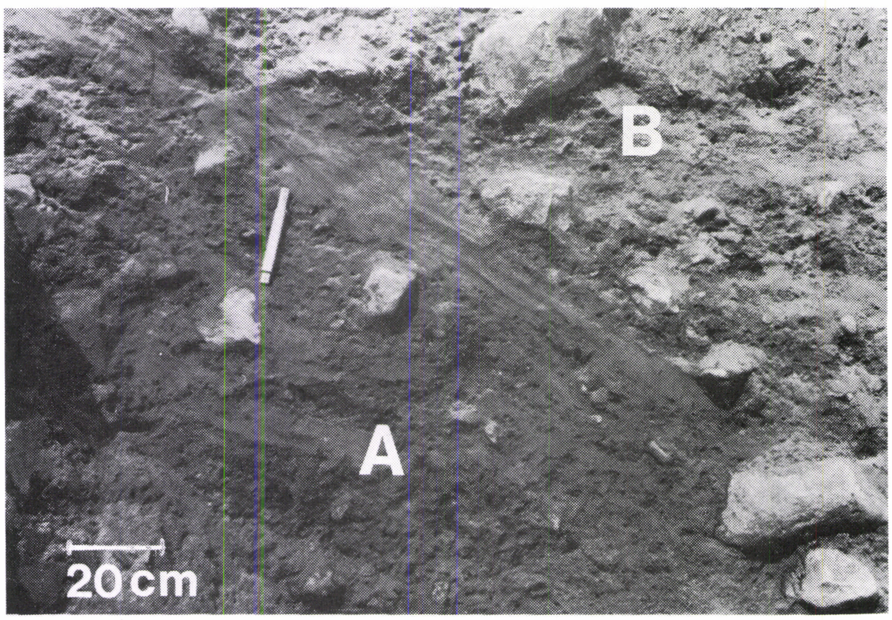

Fig.10 Section in a Rogen type moraine in Åstadalen, showing subglacial melt-out till at the base (A) and supraglacial sediments in the upper part (B).

was low. Such till material is extremely short transported, coarse-grained and contains angular clast material. The thickness is always very small (Fig.2).

A coarse-grained subglacial melt-out till with angular clasts is found locally on the lee sides of hills and valleys (Fig.6). Occurrences of such till can be observed frequently in Norway. Its formation is determined by the steep and variable topography which promoted glacial plucking (HALDORSEN 1977, 1981).

While a lodgement till bears some very typical characteristics, the qualities of a subglacial melt-out till may vary over a wide range. In some cases it may be rather similar to a lodgement till. Then it is very difficult to decide whether subglacial melt-out or lodgement took place. However, as lodgement till is the common till type deposited by an active sliding glacier, it is assumed to be more abundant than subglacial melt-out till.

Supraglacial Tills

A hummocky terrain formed by diamictons and sorted, stratified sediments is found in several inland areas (Fig.11). It was formed mainly in the last phase of the deglaciation when ice remnants still lay in valley areas and depressions. The diamict sediments have usually been interpreted as ablation till. Their formation may, however, have taken place in different ways.

Some of the material was transported down onto the surface of the ice from the ice-free valley sides by solifluction. It was subsequently deposited by lowering and sediment flow when the underlying ice melted away. It frequently formed flow till complexes (Fig.12). Other parts of the diamictons may have originated from glaciofluvial sediments carried into crevasses and cavities in the ice or down to the ground along the ice margins. It is difficult to distinguish such diamict sediments from flow tills. The supraglacial diamictons therefore form a complex sediment group.

Hummocks at Kattugletjern

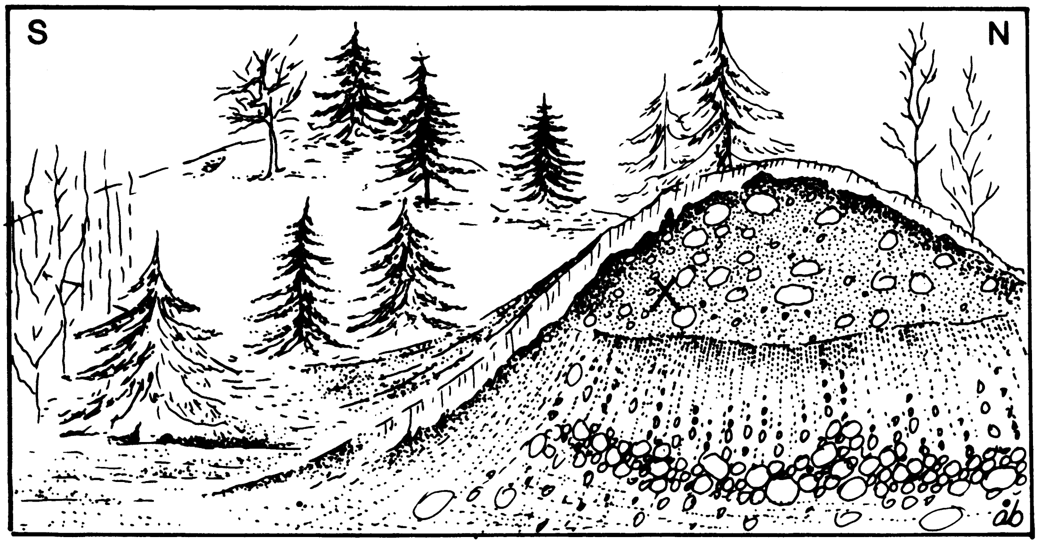

Fig.11 Hummocky terrain in Åstadalen, which is typical for parts of southeastern Norway along the Swedish border. The hummocks are formed from supraglacial sediments.

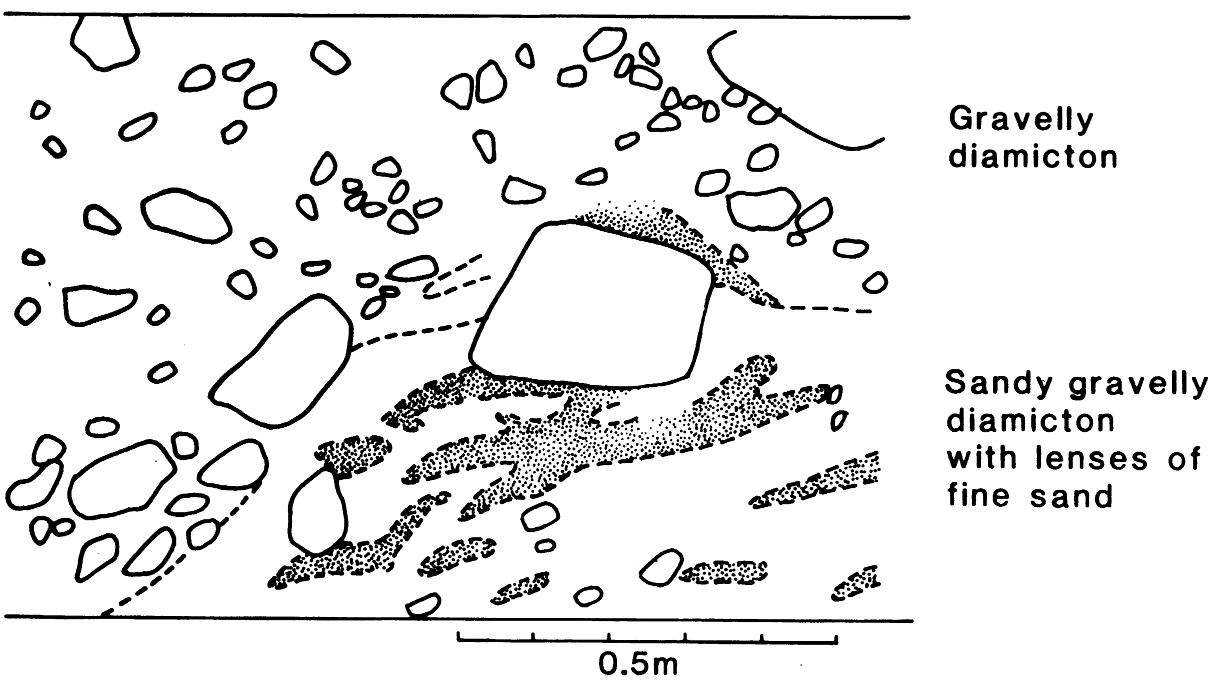

Fig.12 Flow till sequence developed as a debris flow (from the section shown in Fig.11).

Proper supraglacial tills, formed by melt-out of englacial material, have been described. In a Precambrian bedrock area FOLLESTAD (1973) found a till which was completely dominated by long transported material. The genesis of this till could only be explained by englacial transport. Such englacial material was probably formed by lee-side regelation (BOULTON 1976). In Norway the irregular and steep topography in many places would promote such a regelation process.

Proglacial Tills

Along the ice margin proglacial sediments were deposited as end moraines and lateral moraines (Fig.13). Their formation is mainly related to the Younger Dryas and the Preboreal stages. Such deposits have been studied mainly for chronological rather than genetical purposes. Some of the most comprehensive regional descriptions were given by AARSETH / MANGERUD (1974), ANDERSEN (1954, 1960, 1968, 1975), ANUNDSEN (1972), ANUNDSEN / SIMONSEN (1967), BJØRLYKKE (1905, 1914), GJESSING / FJELLANG (1956), FOLLESTAD (1972), SOLLID et al. (1973), SOLLID / SØRBEL (1975), UNDÅS (195 , 1963).

Above the marine limit the proglacial moraines usually consist of coarse material. Along the western coast of Norway such supramarine deposits in places form distinct lateral moraines.

The greatest part of the proglacial deposits are formed beneath the marine limit. They are characterized by a complex internal composition. Rapid facies variations with till, marine sediments, outwash and transitional types form sediment accumulations of a complex origin.

The moraine ridges were partly formed by pushing. This resulted in the incorporation of marine clays with shell fragments or the gradual transition from deformed water-lain sediments to till. The proglacial tills were partly formed form englacial debris. This explains the significant amount of long transported erratics which occur in many proglacial till types.

Flow till complexes which have probably originated from the melting out of englacial debris are found in glaciomarine sequences in the Oslofjord area. Flow till beds here interfinger with regular foreset beds in glacial deltas (Fig.14).

Fig.13 The Vassryggen end moraine in Ryfylke, south-western Norway. This was interpreted as an end moraine in 1824 by ESMARK, a long time before the glacial theory was generally accepted. (Photo: B.G. Andersen)

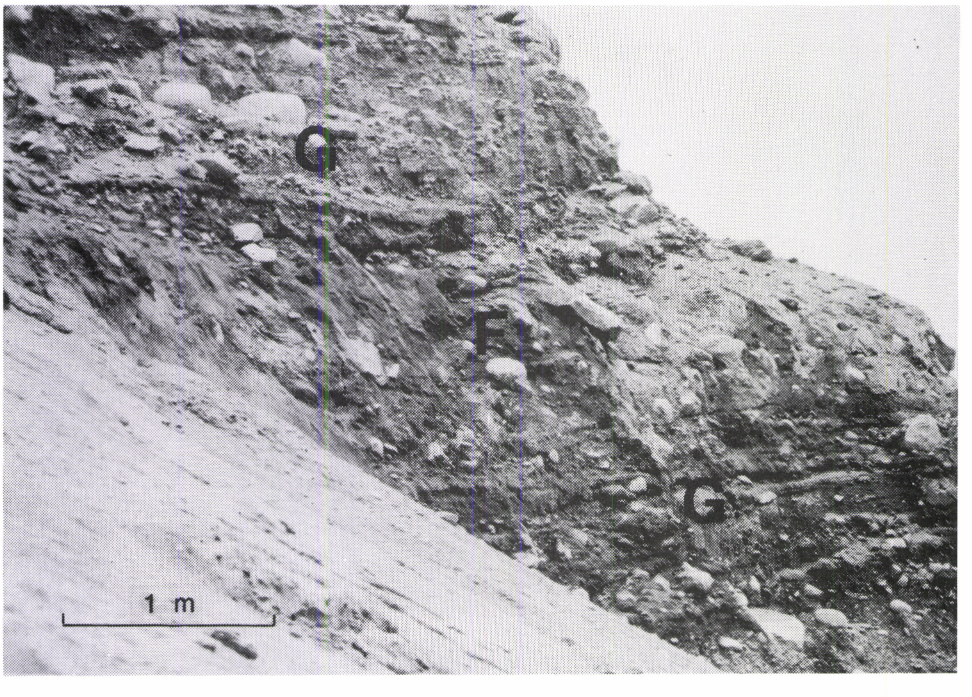

Fig.14 Section in the Ottarsrud glaciomarine delta east of the Oslofjord, showing glaciofluvial foreset beds (G) interbedded with a flow till sequence (F).

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PAPER 3

THE PETROGRAPHY OF TILLS - A STUDY FROM RINGSAKER SOUTHEASTERN NORWAY

SYLVI HALDORSEN

The Petrography of Tills – A Study from Ringsaker, South-eastern Norway

SYLVI HALDORSEN

Haldorsen, S. 1977: The petrography of tills – a study from Ringsaker, south-eastern Norway. *Norges geol. Unders. 336*, 1–36.

The present study of till petrography is concerned principally with the composition of the till matrix, especially the till fractions $<250\mu$. The till material is derived from three main rock-types; Late Precambrian sandstones and pelitic rocks, Cambro-Silurian shales and Precambrian crystalline rocks. The total till matrix petrography throughout the area is dominated by the Cambro-Silurian rock component, and the major petrographical changes in the tills occur at or close to the boundaries of the main rock units. The distribution of different minerals present within the till matrix has been estimated. No significant glacial comminution of mineral grains from sedimentary rocks has been observed, and these grains thus have about the same size distribution in the till as in the bedrock. Mineral grains from the crystalline bedrock were rapidly comminuted during the glacial transport, and are enriched in the coarse silt and fine sand grades of the till. It is clearly demonstrated that the composition of just one grade or of even a selected few till grades cannot be regarded as representative for the total till petrographical composition.

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CONTENTS

Introduction

The present paper describes the results of a petrographical study of till from the Mjøsa district of south-eastern Norway. The investigated area is situated on the Nes peninsula in southern Ringsaker (Fig. 1). This area was chosen mainly because detailed information was available on the bedrock petrography and the Quaternary geology. The work forms part of a more extensive regional investigation of the Quaternary geology of southern Ringsaker, under the leadership of R. Sørensen.

Until recently, as pointed out by Dreimanis (1971) and Haldorsen (1975), lithological investigations of till have mainly been restricted to studies of boulder, cobble and gravel material (e.g., G. Lundqvist (1940) and J. Lundqvist (1969)). Interest in the genesis and lithology of the till matrix is, however, increasing. Here one can mention the study of Gillberg (1965) dealing with the formation and composition of the till matrix. The work of INQUA has also been of great importance in this connection (Dreimanis 1976, 1977).

Goldthwait (1971) and Dreimanis (1976, 1977) have discussed the definitions and characteristics of tills. Based on their work and on the studies of other till investigators, the following factors can be considered as the most important with respect to composition and properties of tills:

1. The nature and properties of the glacier.
2. The morphological features of the area.
3. The grain-size distribution and petrographical composition of the bedrock.
4. The resistance of the rocks to glacial erosion.
5. The resistance of the different rock fragments and minerals to further comminution and abrasion during the glacial transport.

The aim of the present work has primarily been to obtain more detailed information on the various aspects of till formation, and to determine which of the factors mentioned above are the most important with regard to the composition of the till matrix.

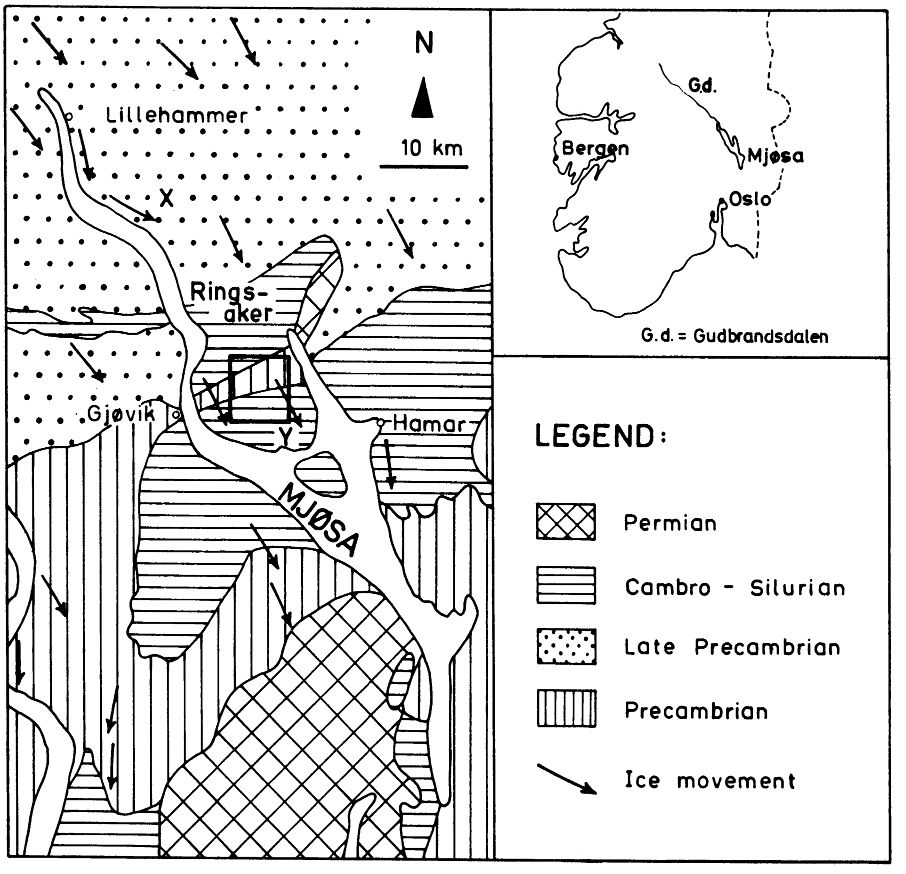

Fig. 1. Simplified geological map of the Mjøsa district (after Holtedahl & Dons, 1960 ice movement after Holtedahl & Andersen, 1960), showing the location of the investigated area (framed). Letters X and Y indicate the end-points of the geological profile shown in Fig. 2.

Geological setting

BEDROCK PETROGRAPHY

The central part of the Mjøsa district (Figs. 1 & 2) consists mainly of Cambro-Silurian rocks. A horst of Precambrian crystalline rocks is situated in southern Ringsaker. The northern part of the Mjøsa district and the valley of Gudbrandsdalen (Fig. 1, inset) are dominated by Late Precambrian sediments. Rocks of this age also occur in a small part of the investigated area (Fig. 3).

These three main rock groups are considered to constitute the source material of the till within the investigated area.

Solbergåsen horst of Precambrian rocks

The Precambrian rocks in southern Ringsaker (Fig. 3) have been mapped by R. Sørensen (pers. comm. 1973, 1974). The western part of the horst con-

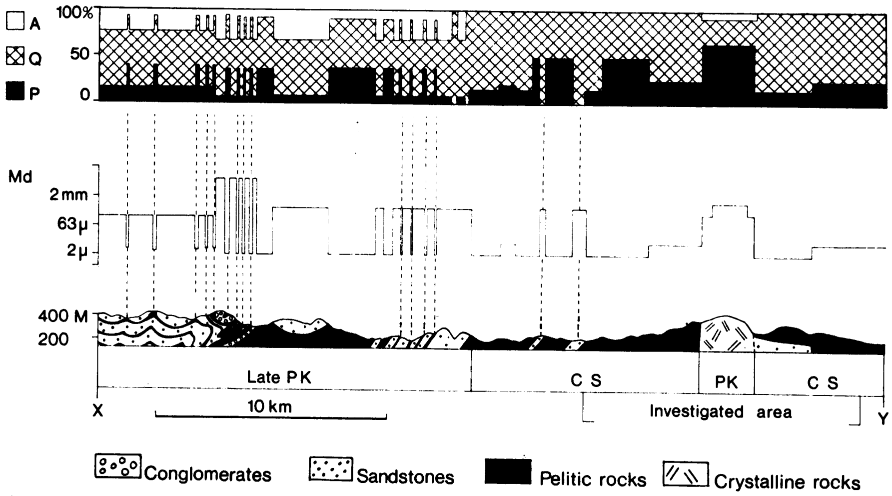

Fig. 2. Schematic NW-SE geological profile (X-Y in Fig. 1), showing the variation of mean grain-size (Md), and the content of plagioclase (P), quartz (Q) and alkali feldspar (A) in the bedrock. (Partly based on data from Kirkhusmo, 1968, Englund, 1972, 1973 and K. Bjørlykke & J. -O. Englund, pers. comm. 1976.) PK – Precambrian; CS – Cambro-Silurian.

sists mainly of relatively fine-grained gneisses, and the central part of coarser-grained plutonic rocks. The gneisses contain bands of amphibolite and zones rich in biotite (Fig. 3).

Thin-sections of twelve rock samples from Solbergåsen have been studied by the author (Fig. 3). Plagioclase is generally the most important mineral (Fig. 2), and the rocks have a granodioritic to tonalitic composition according to the classification of Streckeisen (1976). The plagioclase grains are commonly saussuritized and sericitized, and are therefore easily identified in the till. The plagioclase grains are mainly in the size range 0,5–2,0 mm, while the grains of quartz and alkali feldspar are generally smaller. Phyllosilicates occur both as large single grains and as aggregates consisting of smaller particles.

Late Precambrian sedimentary rocks

Skjeseth (1963), Kirkhusmo (1968), A. Bjørlykke (1971) and K. Bjørlykke & J.-O. Englund (pers. comm. 1975) have mapped and described the Late Precambrian rocks in the northern part of the Mjøsa region. Detailed mineralogical studies of the Late Precambrian rocks in southern Gudbrandsdalen have been published by Englund (1972, 1973).

The highest content of plagioclase is found in the northernmost sandstone formations (Fig. 2); these have been described as greywackes (Skjeseth 1963). Further south, arkosic sandstones rich in alkali feldspar predominate. The content of quartz generally increases towards the south, and quartzite horizons are found near the southern boundary of the Late Precambrian

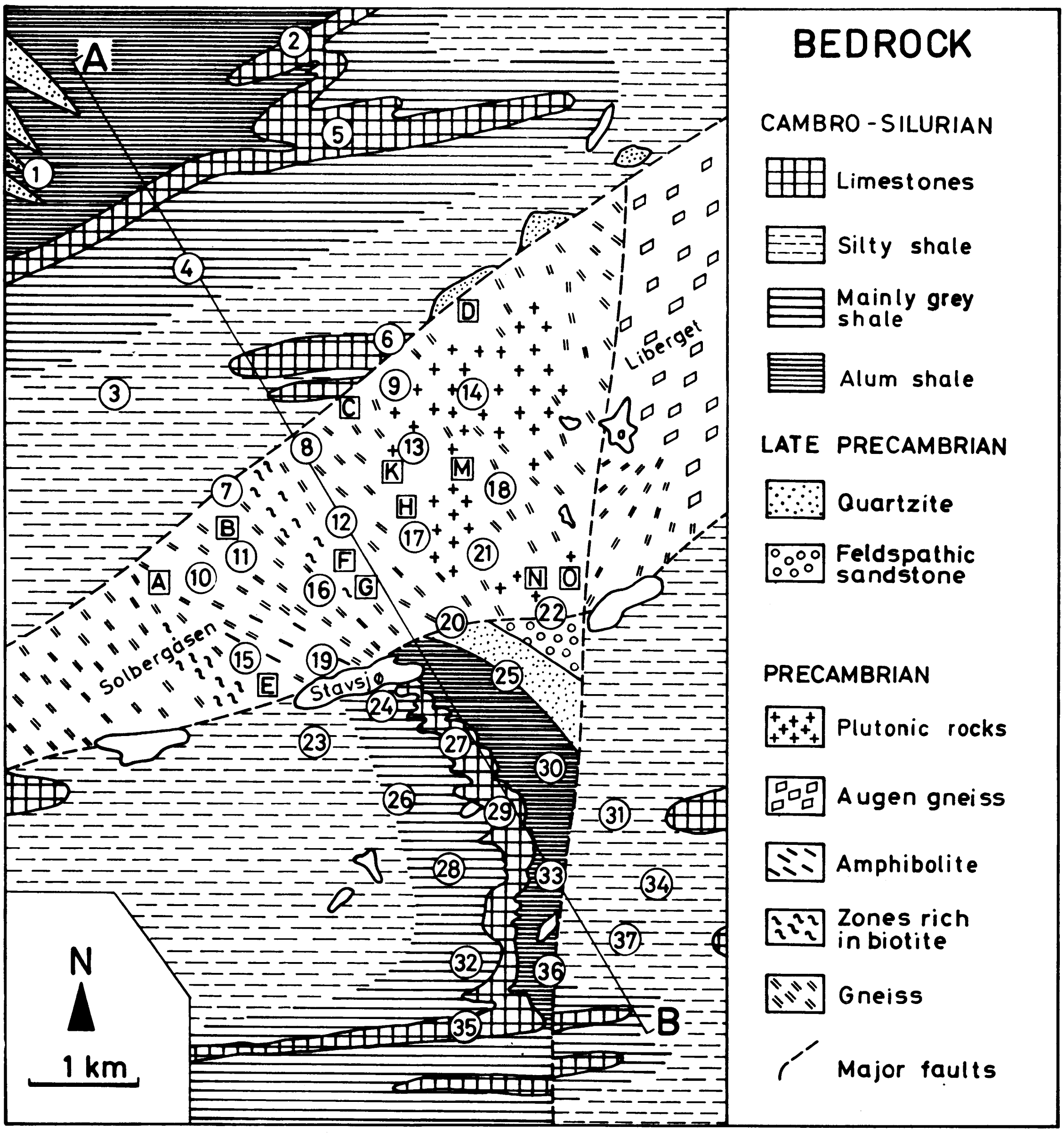

Fig. 3. Geological map of the investigated area (mainly after Skjeseth, 1963, and A. Bjørlykke, pers. comm. 1976). Till samples (1–37) are indicated by circles and rock samples (A-O) by squares. Line A-B marks the profile along which petrographical till parameters (Figs. 7–12 & 19) are projected.

rocks. There are also some minor areas of quartzite within the investigated area (Fig. 3).

Grain-size analyses of Late Precambrian greywacke units (Englund 1972, p. 15) showed median values of 125–500μ. In these rocks feldspar occurs as relatively large grains.

Late Precambrian pelitic rocks have a higher content of illite relative to

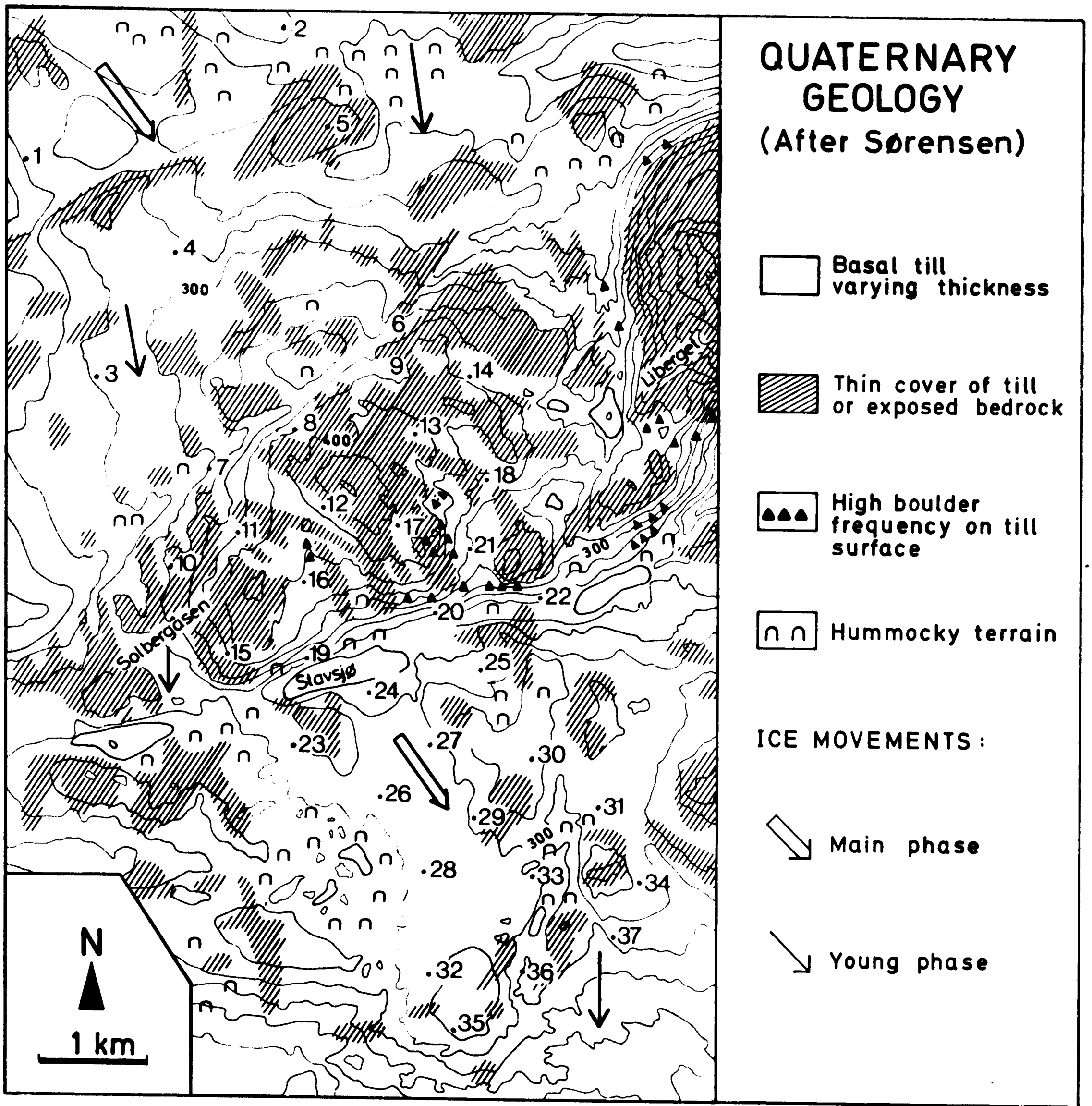

Fig. 4. Map of the Quaternary geology. Till samples are indicated by numbers. Contour interval 20 metres.

chlorite (see Fig. 15), and plagioclase and quartz dominate in relation to alkali feldspar (Fig. 2).

Cambro-Silurian rocks

The Cambro-Silurian sediments at Ringsaker (Fig. 1) have been mapped by Skjeseth (1963) and A. Bjørlykke (pers. comm. 1976). Mineralogy and geochemistry have been studied by K. Bjørlykke (1974 a, 1974 b) and K. Bjørlykke & J.-O. Englund (pers. comm. 1975).

The rocks consist mainly of limestones and shales (Fig. 3). The shales can be divided into three major lithological varieties; (1) coarse-grained silty shale; (2) fine-grained black alum shale; and (3) other fine-grained shales with colours varying from grey to black. The last-mentioned type has a lower content of organic carbon than the alum shale, and will here be referred to as 'grey shale' (Fig. 3).

The silty shale and the grey shales consist of both illite and chlorite. The alum shale does not contain chlorite, and illite is here the dominant phyllosilicate mineral (see Fig. 15). The grey shales have the highest, and the alum shale the lowest content of plagioclase in relation to quartz. The content of alkali feldspar is insignificant in all the Cambro-Silurian rock-types (Fig. 2).

BEDROCK MORPHOLOGY

The morphology of the Mjøsa region is strongly dependent on the relative resistance of the different rock-types (Figs. 3 & 4). The Cambro-Silurian areas in the north and south rise towards Solbergåsen, and it seems as if these rocks have partly been protected from erosion by the Solbergåsen ridge. Solbergåsen is steeper along its southern side than at its northern margin, and the southern slope terminates in a distinct depression in the vicinity of Stavsjø. Smaller depressions are found along the crest of the horst.

In the Cambro-Silurian area, the limestones (Fig. 3) are the most competent rocks and form the ridges. The silty shale is also a relatively resistant rock-type, whereas the alum shale and grey shale are easily eroded and underlie the depressions.

QUATERNARY GEOLOGY

The regional Quaternary geology of the Mjøsa district has been mapped by Holmsen (1954). More detailed mapping of the deposits in southern Ringsaker has been carried out by R. Sørensen (pers. comm. 1973, 1974) and the following description and discussion are based mainly on his investigations (Fig. 4).

Determination of the ice movements is based on observations of glacial striae and boulder-cobble distribution across the area. The main direction of ice movement from the north-west, almost normal to the trend of the Solbergåsen horst, seems to have been relatively independent of the topographical features of the area (Fig. 4). On the other hand, a younger ice movement from the north has been much more influenced by the local topography of the Mjøsa region.

Tills of different types and variable thickness are the dominant deposits within the investigated area. The most continuous cover of till is found above the Cambro-Silurian shale formations. The thickness is normally between 0,5 and 3 m on the silty shale, while on the grey shales and alum shale (Fig. 3) the till is usually thicker, locally up to 10 m.

In the Precambrian area of Solbergåsen, there is generally a thin or discontinuous cover of till (Fig. 4). Along the top of the ridge, large areas of bedrock are exposed, and a continuous cover of till is found only in the depressions. Till thickness here is usually less than 1 m. The slopes of Solbergåsen have a more continuous cover of till with thicknesses on the southern slope locally estimated to be more than 5 m.

The morphology of the till surface is variable, partly gently undulating and following the topography of the underlying bedrock, whereas in other places it is hummocky (Fig. 4). The till of the gently undulating areas has been classified as basal till, most probably of basal melt-out type; at a few localities where it is characterized by high compactness and displays a fissile structure, it is classified as lodgement till (Dreimanis 1976). The hummocky moraine consists of a till which is less compact than the basal till, and which in most cases may be classified as an ablation till.

Methods

SAMPLING

The rock samples from Solbergåsen and all the investigated till samples (Fig. 3) have been collected by R. Sørensen, who also carried out grain-size analyses of the gravel fractions 2–16 mm in the field. About 250 till samples were collected from southern Ringsaker, and 37 of these samples form the basis for the descriptions contained in the present paper (Figs. 3 & 4). Six of the samples have been collected from the northern Cambro-Silurian area (Fig. 3, loc. 1–6), 16 from the Precambrian area at Solbergåsen (loc. 7–22) and 15 from the southern Cambro-Silurian district (loc. 23–37).

Random sampling has, as far as possible, been the aim. The distance between the till samples is from 0,5 to 1,0 km, depending on the distribution of the till cover in the different parts of the area. The sampling depth varies between 0.3 and 1.0 m. Weathering of the till has resulted in a leaching of carbonates from at least the upper 1 m, and carbonate minerals have consequently not been found in the investigated till material.

Most of the samples are taken from basal till, but there are also some which have been collected from areas where a more ablation-like till predominates (Fig. 4).

LABORATORY INVESTIGATIONS

Grain-size analyses have been carried out on all samples. The petrographical composition was determined for the gravel fraction 8–16 mm and for the sand grades between 2 and 0.250 mm with a binocular microscope. For the till grades between 0.250 and 0.016 mm, thin-sections were made by the method of Backe-Hansen (1975).

Thin-section analyses of till samples provide an areal percentage frequency of the different petrographical components. Weight percentage frequency was also calculated for some unmounted samples, and showed that the areal percentage frequency was almost equal to the weight percentage frequency for the various components present in the samples. For samples counted with a binocular microscope (fraction 63–125μ), the percentages of triaxial and oblate grains (shale, mica) were multiplied by 0.8 to make the areal percentage frequency equal to the weight percentage frequency.

Till grades $<16\mu$ were analysed by X-ray diffractometry according to the methods of Kapoor (1972, p. 384) and Roaldset (1972, pp. 341–344). The problems concerned with quantitative determinations of clay minerals are well known (e.g., Gjems 1967, pp. 337–350), and to find the best approximation to a quantitative determination, the X-ray diffractometer diagrams of till samples were compared with basic data from Gjems (1967), Sørensen (1969), Roaldset (1972, p. 343) and Lien (1973), and with mineralogical and geochemical analyses of rock samples from Ringsaker (K. Bjørlykke & J.-O. Englund pers. comm. 1976). The following relative intensities have been used as an approximation to a weight percentage frequency: plagioclase (3.19 Å) 3; alkali feldspar (3.24 Å) 2; quartz (4.25 Å) 1; chlorite (7 Å) 2; illite (10 Å) 2; vermiculite (14 Å) 10; and mixed-layer minerals (10–14 Å) 10. The results are, of course, still semi-quantitative, and the mineralogical data for the clay and fine silt fractions are therefore not entirely comparable with the results from the thin-section analyses.

Results of investigations

GRAIN-SIZE DISTRIBUTION

The upper limit of grain-size of the till matrix has been placed at 2 mm, principally because this size is associated with the transition from rock fragments to mineral grains for material from coarse-grained rocks such as the Precambrian crystalline rocks in southern Ringsaker (Fig. 2). The till matrix thus includes most of the mineral grains from all the source rocks in the area. The content of gravel (2–16 mm) in the till samples varies between 10 and 30% (Fig. 5 A), and the till material in the Cambro-Silurian area contains as much gravel as the tills at Solbergåsen.

In the Cambro-Silurian areas the content of clay ($<2\mu$) is about 10% of the total till matrix (Fig. 6). This is the same value as in till material from other Cambro-Silurian bedrock areas in the Mjøsa district (Follestad 1973, 1974). Till samples from Solbergåsen have a lower content of clay, and the lowest values (about 5% of the total till matrix) are found in the southern part of this area (Fig. 6). The till samples from the Cambro-Silurian areas

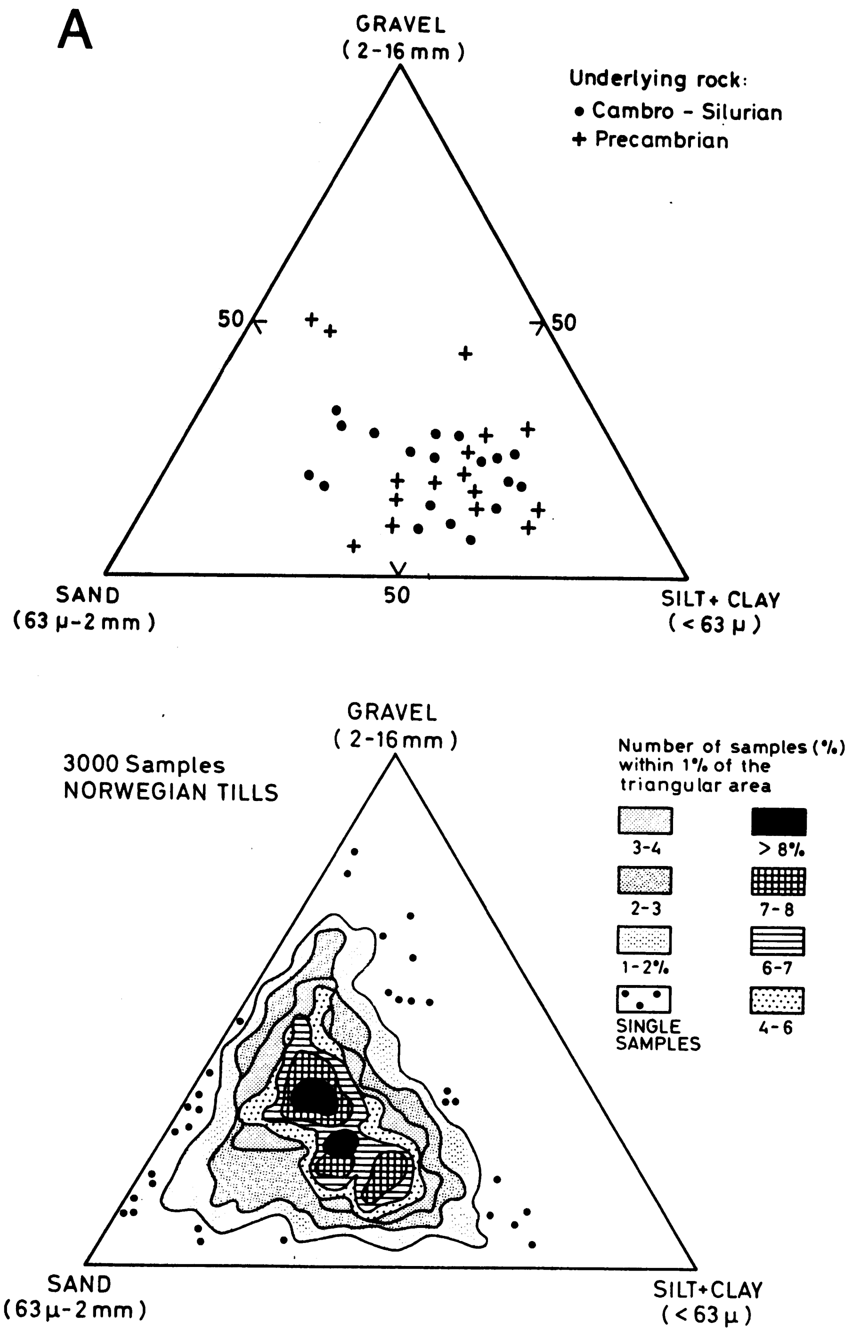

Fig. 5 A. Grain-size composition of till samples 1–37 from southern Ringsaker. B. Grain-size composition of Norwegian tills (Jørgensen 1977). The upper black maximum and the lower-right cross-hatched maximum represent the maxima of samples from areas with crystalline or coarse sedimentary rocks and areas with Cambro-Silurian rocks, respectively.

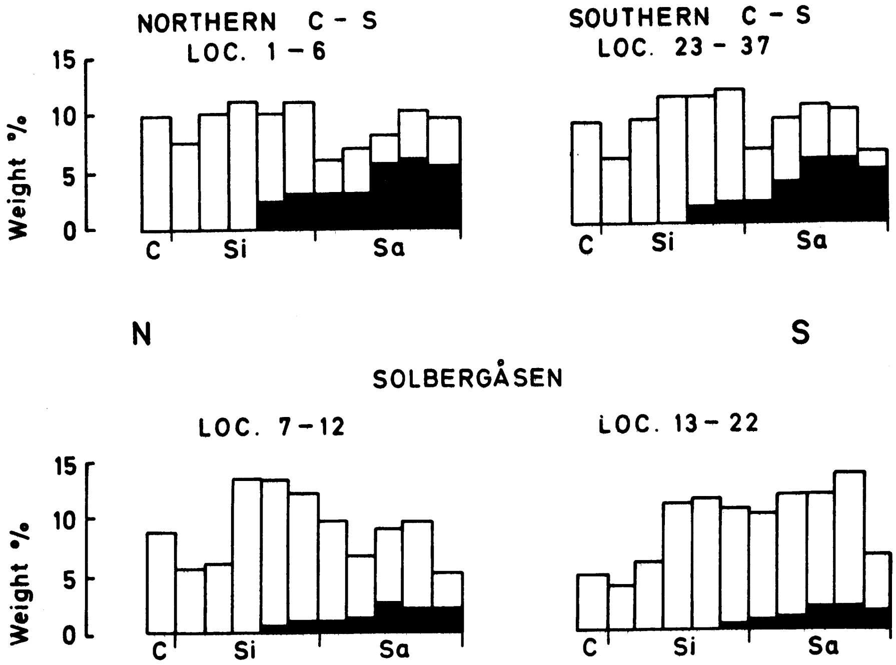

Fig. 6. Grain-size distribution of the till matrix. The class interval is one phi unit. C – clay; Si – silt; Sa – sand. The content of shale fragments, calculated as a weight percentage of the total matrix, is indicated by the black columns.

generally have a higher content of fine silt and a lower content of fine sand than samples from Solbergåsen (Fig. 6). Moving south across Solbergåsen there is a gradation from a till rich in medium silt to a till more dominated by coarse silt and with a higher content of sand (Fig. 6). This change in grain-size distribution is explained by a transition from a till dominated by Cambro-Silurian material to one in which material from local Precambrian rocks is more important.

The regional variations in the grain-size distribution of the tills are, however, generally relatively small, and most of the samples throughout the area have contents of gravel, sand, silt and clay which are similar to those of typical Norwegian tills from Cambro-Silurian bedrock areas (Figs. 5 A & B). The distance of 2–3 km across Solbergåsen does not seem to have been enough for the till material to have acquired the typical characteristics of the underlying crystalline rocks (Fig. 5 B).

CAMBRO-SILURIAN ROCK FRAGMENTS

The highest content of Cambro-Silurian shale fragments in the till matrix is found in the three coarsest sand fractions (Fig. 6). About the same distribution of shale fragments has been found in the Løten area in the central part of the Mjøsa district (Follestad 1973, p. 15).

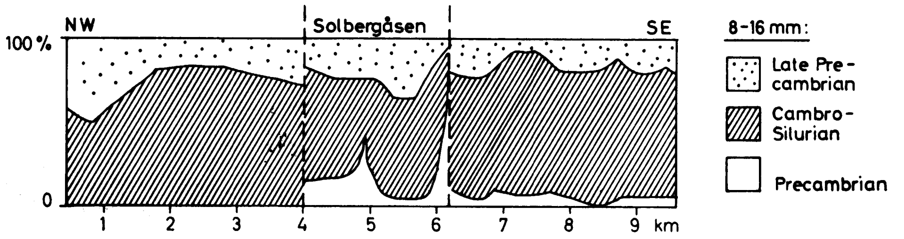

Fig. 7. Petrographical composition (weight percentages) of the gravel fraction, 8–16 mm, along section A–B in Fig. 3.

At Solbergåsen, the weight percentage of Cambro-Silurian shale fragments in the till matrix is much lower than that in the Cambro-Silurian areas, but there are no great differences between the northern and the southern part of the horst (Fig. 6). The percentage of shale in relation to other lithological components in each fraction is, however, higher on the southern side than in the northern part of Solbergåsen, because of the change from a till rich in silt to one relatively richer in sand (Fig. 6).

The distribution of fragments derived from silty shale, grey shale and alum shale horizons (Fig. 3) has been estimated for the different grades of the till matrix. The distribution is dependent on the relative resistance of the different shale types to glacial comminution.

Fragments of silty shale are abundant in the coarse part of the sand fraction. Only a few fragments of this shale have been found in the finest part of the sand fraction, while in the silt fraction rock fragments of this type are not observed. Mineral grains from the silty shale are mainly of medium silt size. The silty shale therefore seems to contribute little material to the coarsest silt and finest sand grades, and indeed a cumulative frequency curve for this rock component depicts a break of slope within these two grades.

Fragments of silty shale are common or even predominant in the gravel fraction 8–16 mm throughout the area (Fig. 7). This shale type, which is more abundant in southern Ringsaker than in other parts of the Mjøsa district, is a fissile rock-type and seems to have yielded a particularly large amount of gravel-size material through glacial erosion. The content of Cambro-Silurian rock fragments is therefore higher in the gravel fraction of tills from Ringsaker than in the tills studied by Follestad (1974) from other parts of the Mjøsa district. Gravel-rich tills dominated by Cambro-Silurian rock material have also been observed in other parts of Norway (Vorren 1976).

Fragments of grey shale and alum shale are frequently found in the coarsest silt and very fine sand fractions, while coarser fragments of these rock-types are mainly found either within or close to their source areas (Fig. 3). Fragments of grey shale and alum shale thus seem to have been rather resistant to comminution within the medium-grade part of the matrix.

PETROGRAPHICAL COMPOSITION OF THE TILL FRACTIONS <250μ

Quartz and plagioclase are the most important minerals throughout the area and are abundant in all till fractions <250μ. The regional distribution of alkali feldspar is rather uniform, and the highest values are found in the fine sand fractions 125–250μ and 63–125μ. There is no systematically regional variation in the content of sericite, the highest values occurring in the silt fractions. The occurrence of hornblende, biotite and trioctahedral mica is local, and these minerals are found mainly in till samples from the western part of Solbergåsen near the amphibolites and the biotite-rich gneisses (Fig. 3).

Rock fragments other than Cambro-Silurian shales are found only in the fine sand fractions of the tills, and are most abundant at Solbergåsen.

In order to estimate the relative influence of the different bedrock lithologies on the compositions of the till fractions <250μ, ratios have been calculated between quartz, plagioclase and shale (Figs. 8–12). The sampling localities are projected along the section-line A–B in Fig. 3.

Fine sand: 125–250μ and 63–125μ

In the northern Cambro-Silurian area the content of quartz and plagioclase in relation to shale is low in the fine sand fractions of the till (Figs. 8 A–B & 9 A–B). On Solbergåsen the relative contents of quartz and plagioclase are higher, and these increase southwards across the horst due to the increased influence of the local bedrock. The local, Precambrian component is most important in the till fraction 63–125μ (Fig. 9 A–B).

The contents of quartz, plagioclase and shale in fraction 125–250μ rapidly obtain 'normal' Cambro-Silurian values south of Solbergåsen where the influence of the Precambrian rocks is insignificant. In fraction 63–125μ, the relative contents of quartz and plagioclase tend to be higher in the southern Cambro-Silurian area than in the northern, indicating a certain influence from the horst rocks (Fig. 9 A–B).

Compared with the composition of the local bedrock, the content of plagioclase in relation to quartz is low in till samples from Solbergåsen (Figs. 2, 8 C & 9 C). However, the fine-grained Cambro-Silurian lithologies north of Solbergåsen do not contain significant amounts of mineral grains of fine sand size, and it is unlikely that the Late Precambrian sandstones, situated even farther north, could have had much influence on the till matrix composition at Solbergåsen. The greater part of both quartz and plagioclase in the fine sand fractions of the Solbergåsen till samples is therefore considered to have been derived from Precambrian rocks, although the content of quartz in the till is here too high as compared with the composition of the bedrock.

In the northern Cambro-Silurian area most of the mineral grains of the till in these fractions have been derived from the Late Precambrian sandstones. The content of plagioclase in relation to quartz is here higher in the till

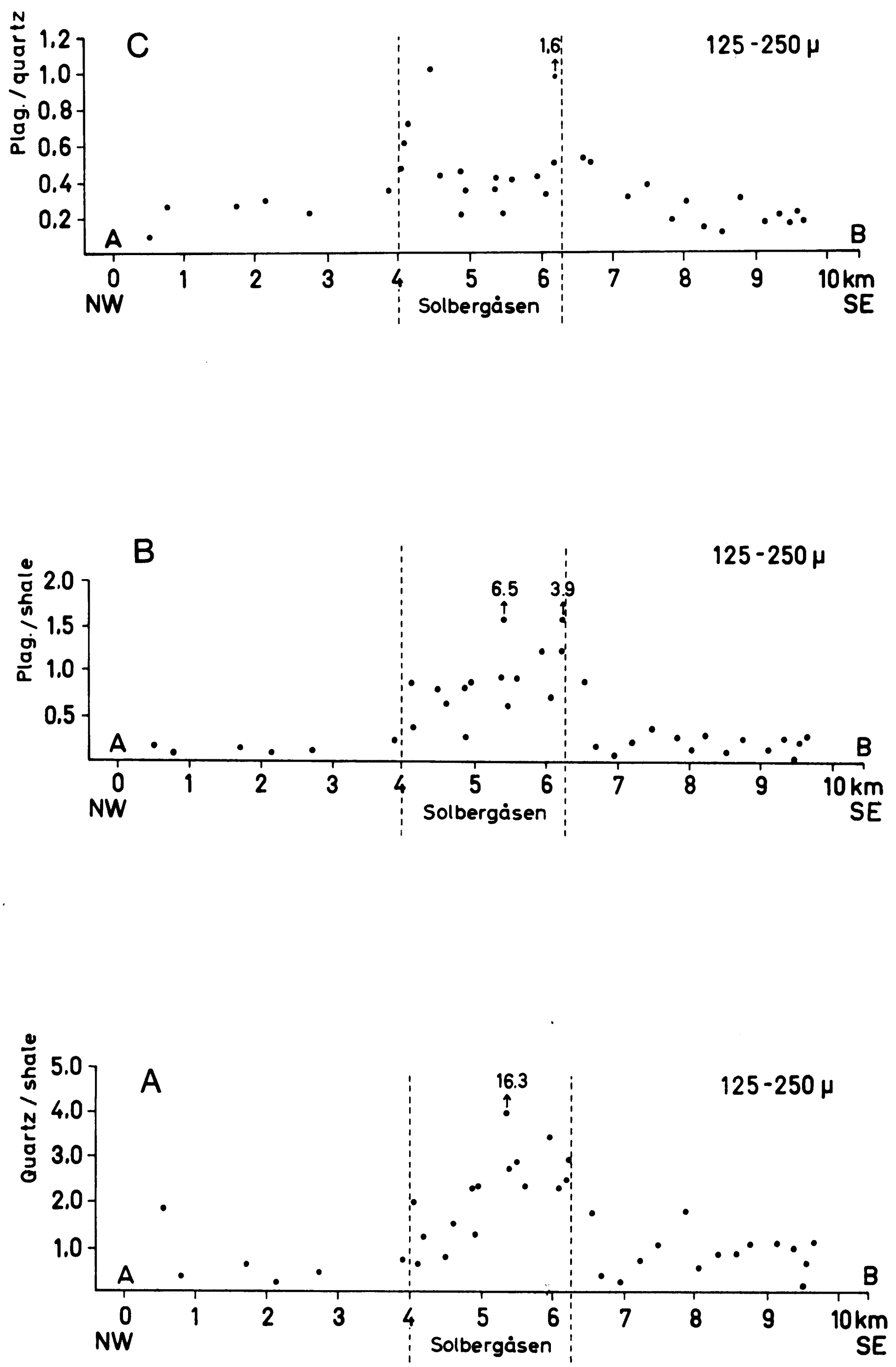

Fig. 8. Variation of petrographical parameters along section A–B in Fig. 3 in till fraction 125–250μ. A. Ratio of quartz to shale. B. Ratio of plagioclase to shale. C. Ratio of plagioclase to quartz.

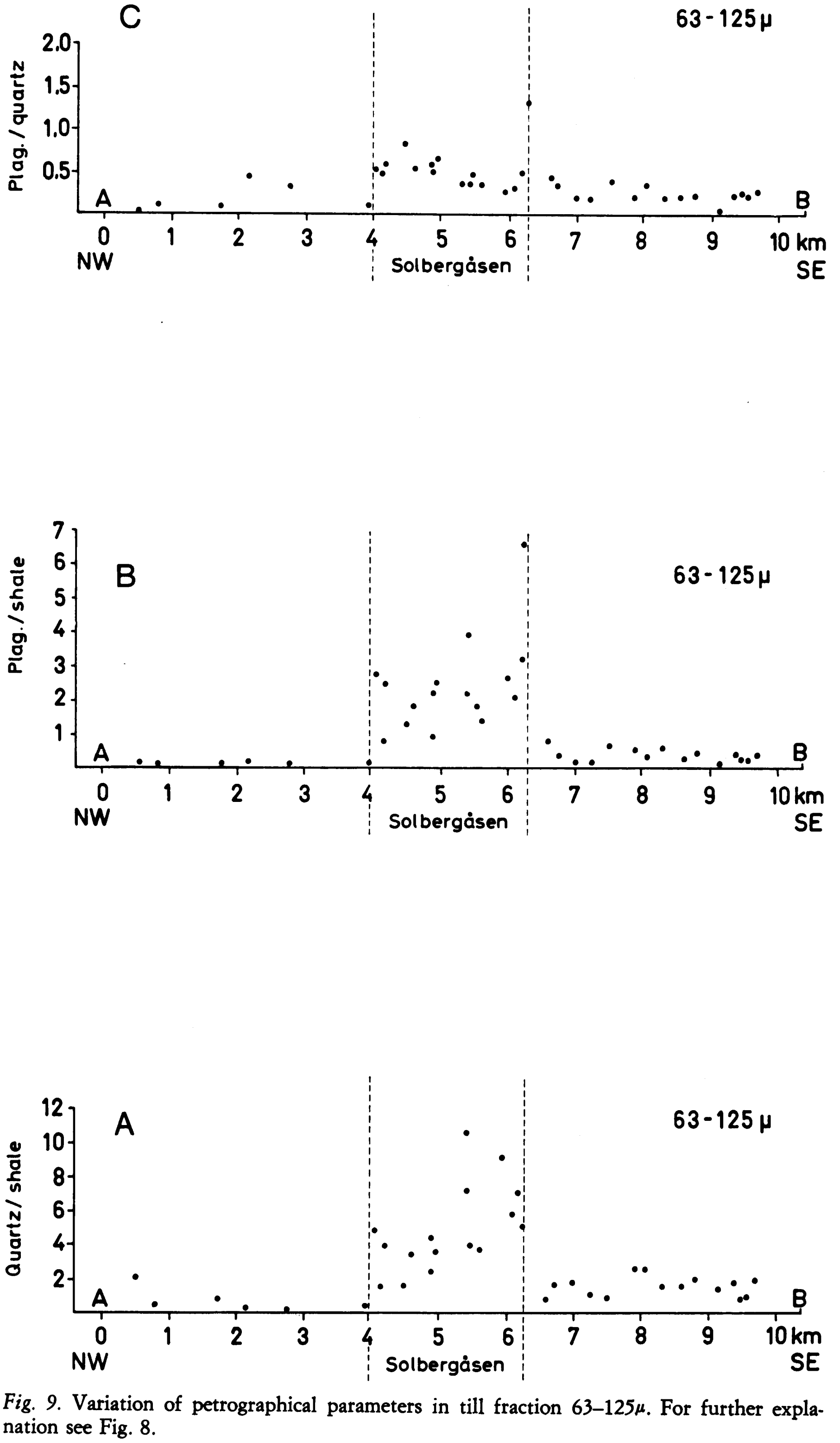

Fig. 9. Variation of petrographical parameters in till fraction 63–125μ. For further explanation see Fig. 8.

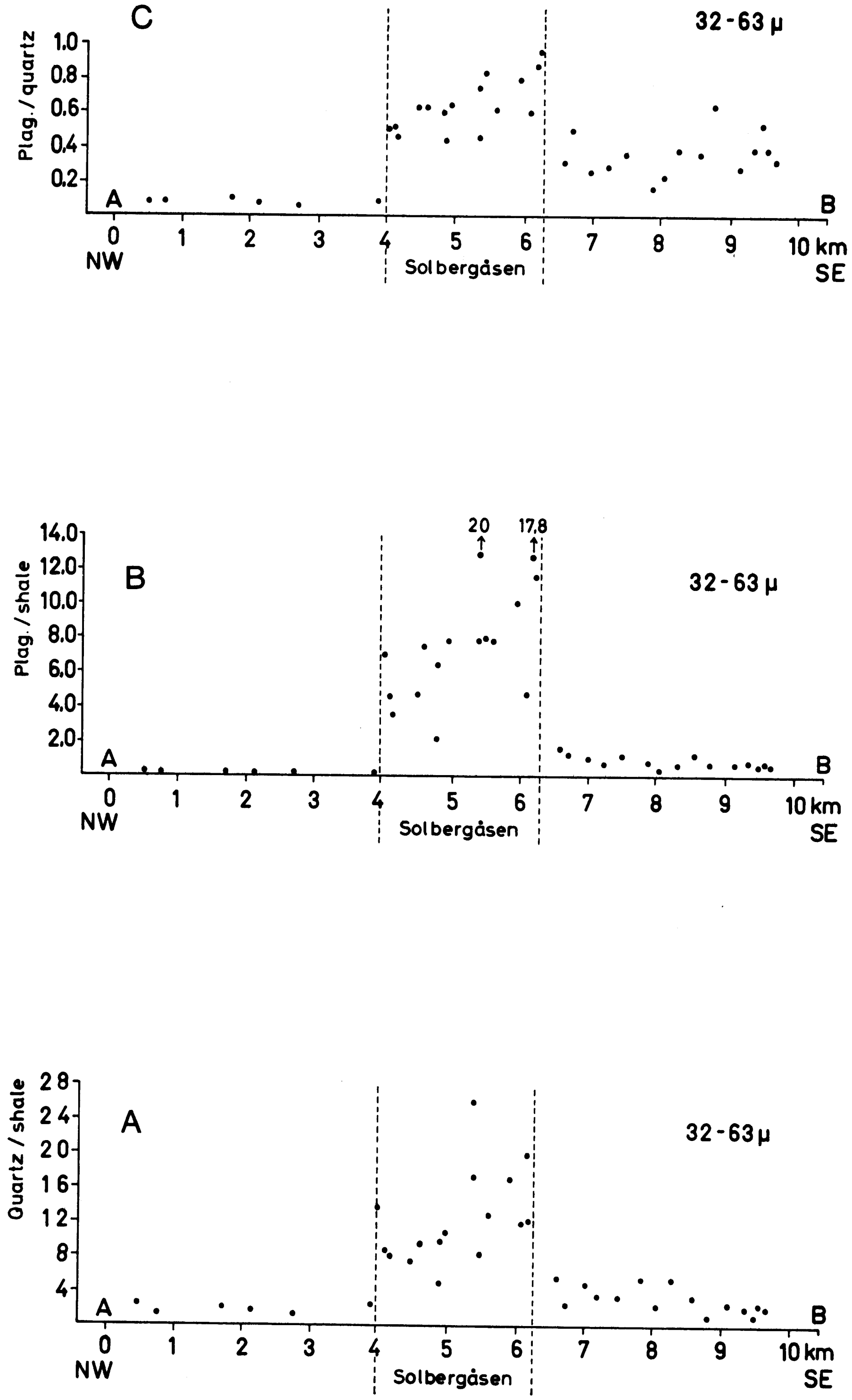

Fig. 10. Variation of petrographical parameters in till fraction 32–63μ. For further explanation see Fig. 8.

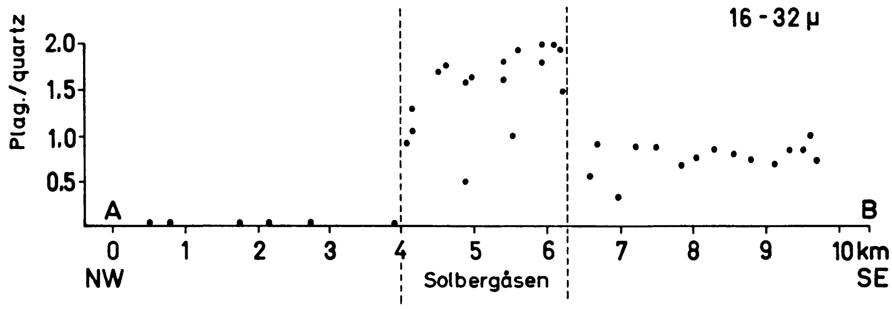

Fig. 11. Variation in the plagioclase/quartz ratio in the till fraction 16–32µ along section A–B in Fig. 3.

material than in the Late Precambrian arkose bedrock, while the content of plagioclase in relation to alkali feldspar in the till is more similar to that of the local greywacke than to that of the arkose. The greywacke units are therefore considered to be the most important contributors of mineral grains to these till fractions in the northern Cambro-Silurian area, and material from both the greywacke and the arkose units is thought to have had a greater influence on the fine sand fractions than material from the quartzite.

Great local variations are observed in the fine sand fractions. Tills located directly on or close to soft shale bedrock, fault zones, quartzite units (Fig. 3) and the small granitic zone at Solbergåsen, for example, have petrographies which are strongly influenced by the composition of the underlying rock-type.

Coarse silt: 32–63µ and 16–32µ

The gradual decrease of shale in relation to both quartz and plagioclase across Solbergåsen (Figs. 10 A–B) is greater in the coarsest silt than in the sand fractions. Fragments of grey shale and alum shale, which are the dominant shale types in the coarse silt fractions, are considered to have a lower resistance to glacial comminution than the silty shale in the sand fractions. The content of these shale types therefore rapidly diminishes in the coarse silt fractions across Solbergåsen where there is no new addition of shale material from the local bedrock.

Plagioclase grains from the Precambrian bedrock are abundant in till samples from Solbergåsen and the southern Cambro-Silurian area (Figs. 10 C & 11). The highest content of plagioclase is found in fraction 16–32µ and the values in the southern parts of Solbergåsen are nearly as high as those in the underlying bedrock. In the southern Cambro-Silurian area there is more plagioclase in the coarse silt than in the fine sand fractions (Figs. 8 C, 9 C, 10 C & 11), in spite of the greater contribution of mineral grains from the underlying Cambro-Silurian rocks to the coarse silt grades.

Quartz grains derived from the Precambrian rocks are not very important in the coarse silt grades. The influence from the Precambrian quartz is, however, still recognizable in the southern Cambro-Silurian area (Fig. 10A).

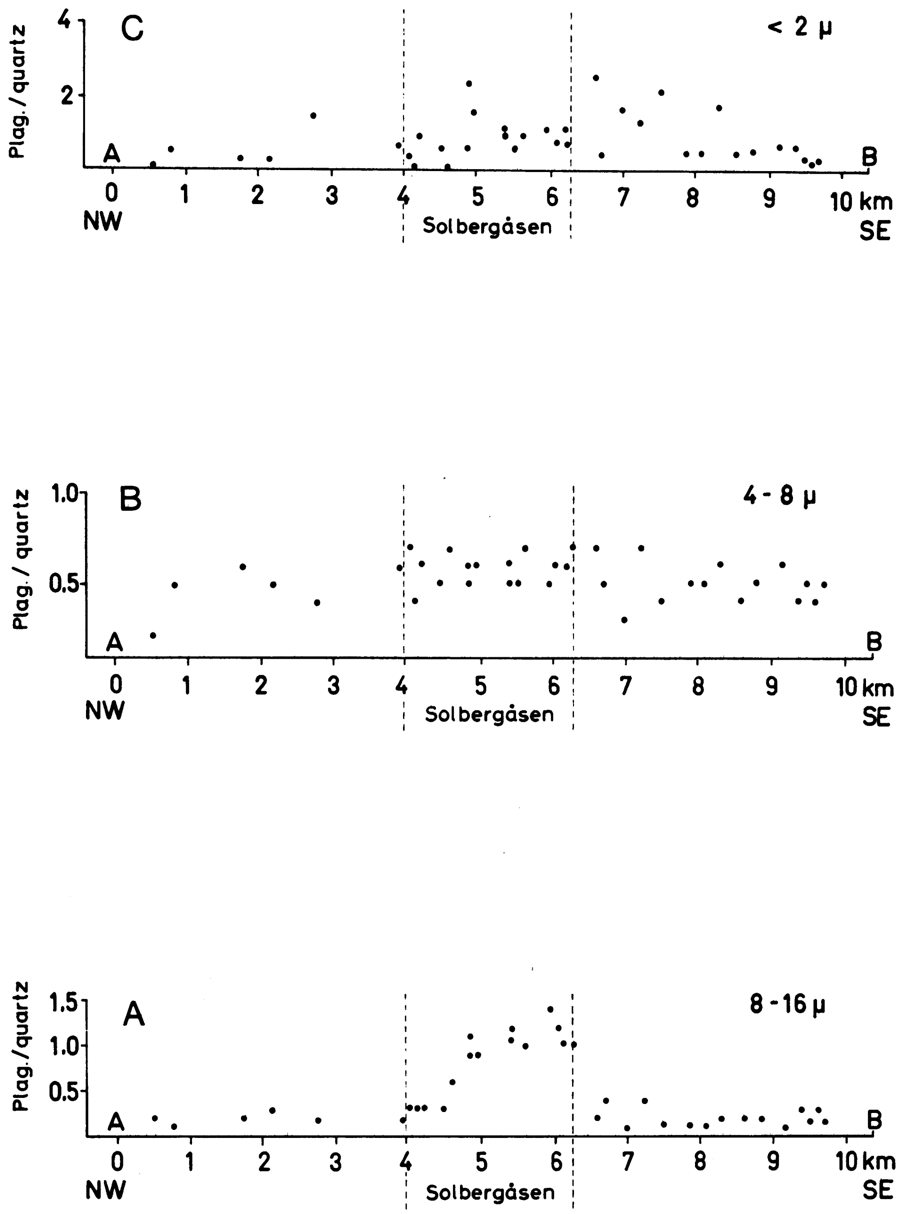

Fig. 12. Variation in the ratio of plagioclase to quartz along section A–B in the finest grades of the till matrix. A. Fraction 8–16μ. B. Fraction 4–8μ. C. Clay fraction.

Medium silt: 8–16μ

Some influence of plagioclase from the Precambrian rocks is discernible in the medium silt grade at Solbergåsen, but the total till component derived from the horst rocks is much smaller in the medium silt than in any of the coarser matrix grades (Fig. 12 A).

The silty shale is considered as the main source of material for this till

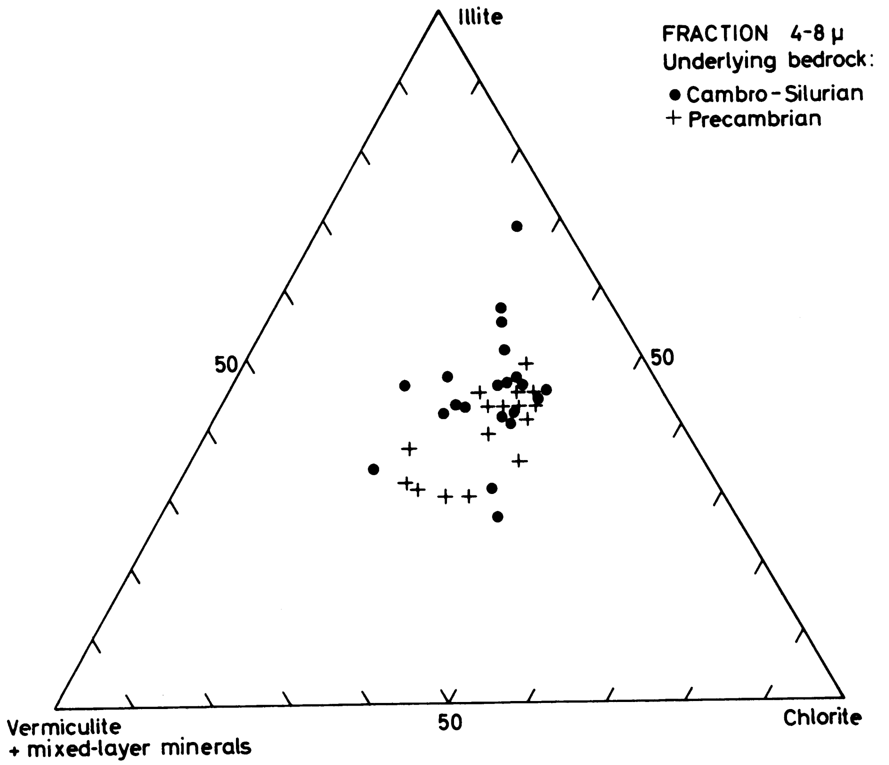

Fig. 13. Clay mineral composition of the till fraction 4–8μ.

fraction over the whole area, including the Solbergåsen horst. In the northern Cambro-Silurian area, the relations between quartz, plagioclase and alkali feldspar indicate only a small influence from the Late Precambrian pelitic rocks.

Fine silt: 4–8μ and 2–4μ

The content of material derived from the Precambrian rocks is insignificant in the fine silt grades of most of the till samples (Fig. 12 B), and both quartz and plagioclase have been transported on to Solbergåsen from the northern Cambro-Silurian area. In the Cambro-Silurian areas, the content of plagioclase in relation to quartz is higher in the fine silt than in the medium silt grades of the tills (Figs. 12 A–B), indicating a more important influence of mineral grains from the relatively plagioclase-rich grey shale and fine-grained silty shale.

Illite is the most important clay mineral and accounts for about 50% of the total clay mineral content in fraction 4–8μ (Fig. 13). The content of chlorite in this fraction varies between 30 and 40%. The content of chlorite is on average a little higher in fraction 2–4μ (Fig. 14), possibly because the chlorite grains in the bedrock are generally of smaller size than the illite (J.-O. Englund, pers. comm. 1976).

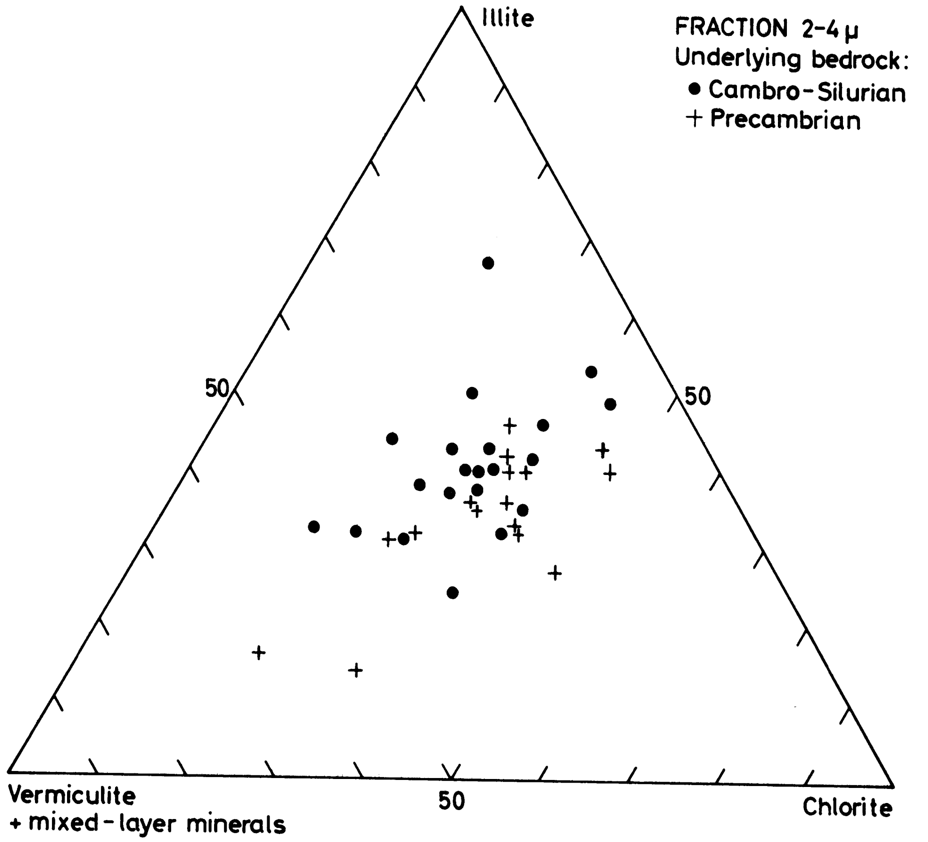

Fig. 14. Clay mineral composition of the till fraction 2–4μ.

The ratio of chlorite to illite in the fine silt fraction of the till is higher than in the Late Precambrian pelitic rock-types, and falls within the range shown for the grey and silty shales (Fig. 15). The grey and the silty shales are consequently considered as the main sources for the fine silt material of the till throughout the area.

Local variations in the type of clay minerals present are observed. The highest amounts of illite (Figs. 13 & 14) are found in tills on and south of the illite-rich alum shale horizons. Some of the till samples from Solbergåsen have a relatively high content of vermiculite (Figs. 13 & 14). This is possibly a result of post-depositional weathering where trioctahedral illite has been altered to vermiculite.

Clay: <2μ

The ratio of plagioclase to quartz in the clay fraction is about the same as that in the fine silt grades (Figs. 12 B–C). South of Solbergåsen, however, there are some till samples with a fairly high content of plagioclase. These samples are collected from areas where grey shales with a particularly high

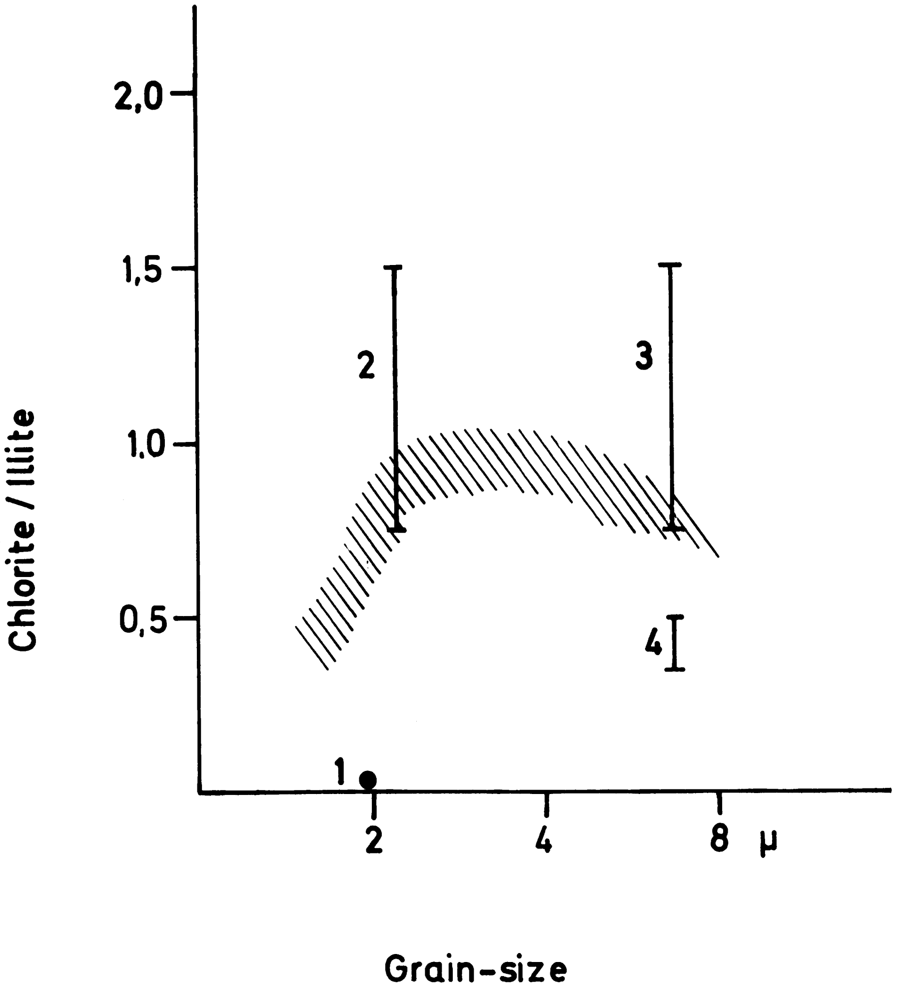

Fig. 15. The ratio of chlorite to illite in the fine silt and clay grades of the till (hatched area) and in the alum shale (1), grey shale (2), silty shale (3) and Late Precambrian pelitic rocks (4). (Bedrock data from K. Bjørlykke & J.-O. Englund pers. comm. 1976).

content of plagioclase dominate in relation to other Cambro-Silurian rock-types (J.-O. Englund, pers.comm. 1975).

The ratio of chlorite to illite is about 0.5 which is lower than that in the grey shale and the silty shale bedrock (Figs. 15 & 16).

The silty shale, which was found to be one of the most important contributors of material to the finest silt fractions, has a smaller influence on the composition of the clay fraction. The influence of the alum shale, on the other hand, is more important in the clay grade than in the silt fractions (Fig. 15). The local effect of the alum shale is also more distinct than in the case of the silt fractions, and some of the till samples taken directly above or close to the alum shale are particularly rich in illite.

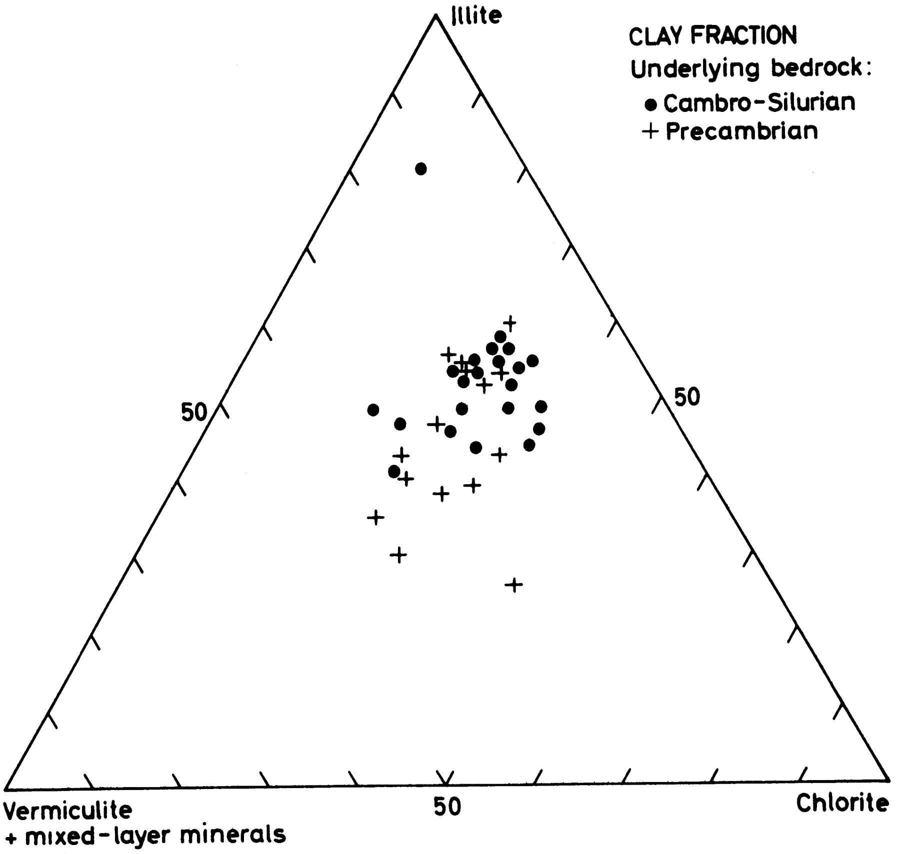

Fig. 16. Clay mineral composition of the till material <2μ.

THE SIZE DISTRIBUTION OF DIFFERENT MINERALS
IN THE TILL FRACTIONS <250μ

To find the size distribution of the most important constituent minerals in the tills from southern Ringsaker, the content of each mineral in the different till grades was calculated as a weight percentage of the total matrix.

Plagioclase

In the northern Cambro-Silurian area there is no great variation in the weight percentage of plagioclase in the different till grades (Fig. 17). The content of plagioclase is a little higher in fraction 125–250μ than in fraction 63–125μ, possibly reflecting the primary size distribution of plagiclase from the relatively coarse-grained greywacke (Fig. 2) which was found to be the most important contributor of mineral grains to the sand fraction. A matrix mode of plagioclase in the 125–250μ fraction has also been observed by the present author in other areas where the till is dominated by Late Precambrian greywacke material.

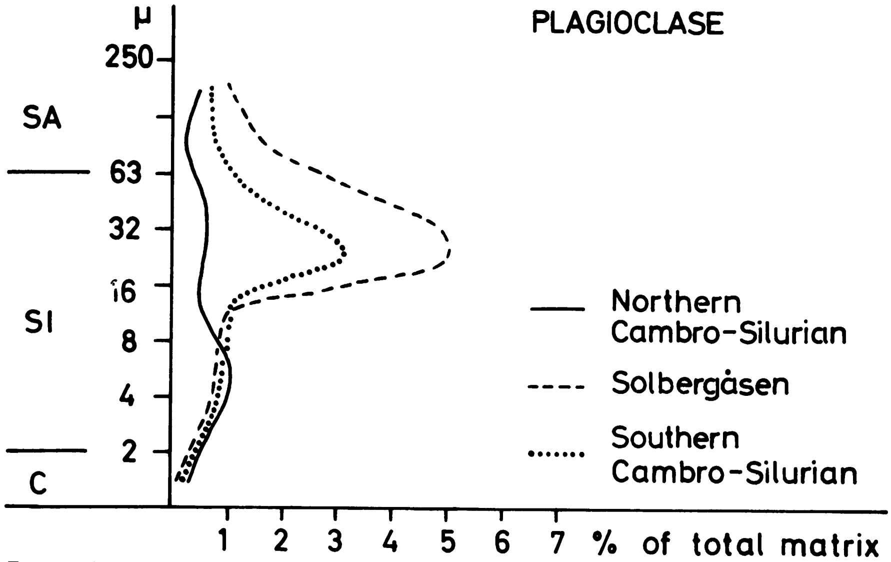

Fig. 17. Distribution of plagioclase (weight percentage of total matrix) in the till material $<250\mu$ in the three different parts of the investigated area.

The highest content of plagioclase in the northern Cambro-Silurian area is, however, found in the fraction 4–8μ, where silty shale and Late Precambrian pelitic sediments were assumed to be the source rocks. The grains have thus about the same size distribution in the till as in the bedrock. Comminution of Late Precambrian greywacke may possibly account for some of the plagioclase in the silt fractions, but it is unlikely that much material from this rock-type has been comminuted to fine silt size.

On Solbergåsen and in the southern Cambro-Silurian area the mode of plagioclase grains from the Precambrian bedrock is lying in the fraction 16–32μ (Fig. 17). The weight percentage of plagioclase in the till grades between 32 and 250μ in relation to that in the grade 16–32μ is gradually decreasing across Solbergåsen. There is therefore thought to have been a certain amount of comminution of the plagioclase grains during the glacial transport across the horst. However, all till samples in the northern as well as in the southern part of Solbergåsen have a plagioclase maximum in fraction 16–32μ. The greater part of the plagioclase grains would therefore seem to have been very rapidly reduced to the characteristic fine-grained mode during the glacial transport. Over the next 4 km of transportation across the southern Cambro-Silurian area, little or no further comminution of the Precambrian plagioclase grains has been detected.

There is a relatively high content of Precambrian crystalline rock fragments in relation to Precambrian mineral grains in the sand fraction of the till. Thin-section analyses of Precambrian bedrock samples show that the plagioclase grains are frequently dissected by fractures which make them readily prone to comminution. During the glacial transport, the Precambrian

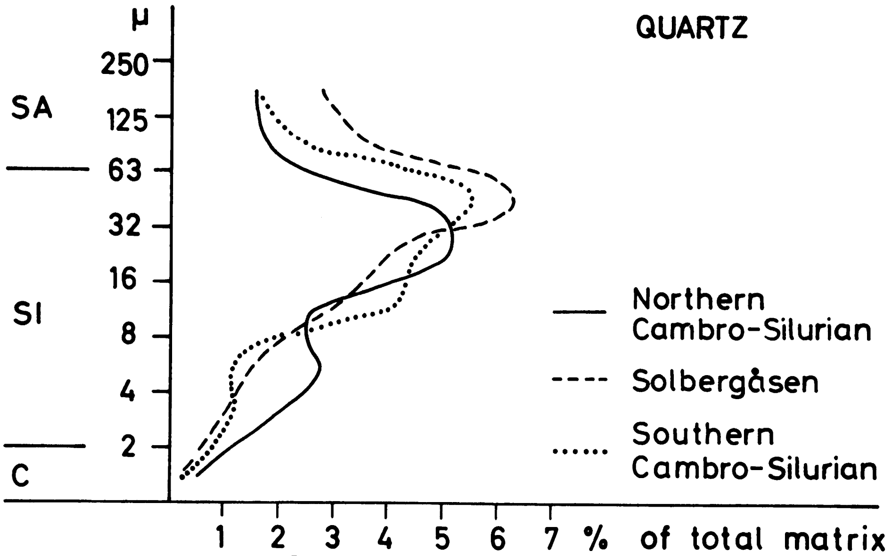

Fig. 18. Distribution of quartz (weight percentage of total matrix) in the till material <250μ in the three different parts of the investigated area.

rock fragments would therefore have been fractured more easily across mineral grains than along the boundaries between the grains.

The sand fraction of the till in the northern Cambro-Silurian area has a rather low content of Late Precambrian rock fragments in relation to Late Precambrian mineral grains, indicating that the Late Precambrian sandstones were mainly comminuted along the boundaries between the mineral grains.

Quartz

In the northern Cambro-Silurian area the quartz maximum is found in the 16–32μ fraction (Fig. 18). This mode is the result of the contribution of mineral grains from the silty shale, the Late Precambrian pelitic rocks and the Late Precambrian sandstones, even though none of these rock-types has a quartz mode within the 16–32μ fraction. The mode of quartz in till from Solbergåsen and the southern Cambro-Silurian area is lying in the 32–63μ fraction (Fig. 18).

In till fraction 125–250μ the ratio of plagioclase to quartz is rather uniform across Solbergåsen (Fig. 8 C). In fraction 63–125μ, however, there is an increase of quartz relative to plagioclase (Fig. 9 C). The Precambrian quartz grains would therefore appear to have been more resistant to glacial comminution than the plagioclase. The weight percentage of quartz in the coarse and medium silt grades is gradually decreasing across Solbergåsen, and the relative influence of Precambrian quartz grains in these fractions was shown to be small (Figs. 10 C & 11) The Precambrian quartz grains therefore seem to have a matrix mode in till fraction 63–125μ and were enriched in this fraction by comminution during the glacial transport. The comparatively greater resistance of quartz also helps to explain the high content of this mineral in the fine sand grades of the till at Solbergåsen. The mode of quartz in fraction 32–63μ at Solbergåsen is consequently not considered as a matrix mode of the Precambrian quartz. The mode is more conceivably a result of a significant contamination by quartz grains transported southwards from the northern Cambro-Silurian area. On average, 20% of material with the same content of quartz as the till in the northern Cambro-Silurian area (Fig. 18) is sufficient to move the mode of quartz from the fraction 63–125 μ to the fraction 32–63μ in the till material at Solbergåsen.

Alkali feldspar

In the northern Cambro-Silurian area, the grains of alkali feldspar from the Late Precambrian sandstones seem to have had about the same degree of resistance to glacial comminution as plagioclase. Alkali feldspar from the crystalline rocks of Solbergåsen is about equally as resistant to glacial comminution as quartz, but considerably more resistant than the plagioclase. The grains of alkali feldspar from all the coarse-grained rock-types in the area are, in fact, generally relatively resistant to glacial comminution.

Except for the Late Precambrian pelitic rocks, the fine-grained rock-types in the area have very low contents of alkali feldspar (Fig. 2). The silt and clay grades of the till therefore contain only very small amounts of this variety of feldspar.

Biotite

The large biotite grains from the Precambrian bedrock are particularly resistant to glacial comminution and are enriched in the finest sand grades of the till. Studies from other parts of Norway (Elverhøi 1977, K. Lien pers.comm. 1973, P. Jørgensen & H. Rueslåtten pers. comm. 1976) have also shown that biotite may be resistant to glacial comminution. This property is probably dependent on the great elasticity, the shape and the orientation of bioite grains in the basal layers of the glacier during the glacial transport.

The more fine-grained biotite from the Precambrian rocks can be recognized in some fine silt and clay samples from Solbergåsen as trioctahedral illite or as vermiculite.

'TERMINAL GRADES'

The definition of 'terminal grades' according to Dreimanis & Vagners (1971 a, p. 243) refers to those mineral grades which are the final product of glacial comminution. For multimineralic rocks, these mineral grades were found to be restricted to certain particle-size grades typical for each mineral. It was suggested that hardness and cleavage of minerals and primary size distribution within the parent rocks have a direct influence upon the 'terminal grade' and an attempt was made to determine characteristic 'terminal grades' of different minerals. It was observed that several mineral types have bimodal or trimodal 'terminal grades' which are due to the influence of different rock-types. Quartz modes were found within grades between 250μ and 4μ and all these grades were designated as 'terminal grades' of quartz (Dreimanis & Vagners 1969, p. 96, 1971 a, pp. 243–245, 1971 b, p. 787).

The concept of 'terminal grades' is very well illustrated by the matrix modes of plagioclase and quartz grains from Precambrian crystalline rocks in the till material from Ringsaker. The grade 16–32μ can thus be named the 'terminal grade' of the Precambrian plagioclase, and the grade 63–125μ the 'terminal grade' of the Precambrian quartz. Similarily, the finest sand grade can be considered as the 'terminal grade' of alkali feldspar and biotite grains from the horst rocks.

The quartz grains in the Precambrian bedrock are generally smaller than the plagioclase grains. The quartz grains are only halved before reaching the 'terminal grade' during the glacial transport, whereas the grains of plagioclase are considerably reduced in relation to their primary size. The 'terminal grades' of the plagioclase and quartz thus clearly illustrate the different resistances of these two minerals to glacial comminution.

At Ringsaker, grains of the same type of mineral, of similar primary size but from different rock-types, in some cases yielded different matrix modes in the till, dependent on the original features of the minerals. Plagioclase from the metamorphic rocks, for example, was found to have a finer 'terminal grade' than plagioclase from the sedimentary rocks.

The present till study also showed that the primary size of mineral grains from pelitic rocks is well preserved during the glacial transport, and even grains from coarser-grained sedimentary rock-types appear to be very resistant to glacial comminution. Till studies from quartzite and sandstone areas in other parts of Norway have also clearly demonstrated the great resistance of mineral material from sedimentary rocks (Mangerud 1965, p. 218, Sørensen 1969).

Grinding of rock material in ball mills has in some cases produced the same bimodal distribution of rock components as observed in basal tills (Buller & McManus 1973, p. 141). Mineral grains and rock fragments thus seem to acquire about the same grain-size distribution through different mechanical crushing processes, not only by glacial comminution. This is mainly the reason why the mechanically stable, clastic grains, which are dominating in most sedimentary rocks, are so resistant to glacial comminution. The formation of mineral modes or 'terminal grades' by comminution of rock material by different kinds of mechanical erosion, including glacial erosion processes, can thus be considered mainly as a primary property of the rocks and minerals.

The determination of characteristic 'terminal grades' for different minerals (Dreimanis & Vagners 1971 a, p. 244) was based mainly on studies of till material derived from metamorphic and igneous rocks. Most of the minerals were found to have major modes in the coarse silt and very fine sand grades. Mineral modes within the same grades as noted in the present investigation, have also been reported by other till investigators from crystalline bedrock areas (Harrison 1960, Lindén 1975), These observations may indicate that mineral material from relatively coarse-grained crystalline rock-types has a tendency to be enriched in these two grades during any moderate mechanical crushing process.

It should also be mentioned, however, that the determination of the 'terminal grades' of quartz was partly based on data from till material derived from Palaeozoic sedimentary rocks (Dreimanis & Vagners 1971 a, p. 245). The present investigation has shown that determinations of characteristic 'terminal grades' should not be based on material derived from sedimentary rocks. By studying different till deposits formed from sedimentary rock-types with different grain-size distributions, one could probably find almost as many different modes for one particular type of mineral as the number of mineral modes within the parent rocks. Consequently, the suggestion of Dreimanis & Vagners (1971 b, p. 787) that one can determine 'a restricted terminal grade which is typical for this mineral or its variety' cannot be upheld.

TOTAL TILL MATRIX PETROGRAPHY AND ITS RELATION TO SOURCE ROCKS

Several till investigators in Scandinavia have observed a quartz content in till material which is too high in relation to the composition of the parent rocks (Korbøl 1972, Dekko 1973, Lien 1973, Lindén 1975, Rosenqvist 1975, M. Perttunen pers. comm. 1974, B. Collini pers. comm. 1975). Such an excess of quartz seems to be relatively commonly associated with basal till.

In southern Ringsaker all the investigated till samples have an excess of quartz in the sand and coarse silt grades in relation to the composition of the local, underlying bedrock (Fig. 3). In the northern Cambro-Silurian area this quartz excess owes its presence to the influence of the nearby Late Precambrian sandstone formations. At Solbergåsen, there is a higher content of quartz in the till than in the bedrock, even in fraction 16–32μ which is the most plagioclase-rich till grade (Fig. 11). The quartz excess in this grade may, however, be explained if about 50% of the material has been transported into the horst area from the northern Cambro-Silurian district.

Throughout the investigated area, the content of quartz in the fine silt and clay grades of the till is about the same as that in the Cambro-Silurian shale formations. The till material from southern Ringsaker thus seems to have a total quartz content which is closely related to the composition of the parent rocks.

The petrographical composition of the till matrix is primarily dependent on the resistance of the different source rocks to glacial erosion and further comminution during the glacial transport. At Ringsaker, the Cambro-Silurian shales are much more easily eroded and comminuted than any of the other

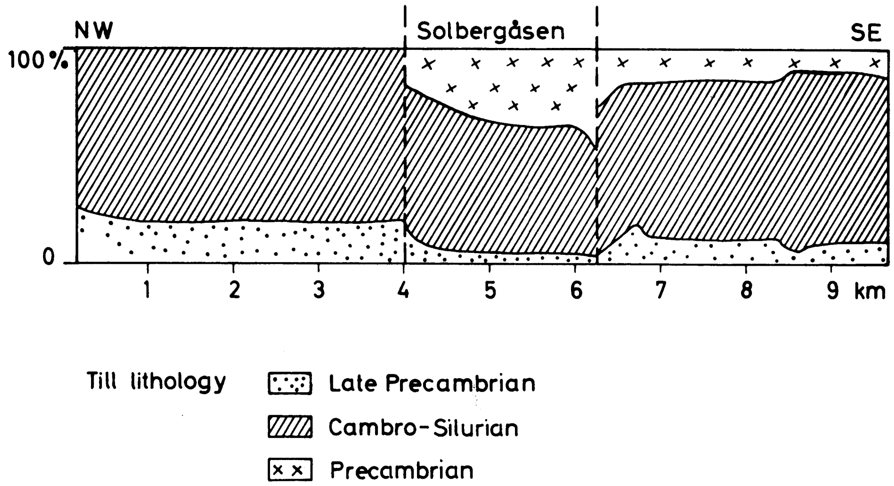

Fig. 19. Petrographical components (weight percentage) of the till matrix along section A–B in Fig. 3.

rock-types. The composition of the matrix is therefore dominated by the Cambro-Silurian rock component over the whole area (Fig. 19).

In the northern Cambro-Silurian area, the Late Precambrian rock component constitutes about 40% of the sand fractions and about 10% of the total till matrix. The presence of far transported material is considered as insignificant.

On Solbergåsen, the material from the local bedrock is most important in the coarse silt grades. The total content of material from the local bedrock is on average 30% of the total till matrix in this area (Fig. 19), the highest values occurring along the southern slope of the horst. About 70% of the total till matrix material has consequently been transported by the glacier towards the south-east, on to Solbergåsen, from the northern Cambro-Silurian area.

The relative increase in the amount of local material across Solbergåsen (Figs. 6, 10 & 11) does not necessarily indicate any significant erosion of the bedrock in the central part of the horst area (Fig. 19). A total dilution of the Cambro-Silurian till component may very well cause the observed change in both grain-size distribution (Fig. 6) and petrographical composition (Figs. 8–12). In the southern Cambro-Silurian area, between 5 and 10% of the total till matrix comprises material from the Precambrian rocks of Solbergåsen (Fig. 19). No significant decrease in this till component has been observed across the area.

Gross & Moran (1971, p. 264) have proposed a theory of progressive dilution of original till material by enrichment with local material. Similarily, Gillberg (1965), Virkkala (1971), Lindén (1975, p. 43), Melkerud (1976) and M. Perttunen (pers. comm. 1975) have observed a considerable dilution of till components over distances of a few kilometres. While such a dilution is not observed in the southern part of the investigated area, its apparent absence is possibly dependent on the special morphological features of the area and on the properties of the former glacier, both of which are discussed later in this paper. It is unlikely that the lithological composition of the bedrock has had any influence in this particular case.

Virkkala (1971) and Lindén (1975), who studied basal tills in uniform Precambrian areas, showed that the till contained gradually more long-transported material with decreasing grain-size. Their results cannot be directly applied in the present investigation, however, since the grain-size composition of the bedrock is so variable in southern Ringsaker. The petrographic composition of the different matrix grades of the till here shows little dependence on the length of transport of the material, and the fine silt and clay grades in places closely reflect the petrography of the local bedrock.

Roaldset (1972), Dekko (1973) and Lien (1973) observed that the lithological changes within the till material in Numedal, southern Norway, were not directly related to the boundaries between the different rock formations. Lithological changes in fact occurred several kilometres south of the formation boundaries. Similar results were obtained by Virkkala (1971) for the fine silt grades of basal till in southern Finland.

In southern Ringsaker, however, the most important lithological changes in the till matrix occur at the boundaries between the three main rock units (Fig. 19). The most abrupt change occurs across the boundary between the Solbergåsen horst and the southern Cambro-Silurian area. At the boundary between the northern Cambro-Silurian area and the horst there is a more gradual change in the matrix composition.

The regional changes in the lithological composition of till material are dependent on several factors. Here, the different resistances of the rock-types to glacial comminution are of primary importance. In this case, material from the Cambro-Silurian rocks north of Solbergåsen has had a marked influence upon the composition of the till on Solbergåsen, because on the horst the amount of material eroded from the relatively hard crystalline rocks has been small in relation to the amount derived from the soft shale units. There is, consequently, a gradual change in the lithological composition of the till in this part of the area. Similarily, the till material south of Solbergåsen, where glacial erosion has been comparatively great, is rapidly dominated by the local Cambro-Silurian bedrock component.

Another important factor is the effect of topographical changes, which in this case are related to the boundaries between the main rock units (Fig. 20). The mode of glacial erosion, transport and deposition, the relationship between basal melting and freezing, and the location of the debris in the glacier, are all strongly dependent on topographical features (G. Lundqvist 1940, Boulton 1970, Hillefors 1973, 1974). The very steep southern slope of the horst might have been a significant factor resulting in the abrupt lithological changes in the till matrix.

A third factor effecting changes in the petrography of till is that of the thickness of the till deposit. The petrography is commonly readilv related to the composition of the underlying bedrock where the thickness of the till is minimal. In the other hand, a downward change from a far transported basal till to a more local one is very commonly found in areas where the till thickness is great (e.g. Gillberg 1969, Hyvärinen et al. 1973, Nichol & Bjørklund 1973, p. 93, H. Gry pers. comm. 1975). In the Cambro-Silurian area at Løten in the central part of the Mjøsa district, for example, an increasing influence of the local bedrock component with depth has been recorded in some till sections (Follestad 1974). This type of vertical, petrographical variation is one of the typical characteristics of basal till.

The till deposits on Solbergåsen are generally so thin as to preclude any vertical variation within the till petrography. In the southern Cambro-Silurian area the till thickness is about the same as that in the Løten area. If here is any vertical downward change in the petrography of this till, the local bedrock component is increasing downwards. The estimated component percentage of the Precambrian rocks in the till of the southern Cambro-Silurian area (Fig. 19) must therefore be considered as a maximum value, and representative only of the upper meter of the till material.

It has been observed that each lithological component of basal tills has one mode within the gravel or sand grade and one or more modes within the matrix, and that the cumulative frequency curves of these components have a break of slope associated with the change from rock fragments to mineral grains (Dreimanis & Vagners 1971 a, Beaumont 1971). In southern Ringsaker, each Cambro-Silurian shale unit is repeated by folding, the strike of the units lying roughly normal to the direction of ice movement (Fig. 3). At any one locality the till therefore consists of both local and long-transported components of each rock-type. Calculation of a mode for the different shale types in the gravel or sand fraction is therefore hardly possible.

The distribution of the Cambro-Silurian silty shale component is of prime importance with regard to the grain-size distribution of the tills and also to the break of slope on the total till frequency curves. Most of the cumulative grain-size curves for the till samples from southern Ringsaker have a break of slope within the finest sand grade. The two main lithological components of the finest sand grade – mineral grains from the Late Precambrian sandstones and quartz grains from the Precambrian crystalline rocks – are quantitatively of little importance as far as the total petrographic composition of the till is concerned.

THE GENESIS OF THE TILL

Throughout the investigated area the cobble and boulder grades in the till are dominated by Late Precambrian rocks, as in other parts of the Mjøsa district (Follestad 1974, p. 19, R. Sørensen pers. comm. 1974). The coarse till fractions at Solbergåsen thus have a very low content of material from the local Precambrian bedrock. The low content of coarse material, the polished

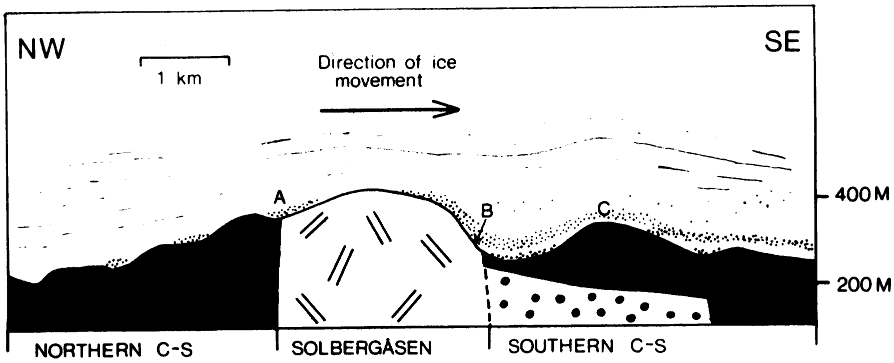

Fig. 20. Model of the conceived situation during the glaciation of the Solbergåsen area showing a possible mechanism of glacial erosion and till formation. Basal till (A) is deposited at the stoss side. B indicates the cavity and the zone of basal freezing on the lee side. At C there is a debris band formed in an englacial position.

surface of the bedrock and the morphology at the northern slope of Solbergåsen (Figs. 4 & 20) indicate that abrasion has been the main mechanism of glacial erosion here, as is normally the case on the stoss side of bedrock obstructions. Along the southern part of Solbergåsen, on the other hand, the higher frequency of boulders of Precambrian rocks and the steeper and more irregular morphology show that lee-side plucking has been effective. Some of the till samples from the southern slope were also found to be of a local coarse-grained type (Fig. 5 B) with a petrographical composition close to that of the bedrock (Figs. 8–10).

The behaviour of glaciers passing over bedrock obstructions has been studied by Boulton (1970). Basal freezing on the down-glacier flanks of the obstructions was found to result in the formation of debris bands in englacial positions. These studies were limited to rather steep sub-polar glaciers on Svalbard, and the bedrock obstructions were only a few metres high. Although the former glacier at southern Ringsaker was presumably quite different from the glacier studied by Boulton, and the dimensions of Solbergåsen different from the obstructions of the Svalbard glaciers, the conclusions of the Svalbard investigation might be applicable, at least to a certain degree, in the Solbergåsen area. Along the northern slope of Solbergåsen, a basal melting process may have caused the deposition of a relatively continuous cover of till with a relatively high content of Cambro-Silurian material (Fig. 20). The irregular surface at the southern side of the horst can then be explained by a regelation process with lee-side plucking. As a result of this regelation or basal freezing process, debris bands with material eroded from different parts of Solbergåsen might have been introduced to a more englacial position above the zone of regelation ice (Fig. 20). From this position it might have been possible to distribute the material over several kilometres within the Cambro-Silurian area without any significant dilution occuring. A similar model of till formation has been suggested by Shilts (1973) from an area in southeastern Quebec.

Even if Boulton's (1970) model should prove to be not entirely acceptable for the genesis of the southern Ringsaker till, it must in any case be supposed that the gradual dilution of till components will have been disturbed in those areas where the glacier passed over bedrock obstructions.

According to Boulton (1970), the material transported by englacial debris bands should be classified as ablation till. Its characteristics can, however, be very similar to those of basal till, and in the field such deposits will probably frequently be classified as basal melt-out tills. The tills in southern Ringsaker have therefore been classified mainly as basal till, even though some of the material may have been transported englacially.

TIME OF TILL FORMATION

The youngest ice movement, from the north (Fig. 4), does not seem to have had much influence upon the formation of till in the investigated area. Fragments from the alkali feldspar-rich augen gneiss bedrock, which is situated directly to the north of the location of the easternmost till samples (Fig. 3), are not observed in the matrix or in the 8–16 mm gravel fraction of the till. The till material was therefore most probably formed during the main ice movement from the north-west, and a transportation of this material towards the south-east has in fact been demonstrated in several cases by the petrographical composition of the matrix. This south-eastward movement probably occurred during the main glacier advance prior to and during the Weichsel maximum, when the glacier was so thick that its movement was largely independent of the local topography.

Significant parameters for till descriptions

Investigations of the boulder, cobble and gravel material are frequently included in till descriptions, mainly because the petrographical identification can be carried out fairly rapidly and because source rock areas, in many cases, are easily determined.

Petrographical studies of the till matrix, on the other hand, are usually much more time-consuming. Lithological components of the till matrix can sometimes be identified by visual criteria, as for instance the different shale types and the saussuritized plagioclase grains in southern Ringsaker. In many cases, however, calculations of the petrographic till matrix parameters have to be based on the ratios between different minerals, because the same minerals occur in several of the parent rocks.

Investigations restricted to boulder, cobble and gravel material have, in some cases, been used to provide a general characteristic of the total till material, and to determine the source material of the till (Låg 1948). In other cases the gravel lithology has sometimes been the main till petrographic parameter in descriptions to maps of the Quaternary geology (Follestad 1973, 1974). The lithological composition of one or a few till grades is, however, not necessarily representative for the total till material. For instance, the gravel fraction, 8–16 mm, and the coarse silt fractions of the till at Solbergåsen are dominated by different rock components, and the cobble and boulder compositions are not at all representative for the till matrix petrography in southern Ringsaker.

The choice of significant parameters for till descriptions will then depend on the purpose of the investigation. When the main purpose is to determine the direction of ice movements and the position of ice divides, studies of the coarse-grained till material can be sufficient. Other types of description, as for instance descriptions to maps of the Quaternary geology, will frequently be used as basic information for areal planning, agriculture and forestry. In these cases information on the till matrix composition will be of more direct interest than the gravel petrography. Certainly, more knowledge about the formation and composition of till, and about the relationship between the till and the bedrock, will simplify the choice of a representative set of parameters for description of the till material.

Conclusions

The total petrographical composition of the till matrix was found to be primarily dependent on the resistance of the different rock-types to glacial erosion. In southern Ringsaker, the Cambro-Silurian rock component is dominant everywhere because of the very low resistance of the shales.

The size distribution of each rock component in the till matrix is dependent on the primary size of the minerals, and on the types of mineral present. Minerals from the Precambrian crystalline rocks were easily comminuted to fine sand and coarse silt grades, and these illustrate very clearly the notion of 'terminal grades'. Mineral grains from sedimentary rocks have preserved their primary size during the glacial transport.

The till matrix composition is generally closely related to the local bedrock petrography in southern Ringsaker, where the till thickness is relatively small. The most important petrographical changes in the tills occur at or close to the boundaries of the main rock units. Topographical changes, which are here associated with the bedrock boundaries, may be important in this connection. The difference between the stoss-and lee-side tills at Solbergåsen demonstrates the effect of the topographical features.

The till matrix petrography can be used successfully to determine the direction of ice movements, but in this respect matrix studies will probably never be quite so important as studies of the coarser material. However, the present investigation has shown that studies of the till matrix can, in certain cases, provide important information concerning the formation and characteristics of till which would otherwise not be available solely through studies of the coarser material. It has also clearly demonstrated that the petrography of just one or two, or even of a restricted number of till grades is not necessarily representative for the total till matrix.

Acknowledgements. R. Sørensen has kindly placed all the till samples and the bedrock samples from Solbergåsen at my disposal. Professor S. Skjeseth and Dr. J.-O. Englund have provided valuable information on the bedrock geology; and J. P. Nystuen, T. Vorren and B. Follestad have given constructive criticism of the manuscript. Dr. D. Roberts kindly corrected the English text of the final manuscript. The laboratory work has been carried out by G. Block. To all these persons I tender my sincere thanks. Financial support, including defraying part of the cost of publication, has been provided by the Norwegian Research Council for Science and the Humanities (NAVF).

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PAPER 4

GLACIAL COMMINUTION OF MINERAL GRAINS

SYLVI HALDORSEN

Glacial comminution of mineral grains

SYLVI HALDORSEN

Haldorsen, S.: Glacial comminution of mineral grains. *Norsk Geologisk Tidsskrift*, Vol. 58, pp. 241–243. Oslo 1978. ISSN 0029-196X.

The factors influencing the comminution of separate mineral grains during glacial transport and the applicability of the term 'terminal grade' are discussed.

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In 1965 Dreimanis & Vagners published the results of their studies on mineral modes in basal tills from Ontario, Canada, where they suggested that mineral grains undergo a restricted disintegration during glacial transport. They then named the final product of the glacial comminution 'terminal grades' as the minerals were not crushed or abraded finer than those modes, even after a glacial transport of several hundred kilometres. 'Terminal grades' of the studied mineral types were most commonly found in the finest sand and coarsest silt grades of the tills. For each investigated mineral, the particle-size range of the 'terminal grades' appeared to be relatively constant, and it was suggested that this would apply to tills also from other areas (Dreimanis & Vagners 1965, 1971a). Later, the concept of 'terminal grades' has been widely used (see Lindén 1975, Mulholland 1976, Svantesson 1976, Perttunen 1977, Vorren 1977, Haldorsen 1977a, 1977b).

The following discussion concerns the glacial crushing of separate mineral grains from different bedrock types and the applicability of the term 'terminal grade' as used by Dreimanis & Vagners (1965, 1969, 1971a, 1971b).

The degree of mineral comminution during glacial transport depends on many different factors, of which the properties of the mineral 'inherited' from the parent rocks are the most important ones (Dreimanis & Vagners 1965, 1969, 1971a, 1971b, Haldorsen 1977a). Generally, every factor which influences the brittleness of the minerals is of importance in this connection. Therefore, one single mineral type from different bedrocks may be expected to have 'terminal grades' within many different till grades, depending on its primary properties.

One important factor regarding the glacial comminution is the preglacial history of the mineral grains. During any interglacial cyclus, sediments from the preceding glacial have been exposed to soil weathering, changing the primary mineral composition in at least the upper half metre of the sediments. This weathering may have an influence both upon the primary size of the mineral grains and their resistance to a new glacial transport. Such factors will apparently be of importance for mineral modes in cases where the till contains a large amount of redeposited interglacial sediments. It is for instance, supposed that a significant part of the Scandinavian till deposits may contain such old redeposited material (Gillberg 1977).

However, even when the till material is formed solely by erosion of unweathered bedrock material, there are a lot of factors influencing the glacial comminution of each mineral grain. The following discussion concerns some of these factors.

Generally, there seems to be a great difference between the comminution of grains from unmetamorphic clastic sedimentary rocks such as shales and sandstones on the one hand and grains from crystalline rocks on the other hand (Haldorsen 1977a).

Unmetamorphic clastic sedimentary rocks have mainly been formed by marine and fluvial sedimentation whereby they were enriched by mineral grains resistant to mechanical weathering. During glacial transport, fragments from such sedimentary rocks have mainly been fractured along grain boundaries, giving a till component consisting of separate mineral grains. These mechanically stable mineral grains are usually not reduced in size even by a rather long glacial transport (Haldorsen 1977a). The very great resistance of mineral grains from such sedimentary rocks is further demonstrated by the works of Mangerud (1965) and Sørensen

(1969). Thus, by studying till material from many different unmetamorphic, clastic sedimentary bedrock areas, one may expect to find modes for a single mineral type in every till grade from clay to sand, dependent on the grain size composition of the parent rock.

Crystalline rocks, on the other hand, commonly consist of mineral grains which to a large extent are unstable when subjected to glacial and other mechanical crushing processes. For instance, the high frequency of crystalline rock fragments in the medium to fine sand grades of the tills at Ringsaker, southeastern Norway, indicated that here the crystalline rock fragments were first disintegrated both across and along mineral grain boundaries, the two mechanisms being of about equal importance. During continued glacial transport, the smaller rock fragments and mineral grains have then been further comminuted to the characteristic fine-grained 'terminal grades'. In that way the unstable mineral grains from the crystalline rocks were considerably more reduced in size during glacial transport than the same mineral from the sedimentary rocks (Haldorsen 1977a).

Cleavage, grain size, and grain shape have been found to be very important factors regarding the 'terminal grade' and it was also suggested that hardness is an important factor in this connection (Dreimanis & Vagners 1969, 1971a). However, flakes of biotite, which is a rather soft silicate mineral, have been found to be very resistant to glacial comminution and become enriched in the coarse part of the till matrix even after a glacial transport of more than hundred kilometres (Elverhøi 1977, Haldorsen 1977a). Also muscovite flakes from different bedrock types has been shown to retain their length and breadth very well during glacial transport (Haldorsen 1977a). The resistance of mica flakes probably depends on their great elasticity and their orientation in the basal ice layers during transport. On the other hand, the thickness of the mica grains is rapidly reduced by cleavage, a process which obviously has nothing to do with mineral hardness.

Primary fractures within the mineral grains, which may or may not coincide with the cleavage planes, are in many cases one of the main factors controlling the degree of glacial comminution. Haldorsen (1977a) found that plagioclase grains which within the bedrock were frequently dissected by fractures, were very prone to glacial comminution, and the mode of those plagioclase grains were found in finer till grades than any of the modes observed by Dreimanis & Vagners (1971a).

One factor of importance which has not yet been regarded is the type and degree of cementation of the sedimentary rocks. It should for instance be expected that grains which are cemented by silica material are more easily disintegrated across mineral grains than when they are surrounded by a soft clay matrix.

The type of grain boundary is also a relevant factor in this connection. Rock fragments from the more metamorphosed Late Precambrian sandstones in southern Norway seem to have a greater tendency to be comminuted across mineral grains than the fragments from the unmetamorphic types. During the metamorphosis, the originally, relatively smooth grain boundaries have been modified to more irregular forms, often accompanied by recrystallization of quartz in the pore spaces, giving modes in finer fractions of the till than are observed for the unmetamorphosed sandstone minerals.

On the other hand, metamorphosed sandstones with a clay matrix may have a film of sericite around the grains, which commonly promotes disintegration of rock fragments along grain boundaries, like that for the unmetamorphosed types.

Unweathered mineral grains from unmetamorphosed sedimentary rocks are commonly very resistant to glacial comminution. Their modes in the basal till are 'interited' and closely reflect the primary size distribution within the parent rocks. The term 'terminal grade' should therefore not be applied in connection with mineral modes from such sedimentary rocks in basal till.

For unweathered mineral grains from coarse-grained crystalline rocks, on the other hand, the modes observed in the till were formed by comminution of individual mineral grains during the glacial transport and the term 'terminal grade' may in some cases be applied.

However, the size-class of 'terminal grade' even for minerals from crystalline rocks has been shown to be dependent on many factors, indicating that the range of mineral modes for any one mineral is much greater than suggested by Dreimanis & Vagners (1965, 1969, 1971a, 1971b).

Acknowledgements. – I wish to thank cand. real. J. P. Nystuen, Prof. A. Dreimanis, Dr. P. Jørgensen and cand. real. R.

Sørensen for valuable discussion and helpful suggestions during the preparation of the manuscript.

January 1978

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PAPER 5

THE GENESIS OF TILLS FROM A CENTRAL PART OF SOUTHERN SCANDINAVIA

SYLVI HALDORSEN

THE GENESIS OF TILLS FROM A CENTRAL PART OF SOUTHERN SCANDINAVIA

Haldorsen, Sylvi: The genesis of tills from a central part of southern Scandinavia.

The genesis of tills in Åstadalen in southeastern Norway is dicussed. Ice movements were from north and later from north-west. Most of the area is covered by a 1.5 m thick till which does not create independent landforms. In the mountainous areas this till is local and coarse-grained and interpreted as a subglacial melt-out till. Here the glacier was probably rather passive when the till was formed. A complex till occurs along the eastern valley side. At typical lee-side localities the local coarse-grained till is most probably of a subglacial melt-out origin. Along the western valley side and western upland area the till is everywhere rather fine-grained and compact, and cobbles and boulders are abraded. Most parts of this till were clearly formed by a lodgement process. Transverse moraine ridges, mainly occurring along the western part of the valley, are composed of till which is interpreted as subglacial melt-out till. Some probably supraglacial material occurs at the top. Hummocks consisting of diamicton are found particularly along the eastern side of the valley. These are composed mainly of subglacially deposited till which was subsequently transported on to the surface of the ice from the valley side. Most of the till material in Åstadalen is therefore believed to originate from basally transported glacial debris.

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CONTENTS

INTRODUCTION

The classification of till related to its genesis has been a subject of broad interest for glacial geologists during the last ten years. The interest has been greatly stimulated by the work of INQUA-Commission on Genesis and Lithology of Quaternary deposits (see Dreimanis 1976, 1979, 1980). The commission has proposed different detailed tentative classification systems for tills (see Dreimanis 1976, Fig.5).

In Norway tills have, for a long time, been divided in two genetical groups; basal till and ablation till (Holtedahl 1953, 754-58, G.Holmsen 1956). The first type refers to deposition of material from the basal part of ice and the second to deposition of supraglacial material. The same division is still used today (see Sørensen 1979a, Sveian 1979, Vorren 1979). It is in many cases difficult to distinguish between these two till types in Scandinavia, because varieties of basal tills may be so similar to varieties of ablation till (see descriptions and discussions in e.g. Hoppe 1963, J.Lundqvist 1969a, Vorren 1979).

The study described here was carried out in Åstadalen, southeastern Norway. The aim has been to see if a detailed genetical interpretation can be given on the basis of morainic morphology, till texture and till structure.

Since there is still no single generally accepted genetical classification system of tills, it is necessary to define the terms used in this paper. They are mainly based on Boulton (1976) and Dreimanis (1976) and on a classification proposed by Shaw (1979a) for the INQUA-Commission on Genesis

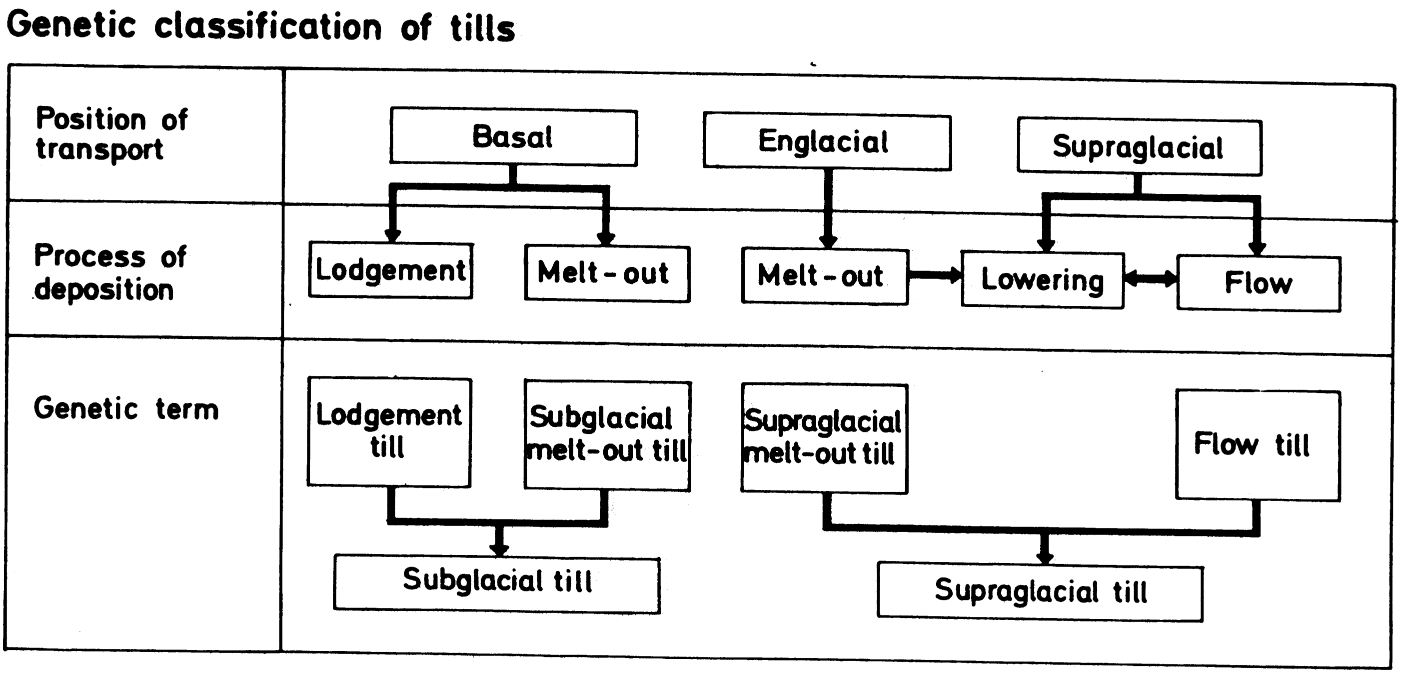


Fig.1 Classification system for tills. Based on Dreimanis (1976), Boulton (1976) and Shaw (1979a).

and Lithology of Quaternary Deposits, Work Group 1. Fig.1 shows the principles of the classification.

Subglacial till is mainly formed by deposition of basal debris (Fig.1). Lodgement till is deposited by lodging of material from the overlying active, sliding ice as described by for instance Boulton (1976, 1978). Friction against the bed forced the clasts to be lodged one by one. By a plastering on they were gradually embedded in more fine-grained till matrix. Subglacial melt-out till (Fig.1) is deposited by a pure melt-out process. Obviously also the lodgement process involves a subglacial melting (Goldthwait 1971) and should logically form one part of the subglacial melt-out tills. However, the processes of lodgement are assumed to form a till with characteristics different from tills deposited by a pure melt-out (see Boulton 1976, 1978). In this paper subglacial melt-out till therefore refers to tills which were deposited where no lodging from sliding ice took place, i.e. from zones of the glacier where total or basal stagnation had occurred (Shaw 1977a, 1979a).

Lodgement till is the "normal" subglacial till type related to temperate glaciers (see Boulton 1976). In Norway the time after the Weichselian maximum probably gave favourable conditions for deposition of lodgement till, since the glaciers then were active during a long period.

Subglacial melt-out till is probably of more local occurrence. It may have been formed beneath the frontal parts of cold-based glaciers (see Shaw 1977a). Subglacial melt-out till is also related to temperate glaciers. Locally such till may have been formed in zones where parts of the basal ice stagnated because of friction against the substratum (see G.Lundqvist 1940), or during the final part of deglaciation by the melting of debris-rich basal ice remnants (see Mickelson 1971).

Supraglacial till refers to glacial debris which occurred at the surface of the ice and which was deposited when the underlying ice melted away (Fig.1). Supraglacial melt-out till is formed by debris which was mainly transported in an englacial position and which afterwards was introduced by melting to supraglacial position. It was deposited by a lowering when the underlying ice melted (Fig.1). Glacial drift may in cases have been transported totally in supraglacial position without any incorporation in the glacial ice. Consequently supraglacial till may also have been deposited by a pure lowering (Fig.1).

Before and during deposition the supraglacial debris might have slid or slumped. The formation of the final sediment has then also included a process of flow. If this flow altered the original texture or structure of the debris significantly, the sediment should be classified as flow till (Fig.1).

It was realized long ago that the properties of tills in Scandinavia are clearly related to the topography of the substratum (see G.Lundqvist 1940). There it is further a clear relationship between till genesis and the related morainic morphology (see general summary discussion in Sudgen & John 1976, 235-257). The following descriptions are

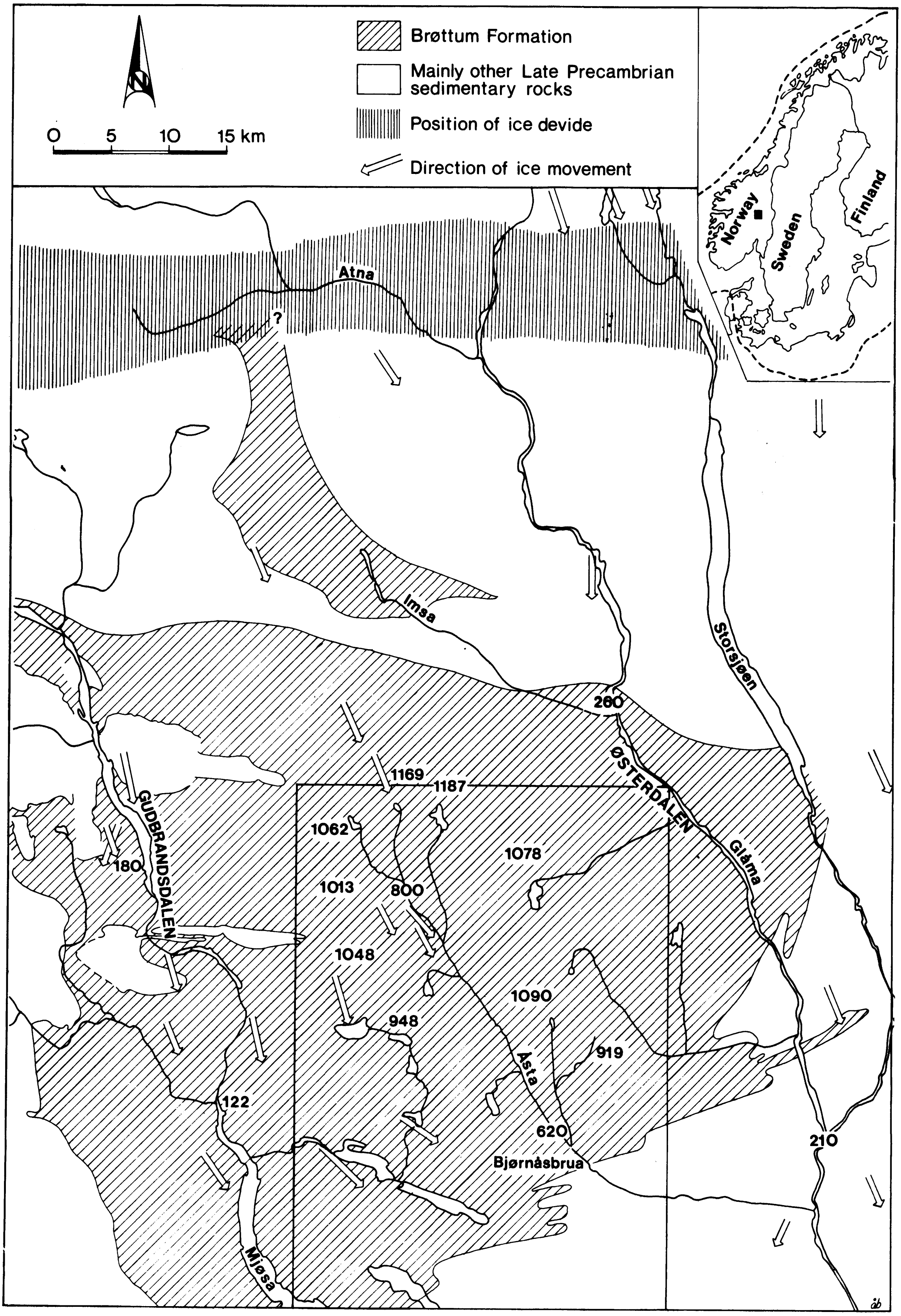


Fig.2 Keymap showing the position of the investigated area (framed). Bedrock geology after J.-O. Englund (1973, pers.comm. 1980) and J. P. Nystuen (pers.comm. 1980). Direction of ice movements after G. Holmsen (1960, Fig.2). Numbers give height above sea level in metres. The stipled line on inset map shows the maximum extension of the Weichselian ice sheet.

related to the main topographical position of the tills and to the main morainic morphology. Till genesis is discussed for each topographical or morphological group separately.

METHODS

The content of boulders and cobbles was calculated in till sections and was usually estimated visually. A few sections were thoroughly cleaned and the area occupied by boulders and cobbles were measured. Both visual and areal methods give rough estimations only.

The material finer than 64 mm was analysed by sieving and hydrometer method.

Standard samples were applied during the determinations of roundness which was calculated according to Krumbein (1941).

Fabric data were evaluated statistically by using the eigenvalue method (Mark 1973). The analysis was performed by computer at the University of Alberta, Edmonton, Canada. At two localities the method of Steinmetz (1962) was applied because eigenvectors had not been calculated.

REGIONAL DESCRIPTION

The study was carried out in the Åstadalen area in central southeastern Norway. Åstadalen is a valley lying between the eastern-Norwegian main valleys of Gudbrandsdalen and Østerdalen (Fig.2). The river Åsta drains into the Glomma in Østerdalen. The investigation has been concentrated in the catchment area of the Åsta north of Bjørnåsbrua (Fig.2).

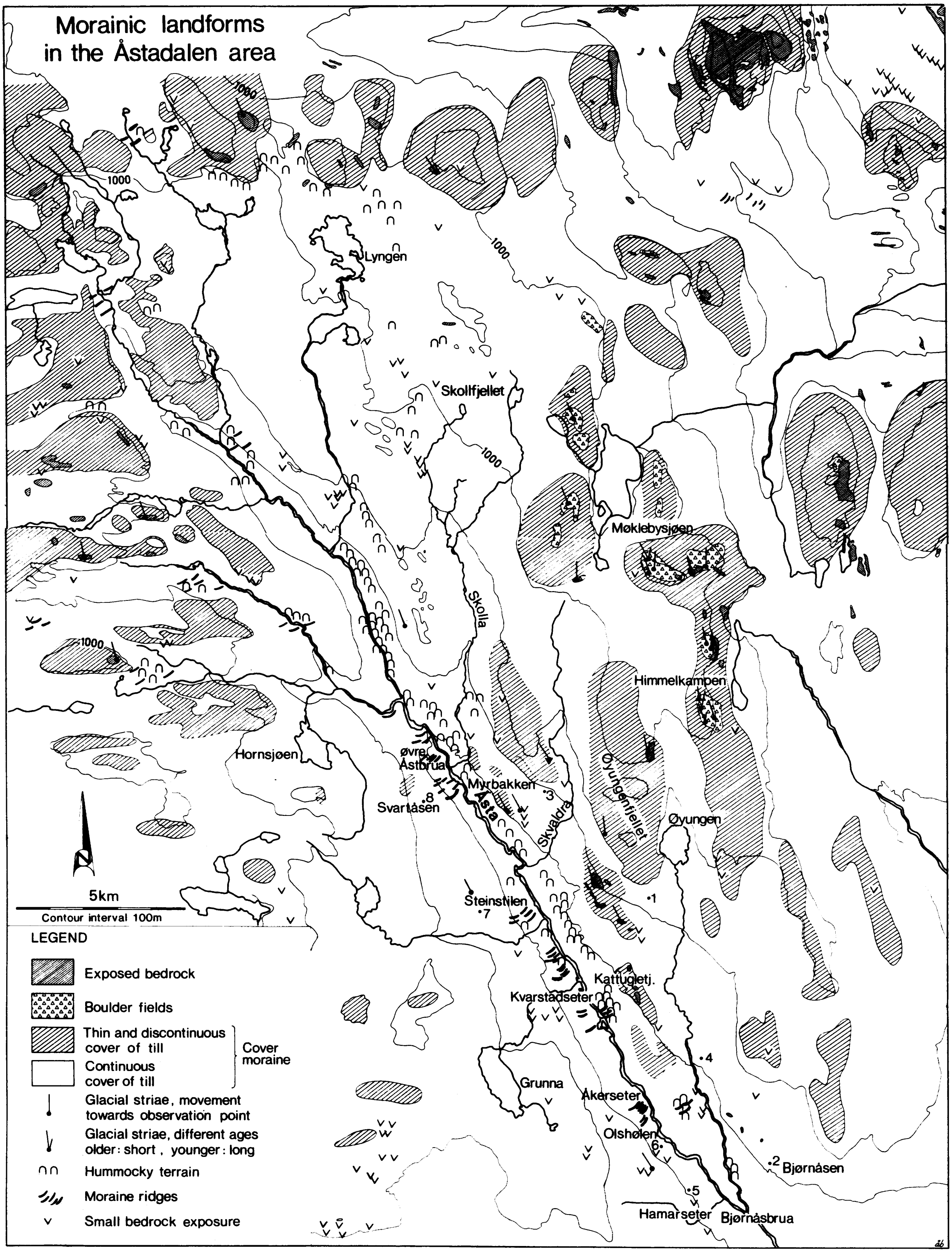


Fig.3 Map of the moraine types, distribution of till and glacial striations in Åstadalen. Partly based on Østeraas (1978, 1981). Sediments other than till are not indicated.

The valley bottom lies at about 800 m a.s.l. in its upper part and slopes down to 620 m a.s.l.at Bjørnåsbrua, and the total area represents an upland area relative to Gudbrandsdalen and Østerdalen (see numbers in Fig.2).

Åstadalen is surrounded by mountain plateaus to the east and northeast with an average level of 800-1000 m a.s.l. and with mountain peaks up to about 1100 m. To the north the catchment area ends in a mountain range with heights from 1000 to 1200 m a.s.l. and to the west in upland areas with mountain peaks up to about 1050 m. The valley is fairly wide with gentle side slopes (Fig.3). The northeastern valley side is somewhat steeper than the southwestern one and passes abruptly into the eastern mountain area, while the western side is a more gradual transition to the upland area.

BEDROCK

The bedrock consists of Late Precambrian sedimentary rocks belonging to the Brøttum Formation (Englund 1972, Fig.17). In the south the bedrock is composed of rather homogeneous sandstones while in the north the sandstone alternates with layers of silty shale (Fig.4). North of the Brøttum Formation other Late Precambrian sedimentary rocks occur (Fig.2), and a great part of them have a composition similar to the Brøttum Formation (J.-O. Englund, pers.comm.1980). The strike of the bedrock is generally E-W (Fig.4). The bedding and the main regional fractures in NW-SE and NNE-SSW

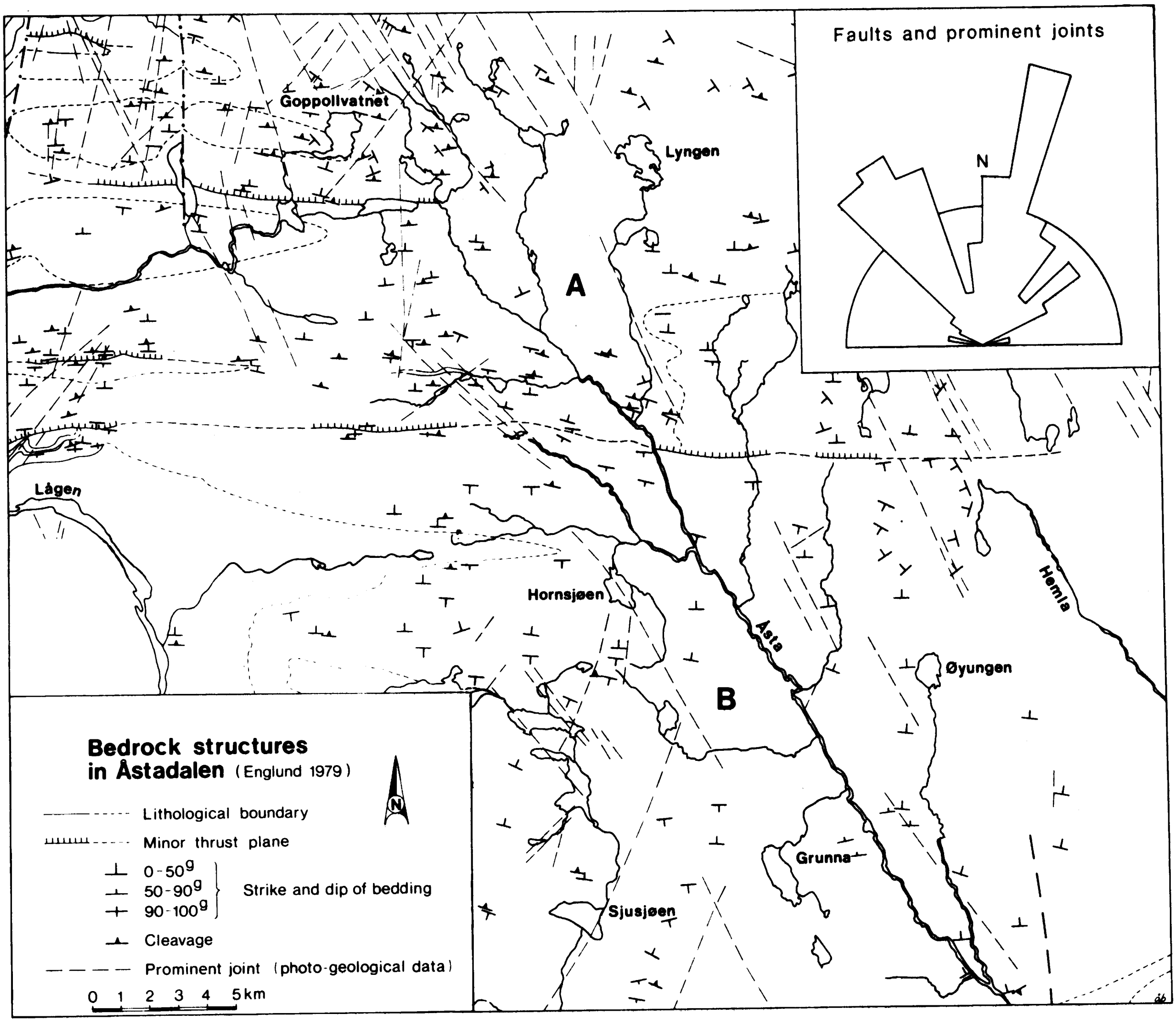


Fig.4 Bedrock geology in Åstadalen. Area A is sandstones with 5% shale horizons, area B is sandstones with some conglomeratic beds.

direction strongly control the morphology.

Above 11-1200 m a.s.l. the bedrock is intensively fractured by frost cracking and the surface is here partly covered by boulder fields (Fig.5). Such fields are common in the central part of Scandinavia and have been described by Holmsen (1960), G.Lundqvist (1951; 81-82) and J.Lundqvist (1969a;119). In many places where the boulders lie in situ and each separate sandstone bed can be traced across the boulder fields.

ICE DIVIDES AND ICE MOVEMENTS

The data of G.Holmsen (1960), P.Holmsen (1951, 1964) and Vorren (1977) indicate that the Åstadalen area lay only a few tens of kilometres south of the ice divide during a large part of the Weichselian (Fig.2). For some time it might even have been directly beneath the ice divide (P.Holmsen 1951, Vorren 1977, Fig.3).

The directions of ice movements are interpreted from striations. A north-south direction is found at several places in the mountains but this is not observed in the valley (Fig.3). North-south striations are also observed at some other places in the Østerdalen region (Fig.2)(G.Holmsen 1960, Fig.2). The dominating striation in the area reflects a glacial movement from the northwest (Fig.3). Crossing striations in the mountains (Fig.3) show that this movement is younger than the one from north. A glacial movement from northwest was also dominant in other places

Fig.5 Typical boulder field at the mountain Himmelkampen.

Fig.6 Cover moraine at Øyungenfjell with characteristic coarse and angular surface material.

in the Østerdalen area south of the ice divide (Fig.2) (G.Holmsen 1960, Fig.2).

MORAINIC MORPHOLOGY AND RELATED TILL TYPES

COVER MORAINE

Most of the area is covered by till of thickness 1-5 m. No morainic landforms parallel with the early glacial movements from the north are observed. An impression from air photos and field interpretations is that the northwest - southeast trending morphology mainly reflects the bedrock structures (Fig.4). It is, therefore, difficult to determine whether the small-scale topography reflects independent moraine forms or the underlying bedrock surface.

Thin till covers like the ones in Åstadalen are common in Norway. The related morphology is classified as ground moraine (see Holtedahl 1960; 389-403, G.Holmsen 1954; 50, 1960; 62). The same classification has been used in Finland (Aario 1977, 88). However, if the definition given by Flint (1971: 199) is applied, a moraine is defined as 'possessing initial constructional form independent of the floor beneath it' and such forms usually are lacking in Åstadalen. The till cover found here is according to Flint (1971; 200) not properly creating moraines 'it is merely a part of a drift sheet, a stratigraphic but not morphologic unit'. Aario (1977; 88) proposed the term 'cover moraine' for the morphology within areas where the immediately

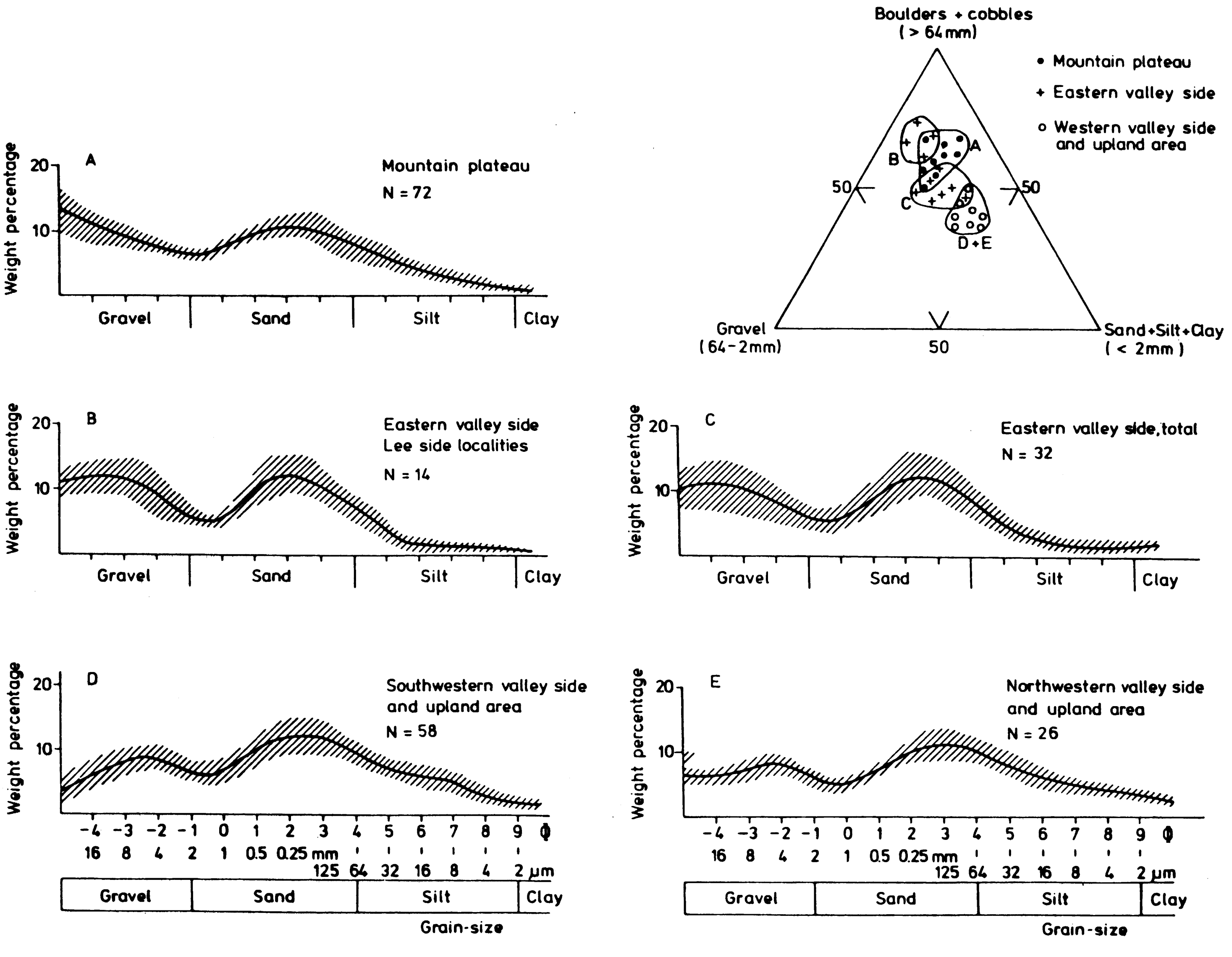


Fig.7 Grain-size distributions of different till types from the cover moraine areas. Shaded: one standard deviation form the mean values. Letters A-E in the triangular diagram have the same meaning as the letters A-E in the histogram.

underlying bedrock is reflected. Although this term is not in accordance with the definition of moraine used by Flint (1971; 199), it applies very well to Åstadalen and is therefore used in this paper.

Related to its topographical position the cover moraine can be divided regionally into three areas. These are (1) the mountaineous areas in north and east; (2) the northeastern valley side and (3) the southwestern valley side and the western upland area (Fig.3).

Mountainous areas

The mountain areas in north and east are generally characterized by a thin till cover and frequently exposed bedrock (Fig.3). A continuous cover moraine is found in depressions only. Glacially abraded bedrock surfaces are rare. The bedrock topography is mainly irregular on both stoss and lee sides. Such an irregular topography probably existed even when the ice melted away, but in many places the present surface may also be the result of postglacial frost cracking.

Secondary frost activity has obviously altered the original till characteristics in several places. Boulders from boulder fields have in different ways moved on to the moraine surface and may even have been mixed into the till material as was described from Sweden by J.Lundqvist (1969a, 119). The till might also have been influenced by talus material in places where the topography is steep.

In addition, the tills have been exposed to frost heave and solifluction. These processes have destroyed the original till structures, the degree of compaction, and the till fabric and have changed the granulometric composition. However, by excluding all such supposed secondarily influences it is possible to recognize some typical original characteristics of the mountain plateau tills:

The surface all over the area is rich in boulders (Fig.6). Some road cuttings show that the boulder content decreases somewhat with depth. The concentration at the surface is probably partly the result of frost heaving. However, the deeper part of the till is also rich in boulders and cobbles and the content of gravel is high compared with sand, silt and clay (Fig.7).

There is no distinct difference in grain-size distribution between tills over the sandstone/shale bedrock in the north and tills over the more homogeneous sandstone bedrock in the south. This is partly because the general influence of the shale in the mountain area is small and partly because neither the shale nor the sandstone have been intensively comminuted. Therefore, material from both these bedrock types are mainly concentrated in the gravel, cobble, and boulder fraction.

The significant content of silt relative to sand and the general lack of sand lenses indicates that the low matrix content (sand + silt + clay) is mainly a primary property and not the result of removal of fine-grained material by melt-water. The coarse-grained texture therefore shows that glacial comminution beyond gravel size has been small and that the relative supply of coarse clasts was always great. An important factor here is the deeply and intensively fractured bedrock which certainly also existed prior to the last glaciation. This was easily incorporated into the glacier and provided a great supply of coarse material.

Some rounded and striated clasts occur, but generally angular material is quite dominant (Fig.8). Part of the angular material was probably formed by frost cracking. However, there is generally a lack of abraded clast surfaces even in the deepest part of the till, and a low roundness index is, therefore, most certainly a primary characteristic of the till material.

It is difficult to give a total genetical classification of this till since parts of it obviously were influenced by secondary processes. However, its local composition and the supposed primary till texture, characterized by high contents of coarse material (Fig.7) and angular clasts (Fig.8) give no indications of a lodgement process. The clasts could hardly have avoided abrasion if they were overidden by an active sliding glacier from the time they were lodged until they were embedded in till material. The lack of influence by an active sliding glacier thus indicate that the till at least partly is of melt-out origin.

Several characteristics indicate that the glacial debris was carried mainly in a basal position. First, it is of a very local origin. This is for instance visible near the boundary between the sandstone/shale in the north and the sandstone in the south.

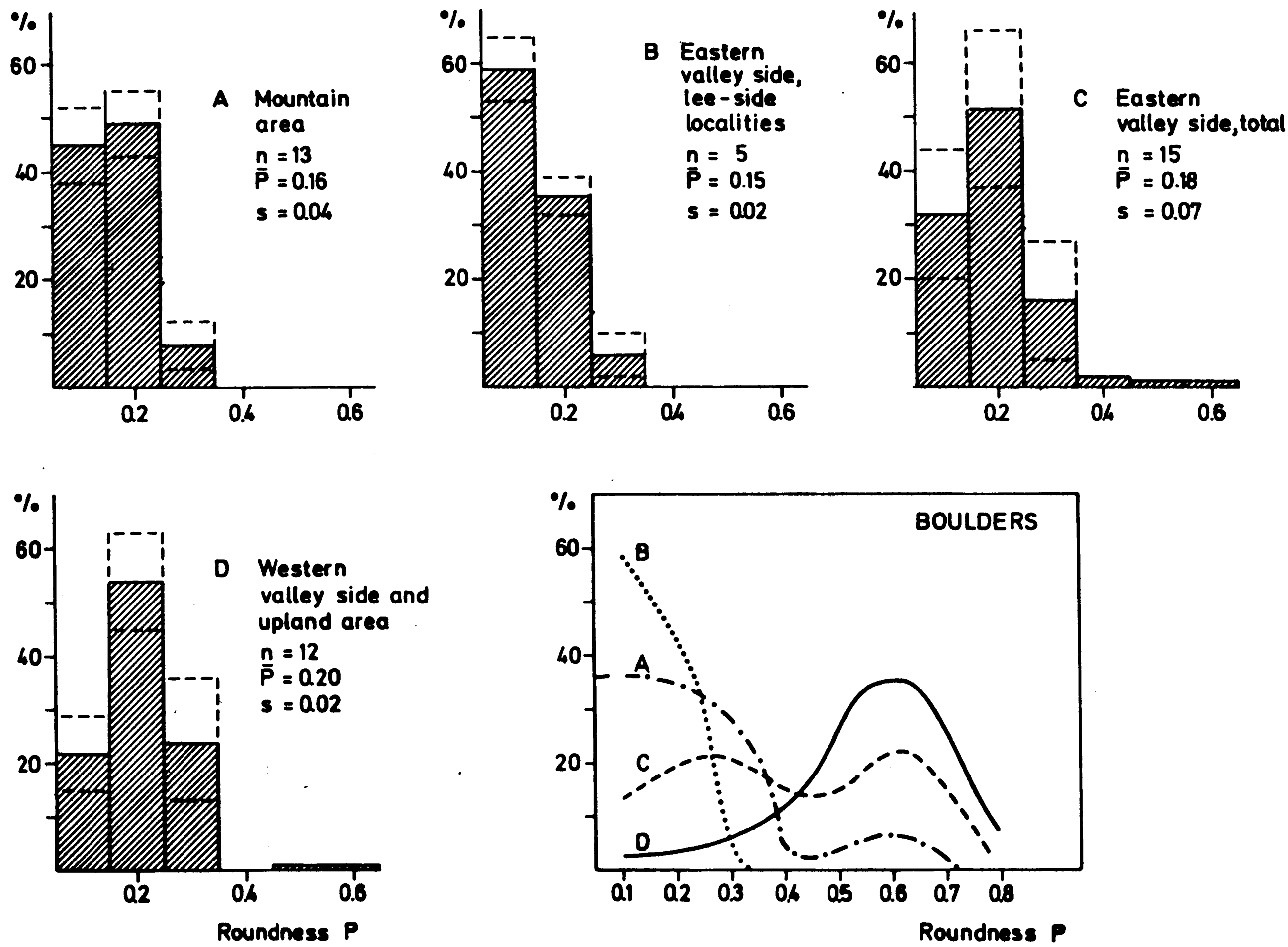


Fig.8 The degree of roundness for till clasts from the cover moraine areas. A-E: gravel fraction 16-32 mm. Stipled: one standard deviation from the mean values. n = number of samples, each sample consisted of minimum 100 particles. $\bar{P}$ = mean roundness after Krumbein (1941), s = standard deviation of $\bar{P}$.
The boulder data are based on about 500 boulders from each till type, letters A -E have the same meaning as in the histograms.

The influence of the shale ends abruptly at the bedrock boundary and shale components are almost absent in all fractions further south (Haldorsen in prep). Furthermore, the described till seems to rest directly on the bedrock and there is no systmatic vertical variation in it. Finally, there is general lack of melt-water channels, glaciofluvial material and dead-ice topography with hummocks and ridges (Østeraas 1978, 1981). There is thus no indication of a lowering by melting of underlying clean ice or of the presence of great amounts of melt-water.

The till may have been formed in the following way: Boulders and cobbles from the intensively fractured bedrock were incorporated into the glacier. This material was relatively slowly transported a short distance in a basal position. Some internal movement in the ice because of shearing or plastic deformation may have caused the clasts to collide or to be pressed against the substratum. Some matrix material was formed by the grinding of small clasts between bigger ones or between bigger particles and the bedrock. Fine-grained material was also formed by abrasion, but this did not significantly change the degree of roundness. After the short and relatively passive transport the material melted out from the ice.

The till characteristics do not reveal much about the general glacial erosion, transport and deposition during the Weichselian, but indicate a relatively low basal activity when the present till was formed. It should be emphasized that the till is rather thin. Its formation may well be related to the period of decreasing glacial activity, a short time before the final deglaciation. The deposition may have occurred mainly after most of the overlying ice was melted and only remnants of the basal ice remained in the area. The deposition of the till then took place both by melting from above and from below. In this case the distinction between subglacial and supraglacial melt-out is not of any significance, and the till should be referred to as basal melt-out till. The qualification basal implies that the debris was transported in a basal position (see Shaw 1977b).

Zones with more abraded clasts occur mainly along some of the marked depressions, for instance at Lyngen and along the upper part of the river Skolla near Skollfjellet (Fig.3). In such cases the abraded particles occur together with quite angular material. One component has been transported along the bottom of the active sliding ice for a relatively long time. Before or during the deposition it has been mixed with very local and angular material. In such cases it is difficult to interprete the till genesis.

Northeastern valley side.

The topography along the northeastern valley side is variable. It is relatively steep along the Øyungenfjell and Hynnlia (Fig.3) and much more gentle where the tributary valleys join Åstadalen. The local bedrock surface shows signs of glacial plucking in many places, in other places there are more abraded surfaces (e.g. the great bedrock exposure SW of Øyungen (Fig.3)). Along the upper part of the valley side the bedrock exposures are frequent (Fig.3) and the till thicknesses, obtained by drilling, are estimated to 1-3 m. The lower parts of the valley side have a more continuous till cover of thickness 2-5 m.

A very characteristic till occurs at localities which were in lee-side positions during both the early and late glacial stages (Fig.3). There are no good sections through this till, but an excavation down to 1.5 m west of Øyungen-fjell (Fig.3) exposed a loose and nearly structureless material. Two fabric measurements carried out at Øyungen (Fig.3, locality 1) and Bjørnåsen (Fig.3, locality 2) show no strong preferred a-axis orientation (Fig.9A & B).

The frequency of surface boulders is usually high. This is only locally the result of postdepositional talus formation. Sections and numerous drillings indicate that boulders and cobbles are also abundant deeper down in the till (Fig.7). The content of gravel is usually comparable with that of sand, and the content of silt + clay is very low (Fig.7B). The total clast material has a high degree of angularity (Fig.8).

The lee-side till shows clear evidence of a local source; In particular the angular clasts in most cases can be traced directly back to the nearest bedrock exposure.

At a locality southeast of Øyungenfjell (Fig.3, locality 1) this till type was studied in more detail (Fig.10). Close to a steep and very irregular bedrock wall there was

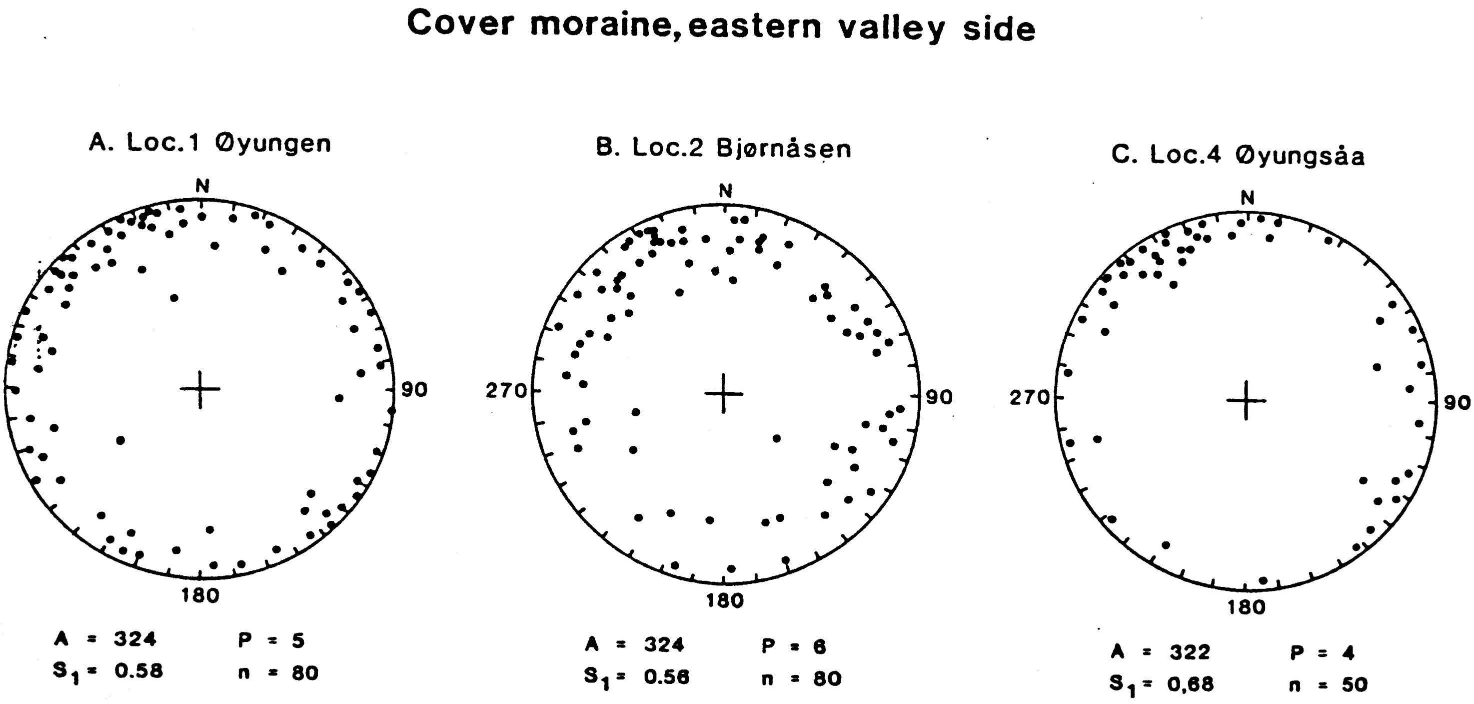


Fig.9 Long-axis orientation and dip of clasts from the eastern valley side. The site of localities 1,2 and 4 is shown in Fig.3. n=number of particles, A and P give the azimuth and dip of the eigenvector V_1 in degrees, S_1 gives the strength of clustering about the mean axis.

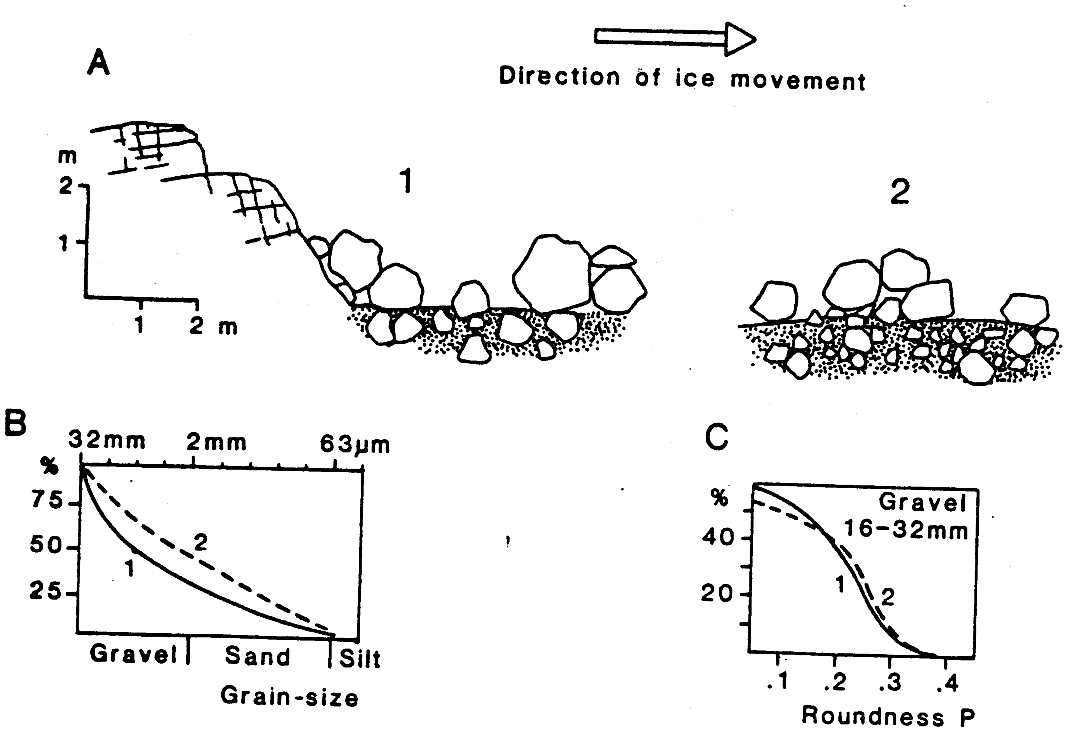


Fig.10 A. Scetch of the lee-side locality 1 south of Øyungen-fjellet (see Fig.3). 1: just south of the headwall, 2: 50 m further towards south.
B. Grain-size distribution, 1 m depth.
C. Roundness of gravel, 1 m depth.

an abundance of big angular boulders which only to a certain degree could have been formed by secondary talus accumulation. Most of them were probably glacially transported. About 50-100 m further south the material was gravelly and sandy and appeared structureless. Some big angular boulders occurred at the surface (Fig.11). At several other lee-side localities there was a similar distribution of material. In some cases the till was very gravelly for some distance from the headwall, whereas at other place, as for instance near Skvaldra (Fig.3, locality 3) it was more sandy. The sandy or gravelly till is not believed to be the result of removal of silt + clay by melt-water. The samples were taken some distance from the visible melt-water channels. The homogeneous till without lenses of sorted material indicates that the influence of concentrated melt-water was small. The till geochemistry is in accordance with the local bedrock geochemistry (Haldorsen in prep.). There is no 'deficiency' on 'excess' of elements caused by removal of fine-grained material.

If the conclusions above are correct, the till texture at the lee-side localities is the result of local glacial erosion, transport and deposition. The coarse material obviously has been eroded from the steep parts of hill sides, where the fractured bedrock was easily exposed to glacial plucking. Afterwards, when the big boulders were transported a short distance away from their source area, they might have been pressed against bedrock or underlying drift material to form effective grinding tools. In most cases this resulted in a gravelly material, but in some cases also in a sandy one.

In this ways the lee-side till has the same characteristics as the mountain plateau till. Its coarseness, and its angular clasts indicate that it is a melt-out till. The lack of melt-water sorting and a local provenance indicate a basal transport. Since the material is so loose and coarse and therefore permeable, the melt-water might have penetrated through it without establishing concentrated channels.

It is difficult to determine whether a comminution like that described above occurred before, during or after deposition. The pressure from big lee-side boulders incorporated in the ice may have gradually crushed the already deposited underlying material. Such a crushing may explain why the particles in the till have a rather broad scatter of a-axis orientation. The big boulders on the top then represent the last, uncrushed material which was finally deposited when the ice melted away. In that case the texture of the underlying material is not only the result of its transport within the ice. Since the comminution is believed to result from subglacial processes and since the material seems to have originated by melt-out, classification as a subglacial melt-out till is appropriate (Fig.1).

The typical lee-side till is regarded as representative for the initial till formation along the northeastern valley side. Along most parts of the valley side, particularly along its lower parts, a much more silty till type occurs with abraded boulders and cobbles. This till is more compact, in part due to its more fine-grained texture. At some localities there is a marked a-axis orientation parallel with the last direction of ice movement (Fig.9C).

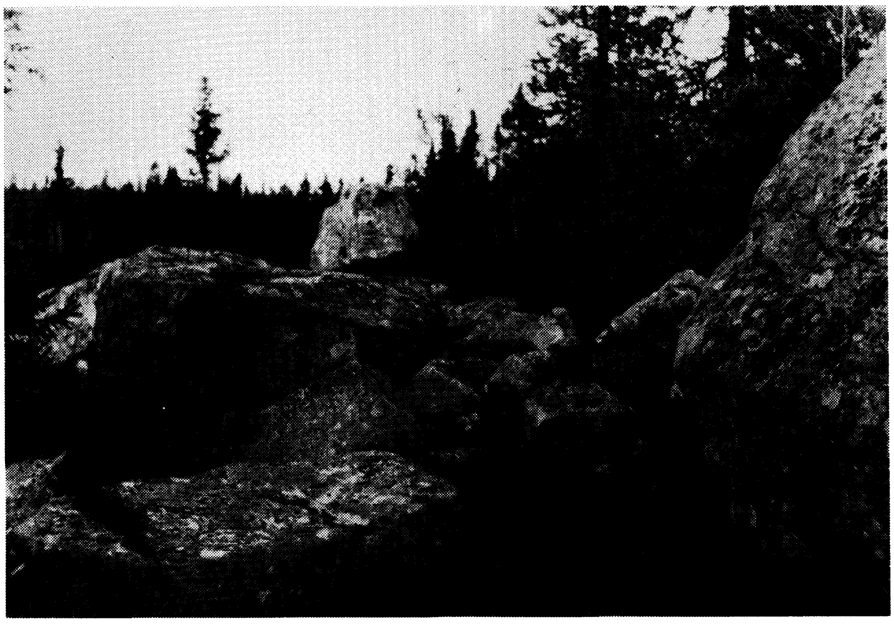


Fig.11 Local lee-side boulders south of Øyungenfjell.

Fig.12 Local, coarse till with angular clasts from an area where much more abraded material dominates. Photo taken southeast of Øyungenfjell.

These characteristics indicate a significant transport along the base of an active glacier and the deposition has probably mainly been by a lodgement. (The criteria of lodgement till are discussed in the next section).
In areas where such material dominates there are local occurrences of coarse till with angular clasts (Fig.12). In many cases there is also a mixture of quite angular and abraded clasts. It is very difficult to find the boundary between the difference types in the field. It is therefore difficult on the basis of the field observations to interpret the till genetically.

Southwestern valley side and western upland area

The topography along the southwestern valley side and the western upland area is rather smooth, and the valley side is gently sloping towards the northeast. There are no marked tributary valleys or any steep mountain sides which had a lee-side position during either of the two ice movements (Fig.3). The few exposed bedrock surfaces are smooth and striated. Based on drilling the till thickness is estimated to be on average 3-5 m.

The road cuts show a compact till with a distinct fissility. The entire till seems to be quite massive except for some thin silt-rich horizons, which occur in particular, at the distal sides of boulders.

At most localities there is a strong a-axis orientation parallel to the late direction of ice movement (see locality

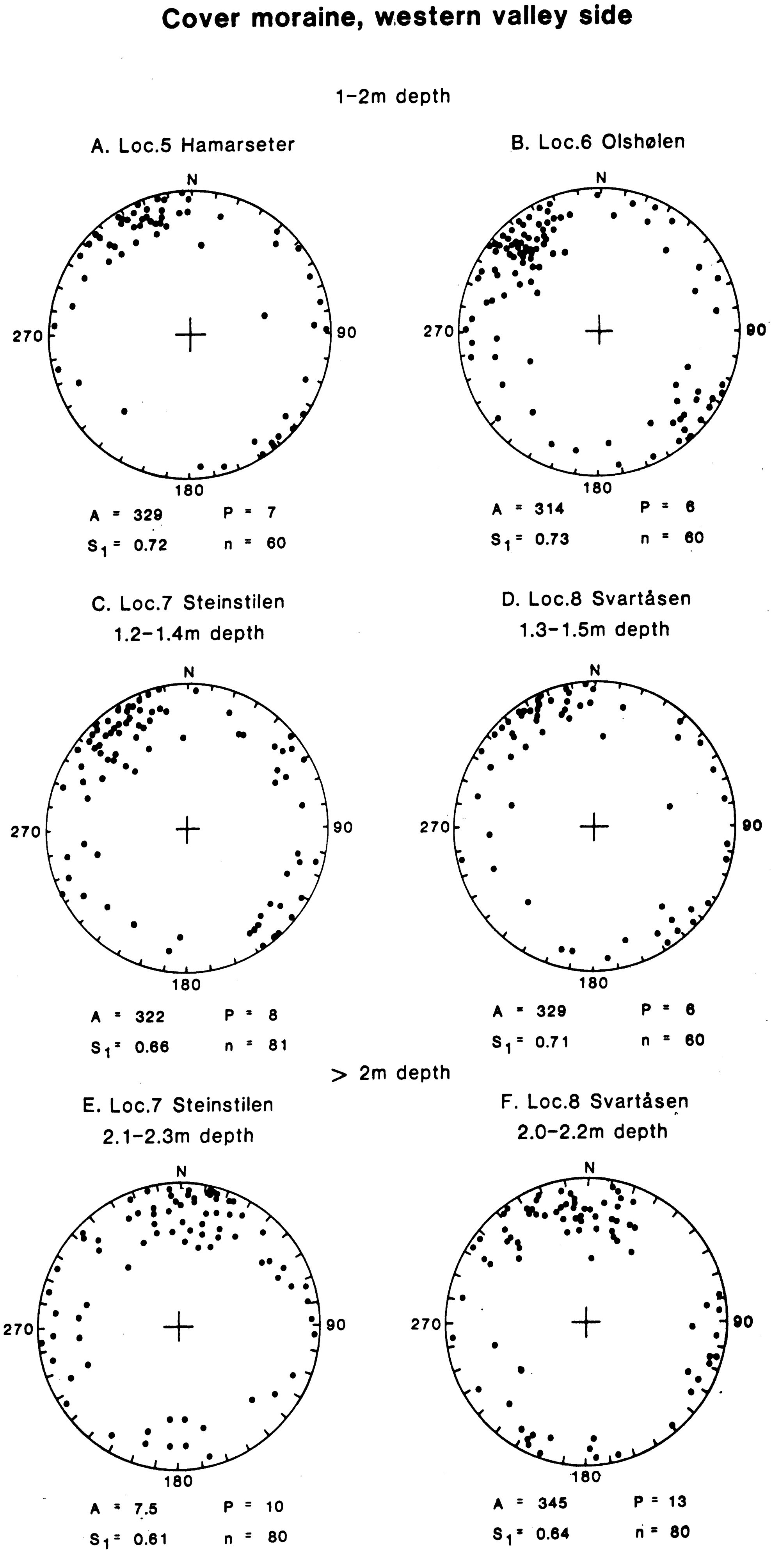


Fig.13 Long-axis orientation and dip of clasts from the till along the western valley side (site; see Fig. 3). For further explanation: see Fig.9.

Fig.14 Imbrication of clasts in subglacial till from Olshølen. Ice movement from the right.

Fig.15 Typical bullet-nosed boulder from subglacial till, Kvarstadseter.

5-8, Figs. 3 & 13). The dip is towards northwest (Fig.13 A-D) and is easily recognized in sections (Fig.14). At two localities (locality 6 & 7, Fig.3) the clasts in the lowermost part of the till, about 2 m below the surface, show a preferred a-axis orientation in N-S direction with a dip towards north (Fig.13 E & F). This may probably reflect the early direction of ice movement. The particles have the regular NW-SE orientation in the upper part of these tills. The orientation in the lower part of the tills is not as strong as in the upper part (Fig.13).

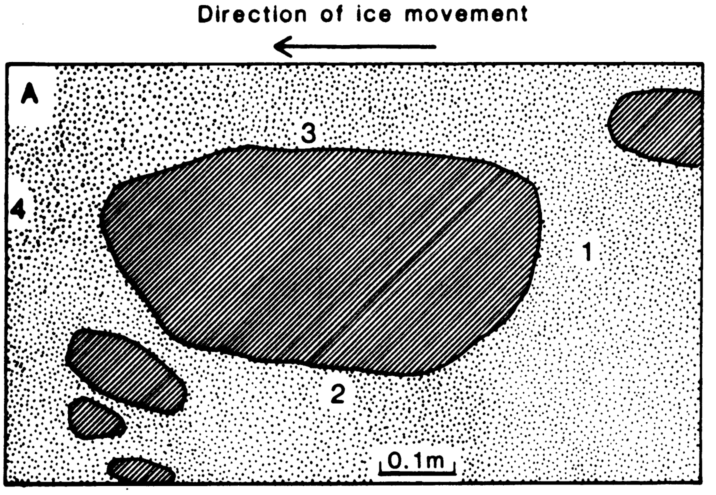
On average the content of boulders, cobbles and gravel, as well as the content of sand relative to silt+clay is considerably lower in the till along the western valley side than in other till types (Fig.7). The gravel is more rounded than in the two other cover moraine types (Fig.8) and the boulders and cobbles are generally more abraded and striated. Many of the boulders have a typical bullet-nosed shape (Fig.15).

The till characteristics clearly prove that the material has been transported in a zone with intensive glacial abrasion and crushing and indicate that the ice was debris-rich. The particles have been in frequent contact during the transport. As the till seems in all places to rest directly on the bedrock the transport has been interpreted as a basal one.

A marked fissility, a strong a-axis orientation, abraded clasts and a high proportion of fine-grained material and bullet-nosed boulders with sharp truncated distal end (Fig.15) as described above, are characteristics which for instance Boulton (1976, 1978) and Dreimanis (1976) regarded as typical for a lodgement till. In the present case they clearly reflect a transport along the base of a sliding glacier. During this transport it is reasonable that a lodgement was the quite dominating way of till deposition. There is, however, a question of whether the characteristic in themselves are diagnostic of the lodgement process as it was defined in the introduction.

The bullet-nosed boulders may very well have been shaped and orientated before they were deposited. Boulders in the area commonly have a triangular shape with a distinct long axis even in their primary stage. During the glacial transport such boulders were probably rapidly orientated so that they afforded the smallest possible resistance to glacial movement; that is with their snout pointing upstream. The proximal part was abraded and became bullet-nosed during transport. The distal, angular end is then not necessarily the result of a lee-side excavation as described by Boulton (1978), but rather the original surface of the boulder which pointed downstreams and therefore avoided abrasion.

The fine-grained till texture does not prove that lodgement took place. Most of the matrix material (sand + silt + clay) was probably formed by intensive glacial comminution of the clasts during the transport. Boulton (1978)



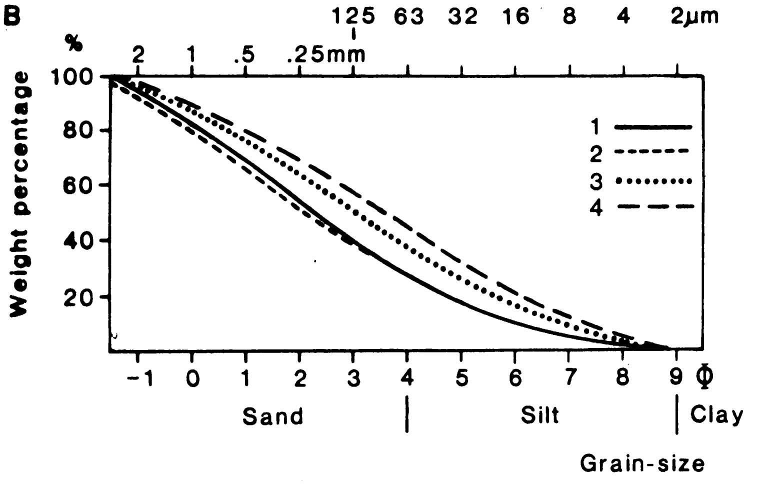


Fig.16 A. Sketch of an abraded boulder in lodgement till at Hamarseter.
B. Grain-size distribution of the finer than 2 mm around the boulder.

described some characteristics which are diagnostic of the lodgement till alone. One of these was that the lodged boulders have an upper surface which is significantly more abraded than other surfaces. Commonly also the upper surface is more uniformly striated, in a manner which clearly reflects the last direction of ice movement. Similar characteristics are found several places along the south-western valley side.

In several cases the till just above, and at the lee-side of boulders is particularly rich in silt (Fig.16). This may be explained as a deposition of fine-grained material formed by abrasion of these boulders, as described above. Such a concentration of silt could hardly occur during the transport.

As the diagnostic characteristics described above are only observed in special cases, they do not prove that the entire till was deposited by a lodgement. However, as pointed out above and also in the introduction, deposition of lodgement till must have predominated as long as the glacier in the valley was active. A pure melt-out process was then probably only of quite local occurrence. During the final part of the deglaciation, on the other hand, a melt-out till may have been deposited from several remnants of debris-rich basal ice. This may form the uppermost part of the regular till sheet. In that case it has been strongly influenced by secondary soil processes and is no longer readily identifiable. Therefore, as the till in the west is so uniform, the total till sheet has here been interpreted as a lodgement till. (Haldorsen 1981).

A comparison between the northeastern and the southwestern valley side.

The till is generally thicker and much more continuous along the southwestern than along the northeastern valley side (Fig.3). This applies even for the rather gentle parts of the northeastern valley side. The difference may be explained in the following way: During the early glacial phase with movement from the north, the northeastern valley side was a lee-side area while the southwestern side was a stoss-side area (Fig.3). The step-wise local topography along parts of the northeastern valley side promoted glacial plucking. When this plucked material was incorporated in the ice, part of it was transported across the valley and upwards along the southwestern valley side. Melting dominated along this stoss slope, and material originating from the northeastern valley side was by time lowered to the zone of traction. Parts of it may have been deposited as a lodgement till. Net erosion probably occurred along the northeastern valley side and less till was deposited there than to the west.

During the late glacial phase material was no longer transported from the northeastern to the southwestern valley side because the flow was then parallel with the valley. New till material was certainly formed and deposited along both valley sides. However, the initial difference between the two valley sides may explain why there is more till in the west today.

Melt-water activity is another important factor in this connection. Much more melt-water occurred along the northeastern than along the southwestern valley side. As a great amount of deposited till and glacial drift was certainly eroded and redeposited as glaciofluvial material in the vicinity of the northeastern slope.

The bedrock structures have obviously strongly controlled the behaviour of the glacier in Åstadalen. The strike of the bedrock is mainly east-west and the dip is towards the north along the central part of the valley (Fig.4). In combination with the main fracture zones (Fig.4) this is responible for the more steep and irregular topography along the northeastern valley side. When the glacier flowed from the north and down into the valley it had to pass from one fractured sandstone bed to another along the valley side. A uniform basal sliding was therefore not etablished. Along the southwestern valley side the ice could more or less follow the surface of one sandstone bed for a long distance. This allowed a more uniform flow. This feature combined with the principles of lee-side plucking and stoss-side abrasion (see Boulton 1970, 1971) gave favourable conditions for the formation of lodgement till and subglacial melt-out till.

approximately conformable with the ridge surface but dips relatively steeply towards the eastern edge of the exposure. Sorted and stratified layers are common above the silt bed, and, although they are less common below this bed, they are to be found there as relatively indistinct sand beds. These beds are commonly truncated by faults and show draping and faulting around clasts.

The diamicton underlying the silt layer (Fig. 10) has a significantly lower silt content than the surrounding till sheet (Fig. 8), but the degree of roundness of gravel, cobbles and boulders is comparable with that of the lodgement till (Fig. 9). Close to the center of the valley (Fig. 9, site B) the ridges contain more rounded gravel sized material (Fig. 9). The degree of roundness indicates that the material in the lateral part originates from glacial debris, probably similar to that forming the lodgement till (Haldorsen, in prep.) while towards the center of the valley more fluvial transported material seems to have been incorporated. The regular ridge morphology indicates that the total ridge complex was formed during the same glacial phase. The lateral facies variation, indicated by the degree of roundness, is therefore, only to be interpreted as a result of increasing water influenced material towards the center of the valley. As this property is a characteristic of the transverse ridges but not of the lodgement till sheet, it is reasonable to assume that melt-water was particularly abundant in the areas of basal stacking or folding of ice. If such local melt-water channels moved because the channels were filled with sediments, because of seasonal variations in drainage, or for other reasons, parts of the glaciofluvial sediments could have been easily incorporated in the glacial ice by even local, limited glacial activity.

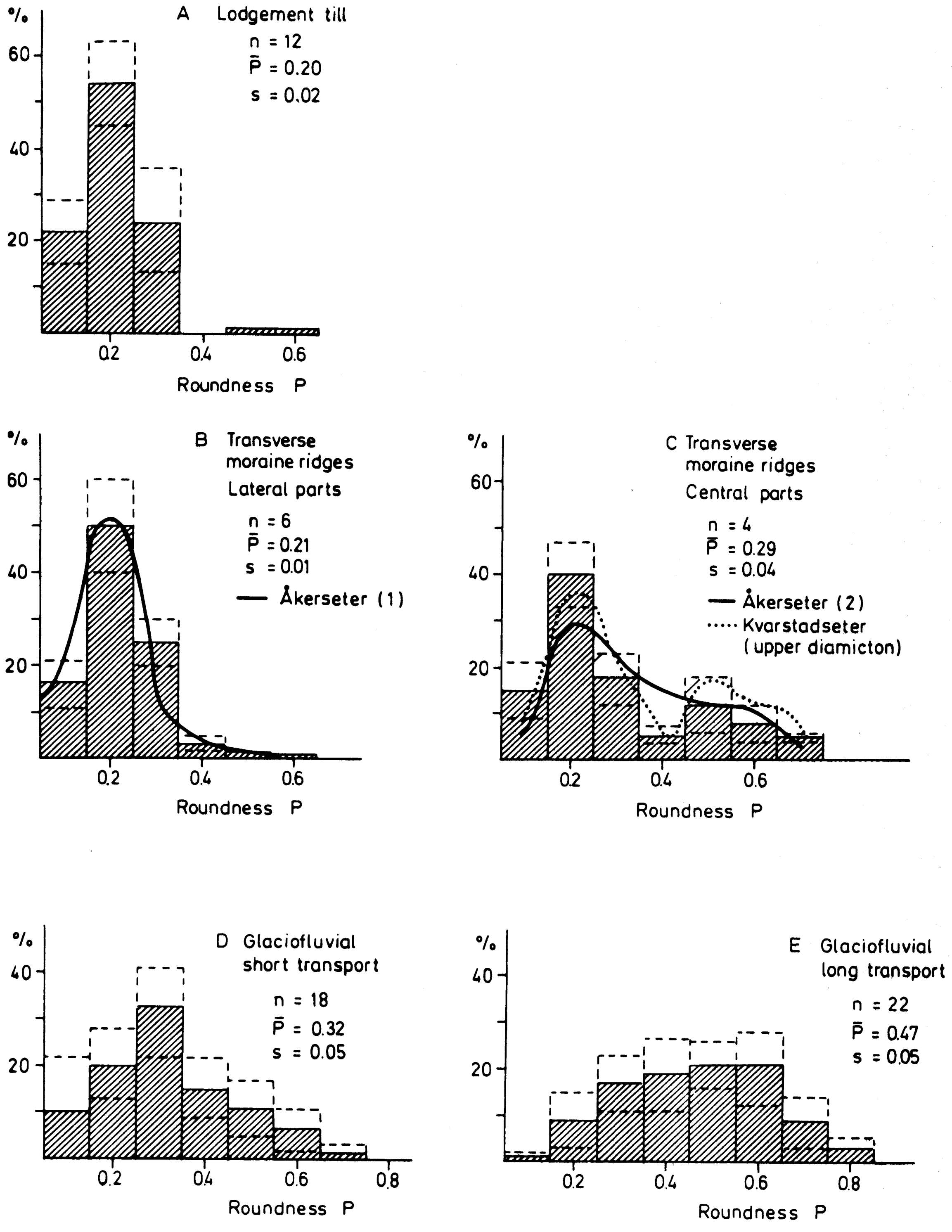


Fig.9 Roundness of glacigenic materials. Åstadalen. Roundness index after Krumbein (1941).

Contour diagrams of the distributions of clast long axes azimuth and plunge and the sample locations are given (Fig. 10). A consistent pattern is obtained with the two distributions sampled (3 and 4) towards the base of the ridge showing relatively poor preferred orientation (low values for S_1) and only a weak tendency to upglacier plunge of long axes. The three samples taken at an intermediate level (2, 5 and 6) show relatively strong preferred orientation ($S_1 > 0.6$) and a consistent upglacier plunge. The azimuths of S_1 all lie at a high angle to the trend of the ridge crest and are close to the regional direction of ice flow. The final distribution (1) shows a relatively weak preferred orientation ($S_1 = 0.52$) and only a weak tendency to upglacier plunge.

Kvarstadseter

The Kvarstadseter area (Fig. 6) has a morphology formed by hummocks and ridges. This morphology is cut towards the river Åsta, where the surficial deposits form a low glaciofluvial terrace (Fig. 6). The ridges are in some places cut by local melt-water channels and the hummocky landscape seems to be partly the result of erosion of more continuous transverse ridges.

A small feeding esker extending from the northwest towards the center of the valley is partly covered by diamictic sediments (Figs. 6 & 11). The esker has been mapped by drilling and during hydrogeological studies. The melt-water forming the esker eroded the underlying lodgement till in some places, which indicates a true subglacial origin for the esker. The esker ends at Kvarstadsetra and the glaciofluvial sediments found there are considered to be a part of the esker.

Sediments. - The total exposure shows a lower part consisting of sorted sediments, mainly sand and diamicton (Fig. 11). No coarse sorted sediments have been found in this part. The frequency of diamictic sediments increases towards the north and west in the section, i.e. upstream along the esker. The sequence of sorted sediments and diamicton is overlain by a rather massive and uniform silty diamicton with an increasing thickness towards the north. The stratified sediments show a variety of sedimentary structures including small-scale cross-lamination, large-scale cross-stratification and graded beds of silt and fine sand (Fig. 12). The stratification is frequently cross-cut by erosional surfaces illustrating frequent episodes of scour and fill. Flow direction estimates based on cross-lamination and cross-bedding give flow directions towards the southeast (Fig. 12). There are minor fault structures and local draping of layers over large boulders. However, the most striking deformation structures are found towards the top of the section in a series of overfolded silts and sands. The fold axial planes dip towards the northwest and the major glide plane for these folds dips towards the southeast (Fig. 12). These folds are clearly a result of local slumping and the existence of several fold sets illustrates that several slump events took place.

In the central part of the section no underlying sorted sediments could be found. Some bands of silt occur in the diamicton, but otherwise the occurrence of sorted sediments in this diamictic sequence is insignificant.

In the northern part of the exposure the silty diamicton is overlain by coarse, gravelly sediments, badly sorted and with a visible stratification only in parts. This sequence is very similar to the upper part of

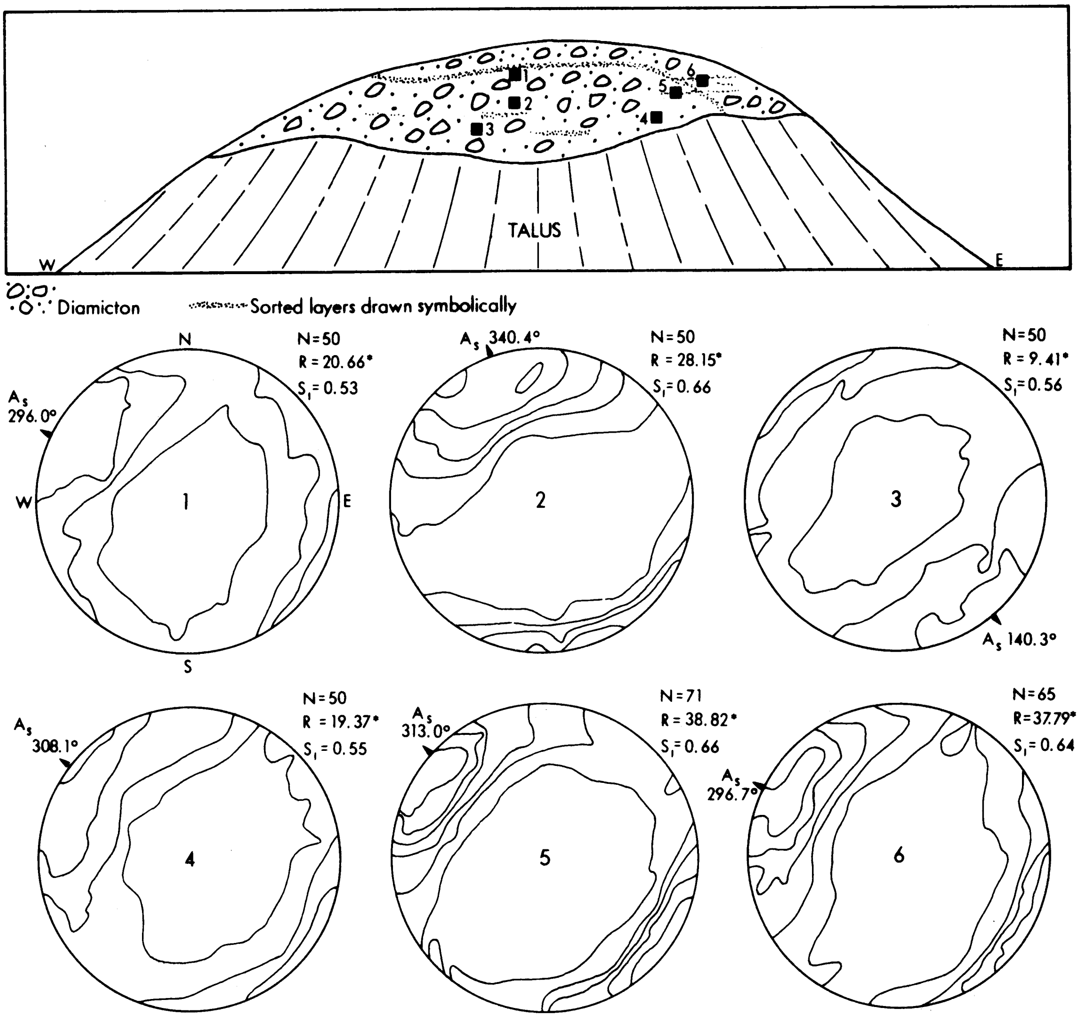


Fig.10 Internal structure of a ridge at Åkerseter. Schmidt equal area nets showing clast long axis distributions contoured at 2 σ according to Kamb (1959). N, number of stones; R, vector strength, asterisk indicates significance at a 5 per cent level; S_1 normalised eigenvalue associated with the principle eigenvalue; A_s, asimuth of the principle eigenvector.

the Åkerseter section, and supraglacial sediments forming hummocks in Åstadalen (Haldorsen, in prep.).

The matrix of all diamictic zones has about the same grain-size distribution through the sequence (Fig. 8). The average roundness of the gravel is higher than in the lodgement till sheet (Fig. 9) and comparable with that of the ridge at Åkerseter close to the center of the valley. The bimodal distribution of the roundness and the relatively high content of silt, which is higher than in glaciofluvial sediments, indicate that incorporated glaciofluvial sediments have been mixed with glacial debris.

All distributions show a preferred direction for the principal eigenvector, and for fabric distributions 1, 2, 4 and 5, there is a relatively tight clustering of the azimuths (range 87.8° - 108.8°), the azimuth for the negative of the principal eigenvector being taken for distribution 5. These azimuths, which give an estimate of preferred orientations of the distributions, do not parallel the valley trend or regional ice flow directions (Haldorsen, in prep.). The azimuths of the principal eigenvectors do correspond closely with the azimuths for the poles to fold axial planes, and to the paleocurrent directions estimated from cross-laminated deposits (Fig. 12). The preferred orientation for fabric distribution 3 is at a high angle to those for the other fabrics at this site. This fabric was sampled close to the margin of a diamicton lens.

Discussion. - The tills in Åstadalen which have been studied extensively may be discussed in detail. The relatively uniform bedrock from which the tills are largely formed allows comparisons of grain size and roundness between tills (Haldorsen, in prep.). In addition, the tills may be interpreted in relation to the glacigenic landforms of the valley. Haldorsen (in prep.) outlined a history of glacial and deglacial phases presented here in the regional description for Åstadalen. It is important to note the similarity of the deglacial setting with that proposed by Goodchild (1875). Widespread stagnation is invoked during deglaciation with increasingly active sub and englacial drainage towards the center of the valley.

The transverse ridges which occur at Kvarstadseter and Åkerseter are associated with obstacles to flow and, during the active phases of glaciation, these areas must have been zones of compressive flow. Such topographic situations are commonly associated with transverse ridges (Lundqvist, 1969b; Minell, 1977; Shaw, 1977; Bouchard, 1980) and these ridges have been ascribed to englacial or subglacial stacking by folding and shearing (Minell, 1977; Shaw, 1977, 1979; Bouchard, 1980). The morphology and position of the ridges at Åkerseter and, to a lesser extent, Kvarstadseter, correspond to those predicted by the model of stacking.

The Åkerseter sediments are easier to interpret than are those at Kvarstadseter. Stratified layers and illdefined layers of better sorting within the diamictons attest to the activity of flowing water during deposition. We are particularly interested in whether these represent a melt-out sequence with englacially deposited stratified materials or whether the intercalation of diamicton and stratified materials involved sediment flows. The fabric patterns are instructive in this respect (Fig. 10). All six fabrics show significant preferred orientation and the azimuths of the principal eigenvectors show the trend of the preferred orientations to approximately parallel the direction of last ice movement and to lie approximately at right angles to the crest of the ridge. Five of the six distributions show a preferred upglacier plunge.

The similarity of the roundness of materials in the lodgement tills of the valley and those in the Åkerseter ridge (Fig. 9) suggests that they both underwent similar abrasion processes with little subsequent modification. Materials towards the center of the valley at Åkerseter provide an exception in that more rounded materials of fluvial origin were incorporated into the tills. However, the sediment in the ridges has undergone considerable syndepositional sorting illustrated by the sorted zones and the low silt content compared to the lodgement tills (Fig. 8).

The conjunction of properties and associations of the till within the ridges at Åkerseter - ridge morphology, fabric closely related to this morphology and the regional ice flow direction, clast shape, and grain size - support an interpretation of deposition by melt out from a zone of englacial stacking. Flowing water was clearly important during this process and the conclusion supports the potential for preserving property P_1 in melt-out tills.

The sites at Åkerseter and Kvarstadseter are similar relative to valley features and, although the transverse ridges at Kvarstadseter have undergone some modification, they are clearly recognisable. The major contrast between the sediments at the two sites is the much higher proportion of stratified sediment at Kvarstadseter. The stratified sediments are associated with a subglacially formed esker and it is reasonable to assume a higher level of melt-water activity at Kvarstadseter. The paleocurrent estimates from the stratified deposits show a flow direction which is oblique to the valley trend but with a downvalley component. Intraformational folding in the stratified sediments shows the importance

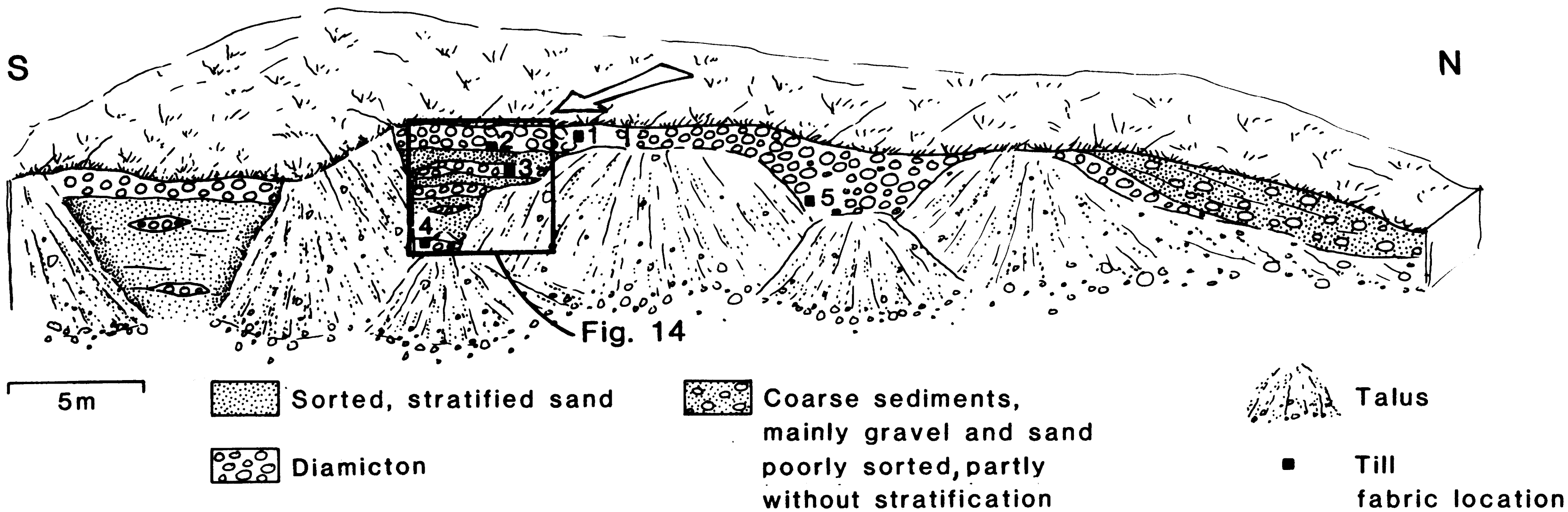


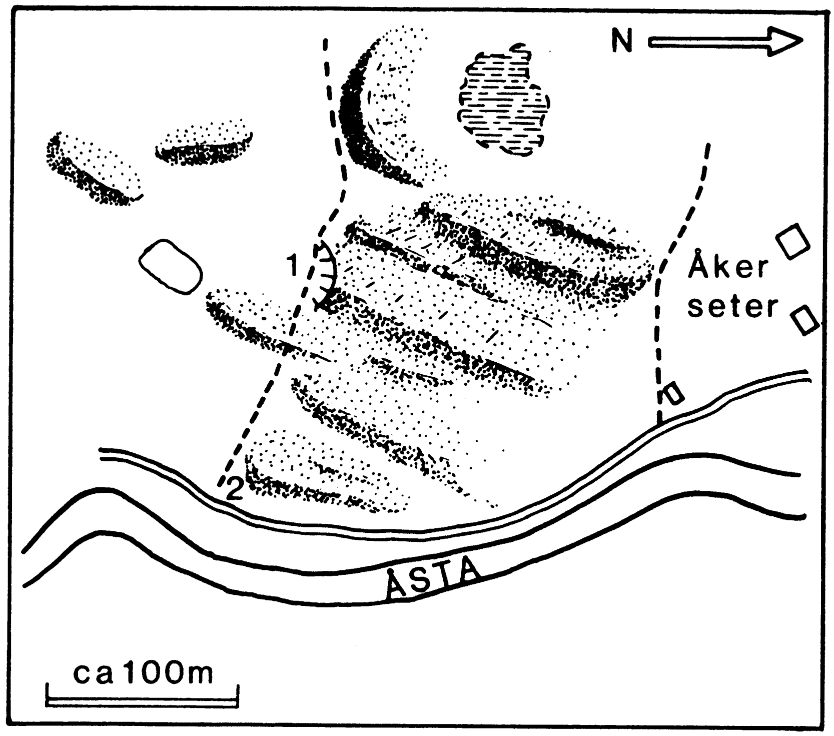
Fig.11 Internal structure of a ridge at Kvarstadseter.
Location of fabrics taken at this site are given.

of local sediment flow and it is probable that the thin diamictons in the middle part of the section (Fig. 12) are till flows. The fabric in one such flow (fabric 3, Fig. 12) shows a preferred orientation at a large angle to those of the other fabrics at this section. The most intriguing aspect of the Kvarstadseter sequence is the origin of the continuous diamicton which drapes the section and thickens in the vicinity of fabric 5 (Fig. 11). From its internal structure, morphological association and stratigraphic position it could be a flow till or a melt-out till. The fabric of this unit is equally equivocal. Although the three fabrics (1, 2 and 5, Fig. 12) show a relatively tight clustering of preferred orientation this is oblique to the regional direction of ice movement and shows similar orientation to the preferred orientation for fabric 4 taken close to the base of the section.

The two plausible interpretations may be considered against the observations. An interpretation of flow involves accumulation of till flows and stratified materials in an ice-walled channel with subsequent accumulation of till flows from a supraglacial position to form the extensive capping diamicton. The deformation structures in the associated stratified sediments count in favour of this interpretation. The fabric pattern could be taken as a response to consistent flow directions down a local slope. However, a question to be raised is why are the preferred orientations for this upper diamicton consistent and those in areas clearly associated with flow not? A rather subjective line of evidence against a supraglacial origin for this deposit is that the upper diamicton appears different to the sediments at the north end of the section which are interpreted to be supraglacial.

A reconstruction of the melt-out interpretation is as follows.

A



B

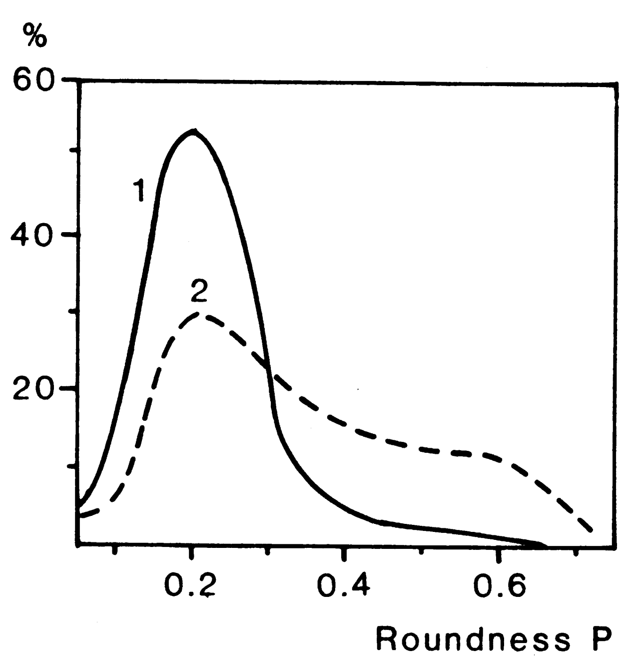


Fig.17 A. Sketch of the transverse moraine ridges at Åkerseter.
B. The degree of roundness of gravel fraction 16 - 32 mm from site 1 in the lateral part of the valley and site 2 in the middle of the valley.

MORAINE RIDGES TRANSVERSE TO THE DIRECTION OF ICE MOVEMENT

Along the western part of the valley bottom there are moraine ridges which are oriented more or less transverse to the latest direction of ice movement (Fig.3). Similar ridges are also found in some places along the eastern valley bottom. The ridges are partly curved with the convex side downstream. The length of the ridges varies from 50 to 200 m, width from 20 to 60 m and height from 2 to 7 or 8 m. The distal slope of the ridges are generally much steeper than their proximal one. The ridges are arranged in groups in a fish-scale like pattern (Fig.17).

The composition and the genesis of the ridges are discussed in a separate paper (Haldorsen & Shaw in prep.) and only a brief description and discussion is therefore given here.

The internal composition and structure of the ridges vary. The local origin of the material is demonstrated by the lateral facies variation. Section from the lateral part of the valley, like the one found at Åkerseter (Fig. 17 A, site 1) show a loose, sandy till. The clast material has the same degree of roundness as the till of the cover moraine along the western valley side (Figs.8 & 17 B, curve 1). Irregular lenses and layers of more sorted material indicate the presence of melt-water during the deposition. The original composition of the drift was probably the same as for the till of the local cover moraine, and fine-grained material seems to have been removed by water during the melt-out process.

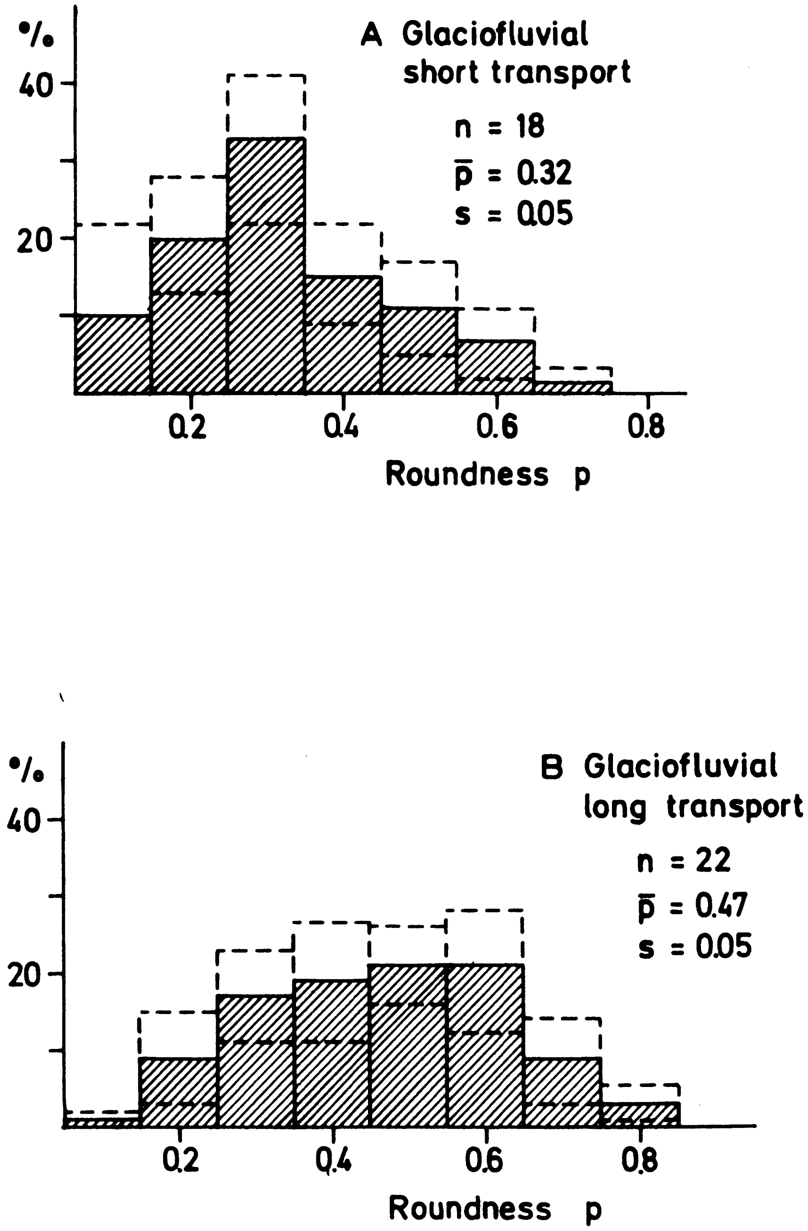


Fig.18 Degree of roundness of gravel material 16-32 mm from glaciofluvial sediments in Åstadalen. A: Kames and local eskers, B: main eskers and terraces along the central part of the valley.

Towards the middle of the valley bottom the ridges contain a gravel component with a degree of roundness comparable to that of short transported glaciofluvial sediments in Åsta-dalen (Fig.17A, site 2 & B, curve 2 and Fig.18) indicating that the till has a fluvial pre-history before the final introduction as glacial debris.

The tills of the transverse ridges are interpreted as subglacial melt-out tills (Haldorsen & Shaw in prep.) similar to the formation of the Rogen moraines in Sweden which have been described and discussed by J. Lundqvist (1969b) and Shaw (1979b).

The undisturbed internal structure and the absence of drumlinization indicate that the tills were not overidden by active ice after their formation. The regional position of the ridges in Åstadalen (Fig.3) indicates that they were formed in areas where the glacial movement slowed down at valley constrictions and bedrock obstacles. The fish-scale like pattern of the ridges may be explained by a stacking of stagnant basal ice layers as was proposed by G.Lundqvist (1943; 21) or by a basal folding like that described by Shaw (1979b). Basal formation is also indicated by the orientation of the long-axis of the clasts which is almost consistently parallel with the last direction of ice movement and with a dip towards north.

The uppermost parts of the ridges - above the zone of proper melt-out till, locally consists of sorted stratified

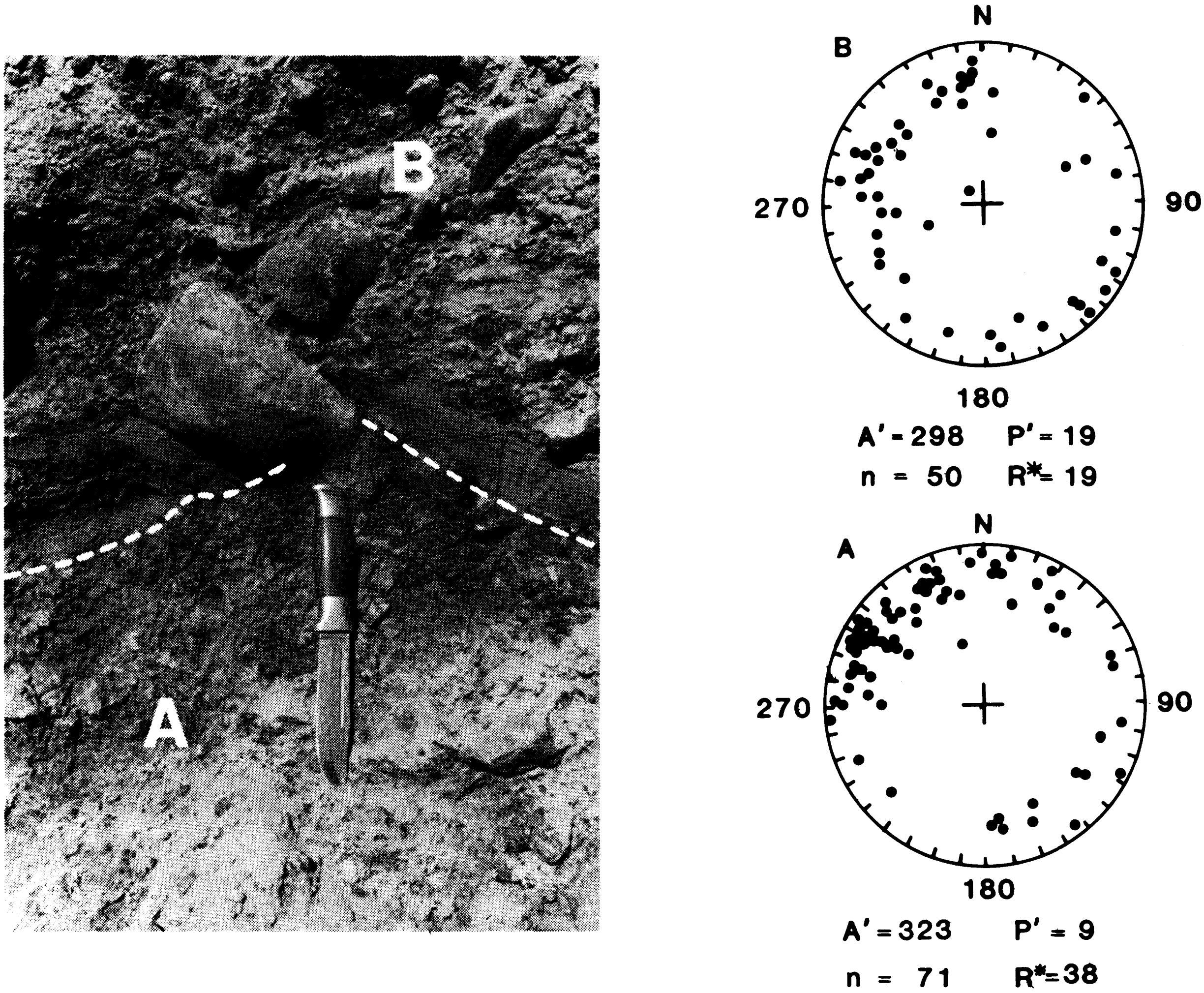


Fig.19 Section in a transverse moraine ridge at Åkerseter (site 1, Fig.17), 1 - 2 m below the surface. To the right, fabric diagrams. Maximum of a-axis orientations is given by the asimuth (A') and by the average dip (P). Magnitude of the resultant vector in relation to the number of observations (n) gives the strength of orientation (values R). A', P', and R are calculated by the method described by Steinmetz (1962). *significant orientation at a 5 % level of significance.

A. Subglacial melt-out till with a prefered long-axis orientation of clasts parallel with the valley.

B. More coarse-grained diamicton of supposed supraglacial origin. A broad scatter of long-axis orientation of clasts is found.

The boundary between A and B is defined by a layer of fine sand and silt.

material and diamiction (Fig.19). The layering is irregular, and the fabric of the diamiction seems to be dependent of the local surface slope. The sediments are interpreted as originally supraglacial sediments or as the uppermost part of the subglacial till which slid during or after the deposition. Such diamictons have mainly the same grain-size distribution as the underlying subglacial melt-out till, or they are somewhat coarser.

Drilling indicates that the transverse moraine ridges rest, in some places, on a smoother sediment surface formed by a silty compact material like the characteristic till of the cover moraine. The a-axis orientation of the cover moraine material in the vicintiy of the ridges is parallel with the valley, indicating that this till was deposited during the late glacial phase, and it is reasonable to believe that the diamicton which underlies the ridges is of the same age.

HUMMOCKS

Hummocks containing diamictons are mainly found along the valley floor. They are most frequent in the east (Fig.3). The hummocks are from 2 to 8 m high. Irregular ridge--shaped forms also occur.

The interiors of the hummocks are exposed in several small gravel pits and road cuts. There is an abundance of

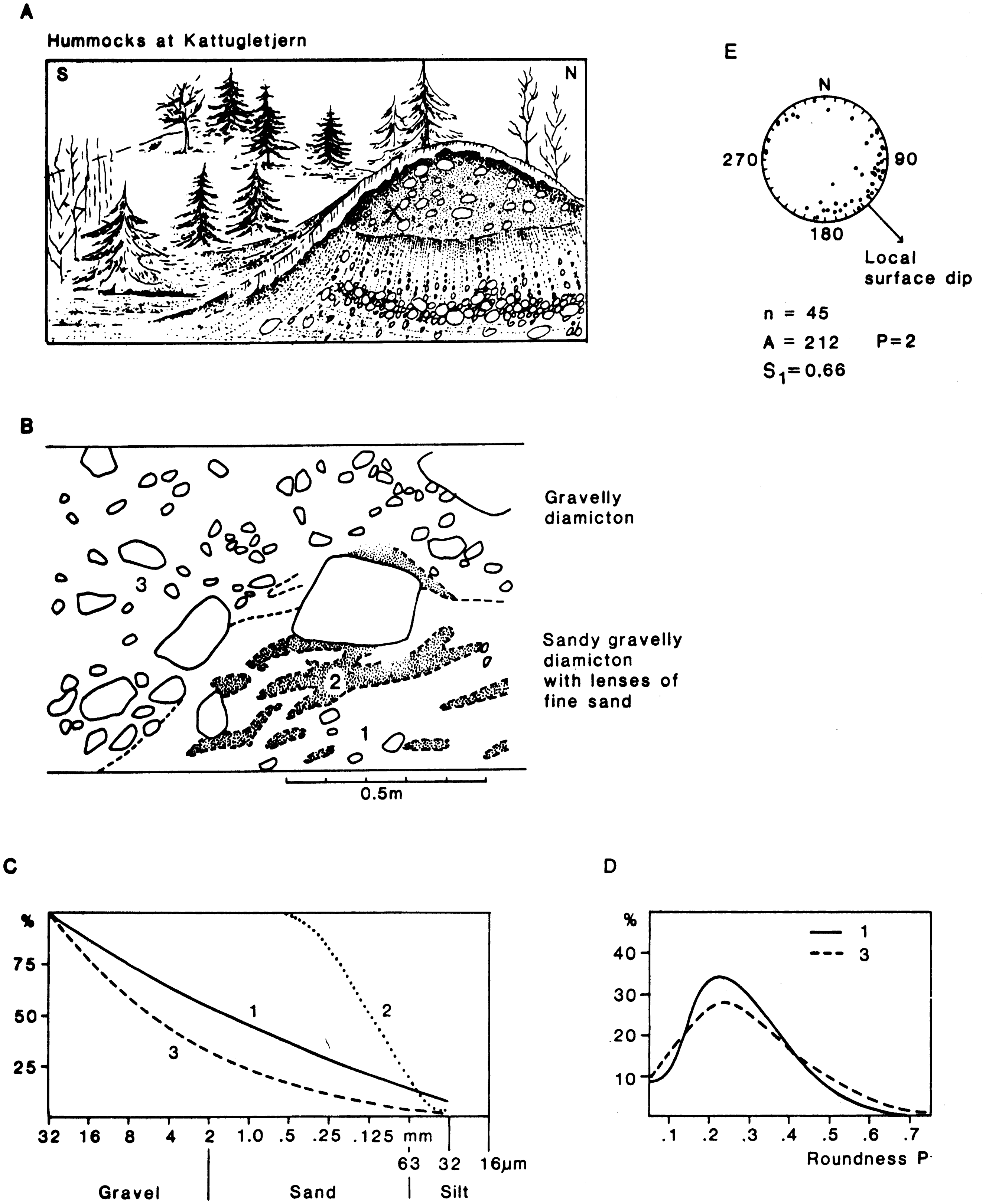


Fig.20 A. Sketch of the hummocky terrain at Kattugletjern.
B. The upper part of the section shown in A (site indicated by X).
C. Grain-size distribution of the three different parts of the section.
D. Degree of roundness of gravel material 16-32 mm.
E. Long-axis orientation and dip of clasts from the lowermost part of the section shown in B. Further explanation: see Fig.9.

sorted zones, mainly in the form of irregular bands and lenses. The diamictons are commonly rich in gravel and have a sandy and loose matrix. They are several places overlain or underlain by sorted, stratified material. There is in most cases no consistent accordance between the directions of ice movement and the long-axis orientation of clasts.

The hummocks are mainly found in areas where eskers and kames are frequent. Drilling showed that they occasionally rest on a homogeneous silty diamicton. Probably this is a till of the same type as that of the cover moraine. In some places the hummocks are found on eskers. This and the fact that they are clearly influenced by melt-water and have disturbed internal structures indicates a supraglacial origin.

The genesis of these sediments has been studied in detail at two localities. Fig.20 A shows a hummocky terrain at Kattugletjern (Fig.3). A section through the upper part of a hummock is shown in Fig.20 B. The lower part of this consists of a sandy, gravelly diamiction (Fig.20 B & C; 1) with irregular lenses of fine sand (Fig.20 B & C; 2). The upper part consists of a diamiction with a low content of sand and silt (Fig.20 B & C; 3). Part 1 is rather massive while part 3 has a diffuse stratification. There is no sharp boundary between part 1 and part 3. The gravel has the same degree of roundness in both parts (Fig.20 D) and this implies that the gravel is of the same origin through the entire section.

The preferred long-axis orientation is roughly parallel to the local surface slope (Fig.20 E). The long-axis dip is somewhat lower than the surface gradient.

The precence of sorted material (Fig.20B; 2) and the long-axis orientation of pebbles in the diamicton indicates a deposition by flow. The cap of coarse material at the top of the diamiction is a characteristic which Nemec et al (1980) regarded as typical for subaerial debris flows. The lower part of the section Fig.20 B; 1) could represent a true debris flow, with a high concentration of solids. The upward movement of pore water may have given an increased concentration of water towards the top of the flow. The material here has been totally liquified and the fine-grained material was thereby removed. This facies may be represented by the upper, gravelly part (Fig.20 B; 3). The coarse-grained texture is thus believed to be a primary property and not the result of a secondary removal of fines.

At Myrbakken (Fig.3) a section in an irregular ridge was studied (Fig.21). The lowermost part (Fig.21 A; 1) consists of stratified sediments with a variable gravel content. The material finer than 2 mm contains $<$ 10 % silt + clay (Fig.21 B). The stratification is partly disturbed.

Above these sediments there is a sandy, gravelly diamicton (Fig.21 B; 2) with a silt content of about 10 % (Fig.21 B) and with a poorly developed stratification and irregular lenses of coarse sand (Fig.21 A). There is no sharp boundary between the diamicton and the underlying

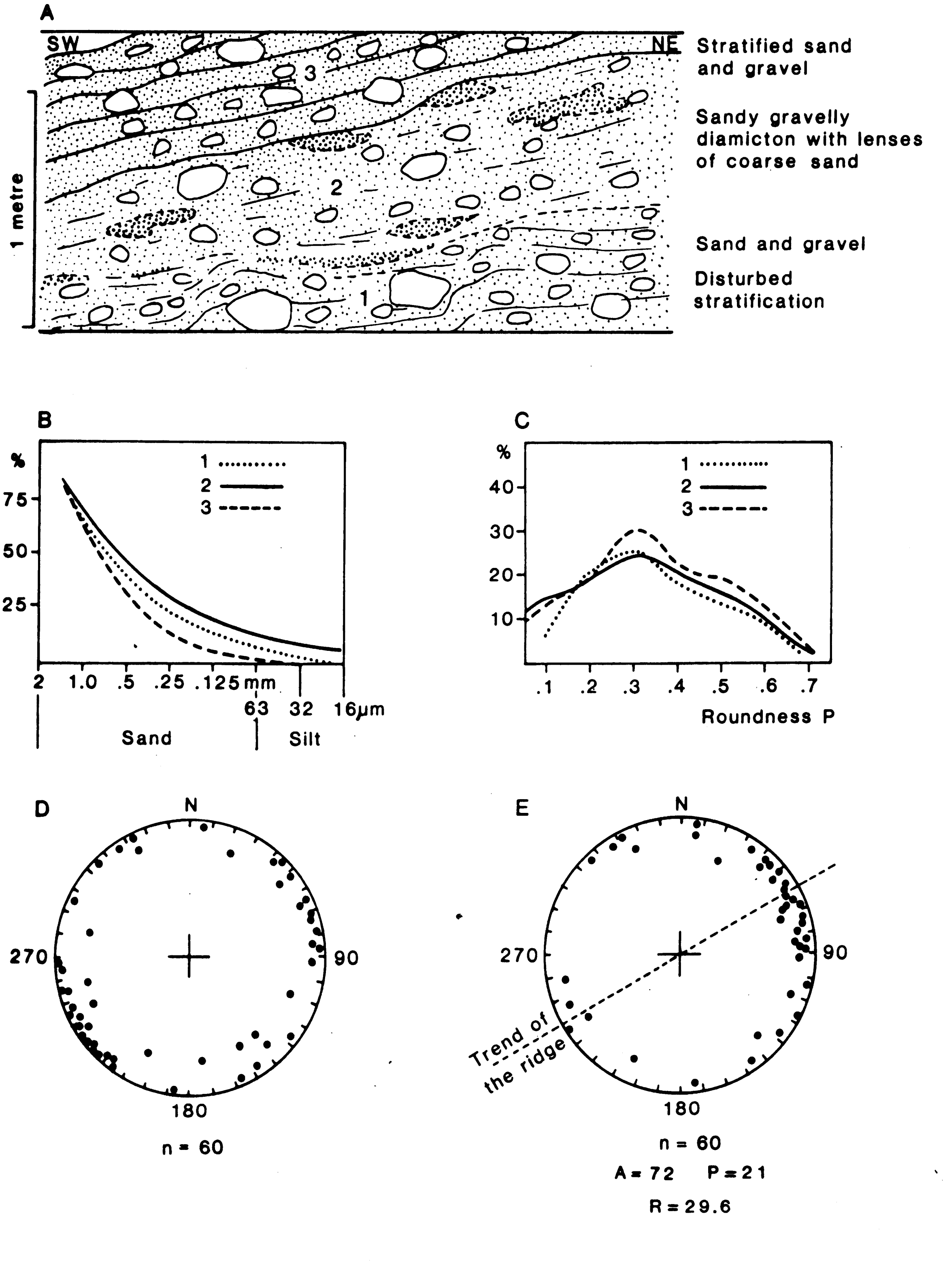


Fig.21 A. The internal part of an irregular ridge at Myrbakken, 1-2.5 m depth.
B. Grain-size distribution of different parts of the sediments.
C. Degree of roundness of gravel fraction 16-32 mm.
D. Long-axis orientation and dip of clasts from the whole diamicton shown in A.
F. The same long-axis orientation and dip of clasts as in D, related to the surface of sedimentation. Values calculated by the method of Steinmetz (1962) (further explanation, see Fig.19).

stratified sediments or between the diamiction and the sand lenses.

At the top of the sequence there are layers with sorted and stratified sand and gravel (Fig.21 A; 3) with a well defined boundary to the underlying diamicton which seems to represent an erosional contact. The upper sediments have a silt content below 5 % (Fig.21 B).

The gravel material has about the same degree of roundness through the whole section (Fig.21 C) and is considerably more rounded than the gravel in most of the subglacial tills (Fig.8). This indicates a fluvial transport even for the gravel of the diamicton (see also Fig.18).

The long-axes of clasts in the diamicton lie in the whole section close to the horizontal plane (Fig.21 D) but compared with the surface of deposition there is a distinct dip towards northeast (Fig.21 E). If the long-axis orientation was parallel with the movement in the diamicton during its deposition, this implies a transport from northeast.

The sedimentation history may be the following: The whole sequence consists of material which has undergone a rather short glaciofluvial transport. This is indicated by the low silt content (Fig.21 B) and by the roundness of gravel (Figs.18 & 21 C). Such sediments were deposited as part 1 (Fig.21 A), probably in a crevasse with a northeast-southwest directon. Part of these deposits - or other material with the same composition - afterwards flowed by gravity down along the crevasse, in a southwestern direction towards the center of the valley. This formed the diamicton (Fig.21 A & E). The top of the diamicton was probably eroded by melt-water before sediment unit 3 was deposited.

The deformation of the sediment 1 may be the result of melting of underlying ice. It is reasonable to believe that the processes which caused the deformation also caused the sediments to flow. The flow may thus have been approximately contemporaneous with the deformation. The undisturbed stratified sediments at the top indicate on the other hand that no significant lowering occurred after the deposition of part 3. The deposition probably occurred during the very last part of the deglaciation when subaerial crevasses extended to the subglacial surface.

Alternative sources of the supraglacial sediments are shown in Fig.22. The eastern valley side and the eastern mountainous areas were probably nearly deglaciated while the valley bottom was still filled with ice. Much of the supraglacial material may therefore originate from earlier deposited till from the deglaciated areas (Fig.22 C). The concentration of hummocks in areas where melt-water channels are frequent along the upper part of the valley side, and the degree of abrasion which is comparable with that of the lodgement till, indicate that this source has been important. This material may have been transported down to the surface of the ice by mass movement or water (Fig.22 A-C-(E)-D).

Basal drift may have been lifted to an englacial position in several places along the eastern valley side where the topography is variable. However, during the last part of the glaciation there was certainly an overall net melting along the base of the glacier. Most of the basal drift was deposited as subglacial till. Englacial drift of this kind (Fig.22 B) cannot, therefore, account for more than a

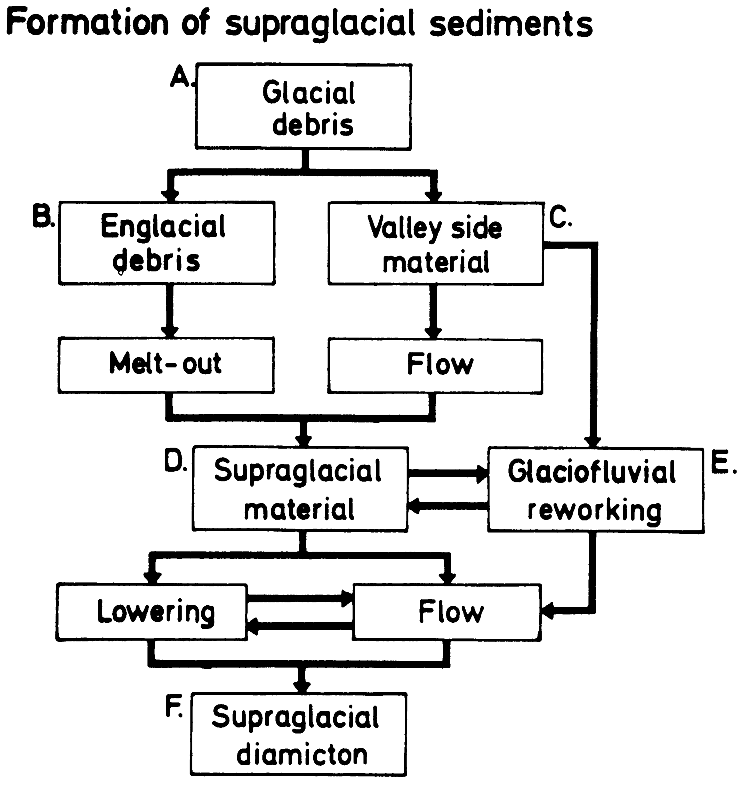


Fig.22 Alternative sources of supraglacial sediments in Åstadalen.

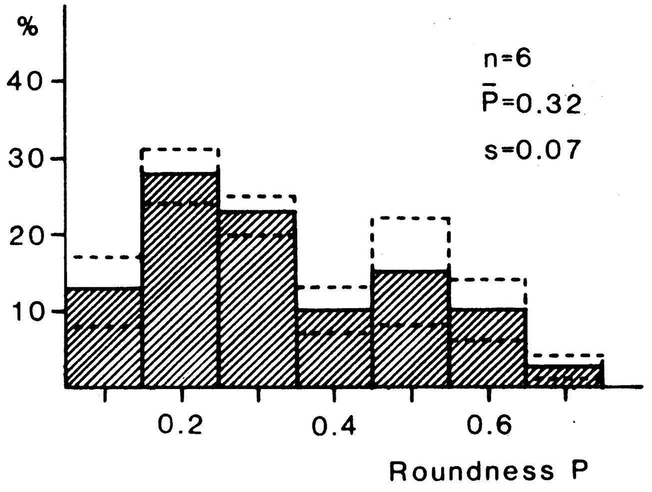


Fig.23 Degree of roundness of gravel material 16-32 mm from diamictons forming the hummocks along Skolla. Each sample consists of 100 particles. Further explanation: see Fig.8.

minor part of the supraglacial sediments.

The supraglacial sediments may have had a complex history also after their introduction to a supraglacial position. It is difficult to decide in which cases the supraglacial sediments should be classified as till.
This is well demonstrated by the two studied sections and also illustrated in Fig.22 D-E-F. All the supraglacial diamictons which have been studied in sections bear evidence of flow. None of them can, therefore, be classified as supraglacial melt-out tills or lowered supraglacial tills (Fig.1). In fact, the active processes which occurred in the supraglacial position were either flow or transport by water. The only till type which was formed from original valley side material was consequently a flow till (Fig.22). Diamictons which have a grain-size distributions and a clast appearance similar to that of the original till, can thus be classified as flow till. The debris flow sediments at Katt-ugletjern (Fig.20) is of this kind. The diamicton at Myrbakken (Fig.21), on the other hand, should definitely not be classified as a till. At other localities an original glacial till may have been mixed with glaciofluvial sediments during flow. This is indicated along Skolla (Fig.3) where the diamictons include gravel with a bimodal roundness distribution (Fig.23). The grain-size distribution is here variable. Zones with silty material occur frequently and are interpreted as fine-grained material from the original till. Diamictons of this kind are not true tills.

There may be several reasons why the hummocks are more common along the eastern than along the western valley side. The eastern valley side is steeper and the mountain area east of the valley is generally higher. These areas where probably free of ice before the western upland area (Fig.3). Further the eastern side is the sunny side of the valley (Fig.3) and, therefore, a greater melting rate occurred here than along the western side. The surface of the ice may for a time have sloped towards northeast. Eventual supraglacial material along the western valley side could have been transported towards the east and there contributed to the supraglacial sediments.

TILL GENESIS - CONCLUDING REMARKS

Fig.24 shows the supposed formation of different till types in Åstadalen. Most of the material is interpreted as subglacial. Nowhere has a true till been found that indicates an original supraglacial formation. The conclusion is, therefore, that the greatest part of the drift was transported in the basal zone of the glacier and not englacially or supraglacially.

Lodgement till is probably the predominant till type in the valley. However, this conclusion is based more on general glaciological considerations than on diagnostic characteristics of the till itself.

Local lee-side till and a significant part of the sparse till cover in the mountain areas have been classified as melt-out till. This interpretation is based on the conclusion that the material could not be identified as lodgement till. In addition the melt-out till may locally constitute parts

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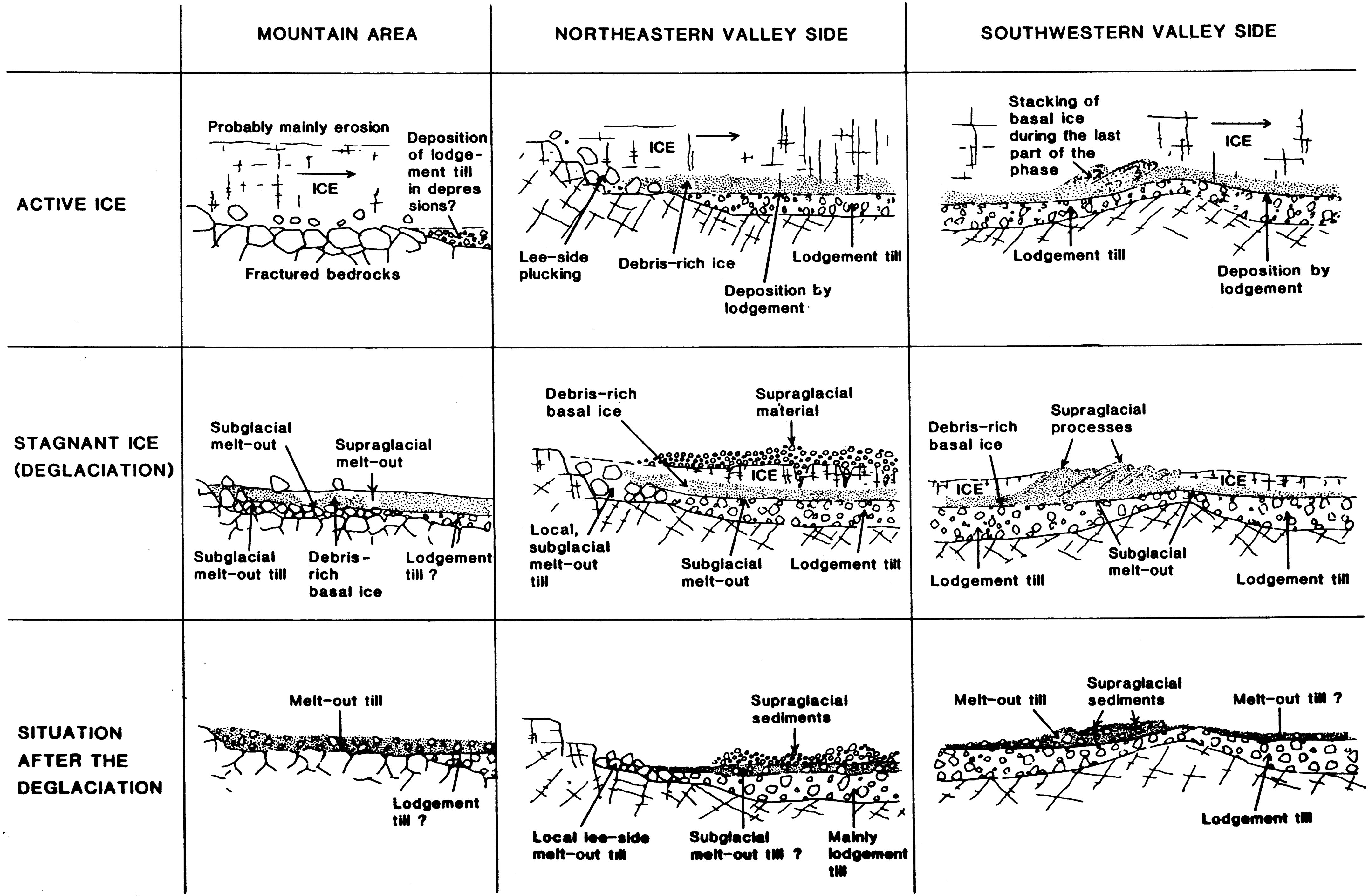
Fig.24 Formation of tills in Åstadalen.


MOUNTAIN AREA
NORTHEASTERN VALLEY SIDE
SOUTHWESTERN VALLEY SIDE
ACTIVE ICE
Probably mainly erosion
ICE
Deposition of lodgement till in depres sions?
Fractured bedrocks
ICE
Lee-side plucking
Debris-rich ice
Lodgement till
Deposition by lodgement
Stacking of basal ice during the last part of the phase
ICE
Lodgement till
Deposition by lodgement
STAGNANT ICE (DEGLACIATION)
Subglacial melt-out
Supraglacial melt-out
Subglacial melt-out till
Debris-rich basal ice
Lodgement till ?
Debris-rich basal ice
Supraglacial material
ICE
Local, subglacial melt-out till
Subglacial melt-out
Lodgement till
Debris-rich basal ice
Supraglacial processes
ICE
ICE
Lodgement till
Subglacial melt-out
Lodgement till
SITUATION AFTER THE DEGLACIATION
Melt-out till
Lodgement till ?
Supraglacial sediments
Local lee-side melt-out till
Subglacial melt-out till ?
Mainly lodgement till
Melt-out till
Supraglacial sediments
Melt-out till ?
Lodgement till

of the regular till sheet in the valley (Fig.24). The studies actually indicate that it is often easier to tell what is not a lodgement till than to tell what is not a melt-out till.

It has been difficult to distinguish between subglacial and supraglacial melt-out till as both are formed from melt--out of basal drift and since the melt-out process probably was mainly related to the final part of the deglaciation phase (Fig.24).

The relation between tills formed from basal drift and diamictons formed from supraglacial material is in many cases complex. The work of Haldorsen & Shaw (in prep.) indicated that the transverse moraine ridges in Åstadalen (Rogen type moraines) were formed mainly by melt-out of subglacial debris. As shown in Figs.19 & 24 this material may be covered by a cap of supraglacial sediments. The hummocky moraines, on the other hand, were probably mainly formed from supraglacial sediments. The source of such sediments may in most cases have been subglacial till from the valley slope. The study illustrates that it is in many cases difficult to define what is a "basal till" and what is an "ablation till", in the way these terms were defined in the introduction . The investigation also demonstrate that it is in cases even difficult to determine what is and is not a till.

CHRONOLOGY OF TILL FORMATION

Åstadalen was certainly not swept completely free of sediments before the present till was formed. This is demonstrated at Øvre Åstbrua (Fig.3). Sorted sand and silt with lumps of of clay is found there beneath a till from the early glacial phase (Fig.25). The clay contains remnants of turf and mosses from an ice-free period and the till contains significant amounts of subrounded gravels which indicate an incorporation of water transported material (Fig.25).

The organic matter in the sub-till sediments at Øvre Åstbrua has a sparse pollen content. The pollen composition may indicate an interstadial origin (R. Sørensen pers.comm. 1980). The material has not been dated, but it may for instance be of the same age as the sub-till sediments in Gudbrandsdalen (Bergersen & Garnes 1981) or the organic material in Brumunddal, 30 km south of Bjørnåsbrua (Helle et al 1981). These are related to Early Weichselian interstadials, and may represent the last time in the Wiechselian that the Åstadalen area was deglaciated.

No defined boundary between the lower till transported from north and the upper till transported from northwest has been recognized. The difference between them is only reflected in the fabric. There is therefore no indication of an ice-free period after the deposition of the lower till. This till is obviously younger than the organic material at Øvre Åstbrua, and is most probably younger than the last ice-free period in the Weichselian.

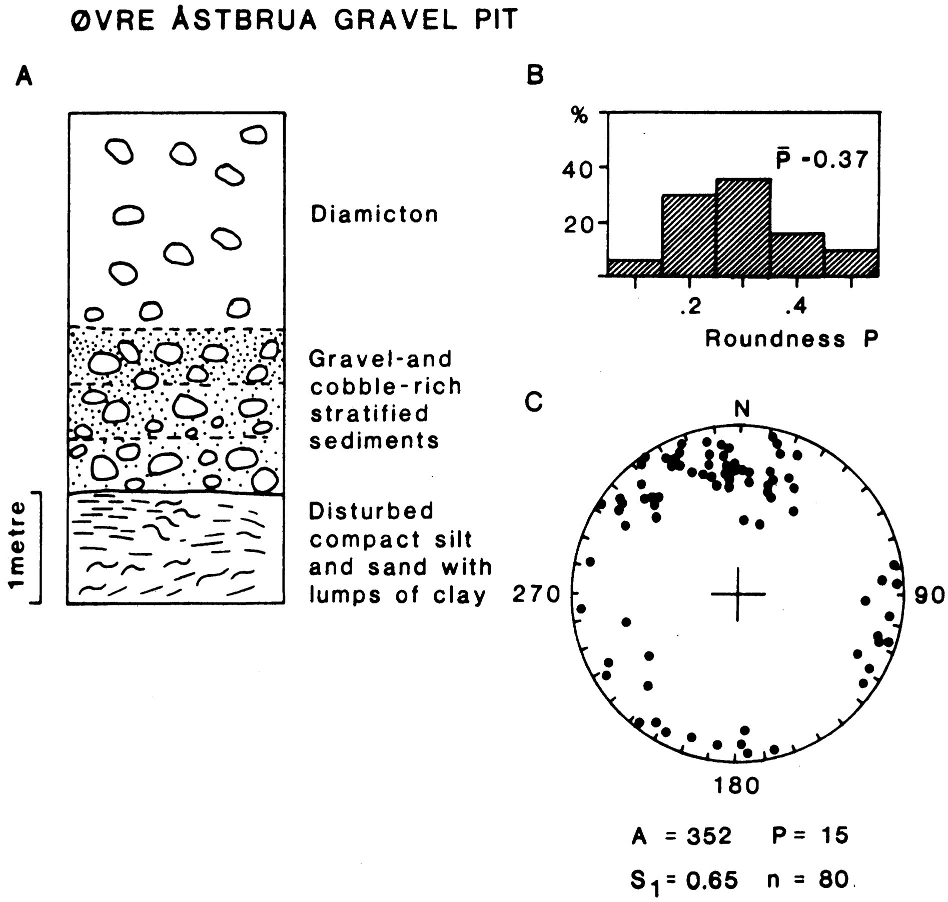


Fig.25 A. Stratigraphy of the gravel pit at Øvre Åstbrua.
B. Degree of roundness of gravel material 16 - 32 mm from the base of the diamicton.
C. Long-axis orientation and dip of clasts from the base of the diamicton.

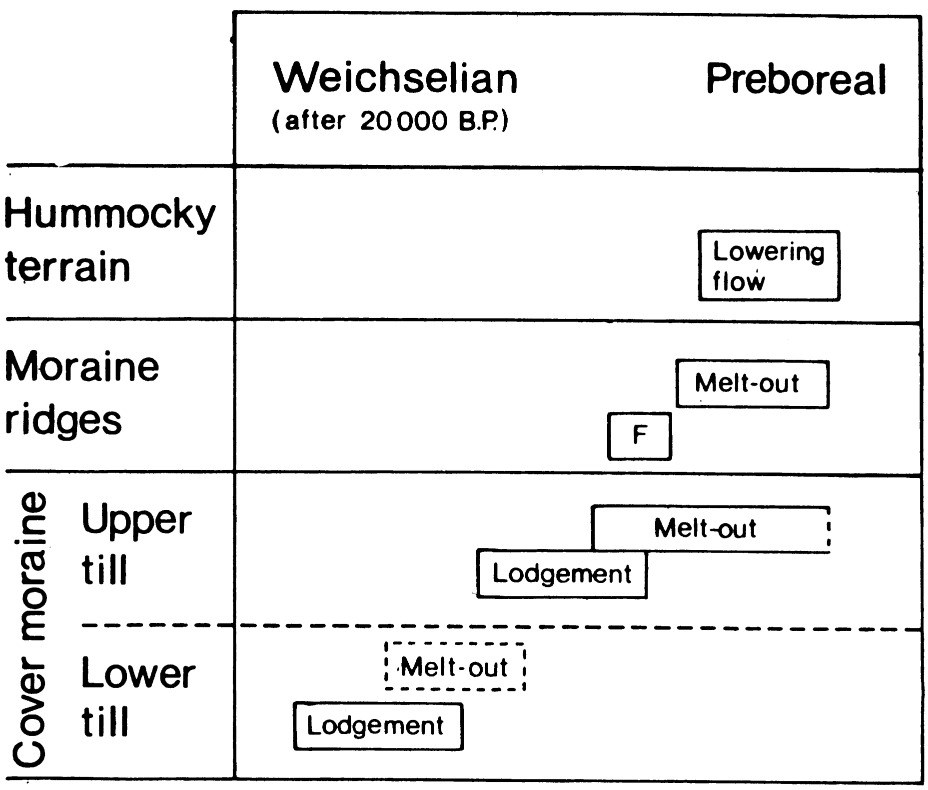


Fig.26 Chronology of till formation and deposition in Åstadalen. F=formation of moraine ridges.

It is not known when the early glacial phase started nor how long it lasted. It may have started shortly after the last interstadial and thus a long time before the Weichselian maximum. There is, however, no indication of a gap in time between the formations of the lower till and the upper till. On the contrary sedimentation seems to have been continous. The early glacial movement from north could therefore be younger than the Weichselian maximum and for instance represent part of the Late Weichselian (Fig.26). This movement may have lasted until the ice movement became southeasterly. Such a change was probably caused by a shift of the ice accumulation centre, and it lasted until all glacial activity stopped, as the general topograhical features also have a northwestern-southeastern direction (Figs.2 & 4). A change in the direction of basal ice flow would have been immediately reflected in the fabric of the lodgement till.

If the total till was formed after the Weichselian maximum there is a difference of several thousand years between the formation of the organic matter at Øvre Åstbrua and the deposition of the till. A long time was thus available for the removal of old sediments before the present till was formed. Is should be emphasized that Åstadalen is an upland area and therefore also an area of erosion compared with Østerdalen and Gudbrandsdalen (Fig.2). It is also important to emphasize that the time after the Weichselian maximum involved periods with a great net melting and thus a net deposition. It is therfore not necessarily representative of all stages of the last glaciation. The Weichselian might well have included periods with significantly more erosion than during its late stages.

During an early part of the late glacial phase the ice seems to have slid along the western part of the valley independent of the undulating morphology. Deposition of lodgement till was probably dominating during this time (Fig.26).

As the thickness of the ice decreased and the supply of ice from the accumulation zone was depleted, the glacier became more passive. The stacking of debris-rich ice in the fish-scale like ridges probably occurred during the more passive phase. The valley narrowings and bedrock ridges then acted as obstacles and forced the basal ice to slow down or to stagnate.

During or before this phase a subglacial melt-water drainage was established. The freezing of glaciofluvial sediments occurred locally where the melt-water drainage stopped or the melt-water channels moved.

Melt-out was now probably the most important way of till formation (Fig.26). The deposition of basal melt-out till may have occurred along the valley until the very last part of the deglaciation (Fig.26).

I has been postulated that a regional glacial stagnation occurred over many inland parts of southern Norway (Reusch 1901; 88, Strøm 1943, Mannerfelt 1945, Holtedahl 1953; 753). The time of regional stagnation is not known in Åstadalen. The valley bottom lies at about 200-300 m below the general level of the mountain area in the east and north (Figs.2 & 3). The glacier was, therefore, probably still moving along the valley after the mountain areas were partly free of ice.

There might have been activity along the valley until the glacier disintegrated and ice occurred only as stagnant remnants along the valley floor. Such a stagnation may have happened rather early in Åstadalen compared with Gudbrandsdalen (Fig.2) which was a drainage channel for ice from the high mountains of Jotunheimen.

The mountain area was probably not deglaciated before the end of the Preboreal time (Sørensen 1979b). Most of the supraglacial sediments in the eastern part of the valley were formed during this time. If transverse ridges of subglacial origin were ever as frequent in the eastern as in the western part of the valley, they were partly covered by the supraglacial sediments, or parts of them may have been eroded by the melt-water which flowed along the eastern valley side until deglaciation was complete.

CONCLUSION

This study concerns the genesis of tills which were formed in an area beneath the central part of the Scandinavian ice sheet.

The greatest part of the area is covered by a 1-5 m thick till which does not create an independent morphology. In accordance with Aario (1977) it is classified as a cover moraine. The cover moraine area is divided into three different topographical subareas.

The mountain plateau area with levels from 900 to 1100 m a.s.l. is covered by a thin, local coarse-grained till with angular clasts. It is believed to have been formed in a basal position. It is interpreted as a melt-out till since it shows no signs of a transport along the base of an active sliding glacier and no signs of deposition by a lodgement process.

The northeastern valley side has a variable till. At lee-side localities a local, coarse-grained till with angular clasts was deposited. It is rather similar to the till on the mountain plateau. This till is also interpreted as a sub-glacial melt-out till, and it is believed to represent the incipient till formation along the northeastern valley side. Material of this type was further transported near the base of the glacier and later it was probably deposited mainly by a lodgement process. Such tills contain abraded cobbles and boulders. In places the abraded material was mixed with locally eroded bedrock material and a till with both rounded and angular clasts was deposited.

Along the southwestern valley side and at the western upland area the till is mainly continuous. The material is relatively rich in silt and sand. The boulders and cobbles are dominatly abraded and striated. The till characteristics indicate transport along the base of sliding glacier. In some places the till properties show that deposition took place by lodgement. This is believed to be the dominant mode of till deposition in this area. Till material with similar characteristics might locally have been deposited by a pure melt-out process where part of the basal, debris-rich ice stagnated.

The transverse moraine ridges constitute the second morphological unit within the area. They are mainly located at and proximally of valley constrictions and bedrock ridges. They were most probably formed during the last part of the active phase when the ice was no longer able to slide uniformly across such bedrock obstacles. The material within these ridges shows clear evidence of melt-water. It is loose and sandy and includes lenses and irregular bands of sorted material. Deposition probably took place by a basal melt-out process.

The third morphological unit is the hummocks which occur along the valley floor. They consist of diamictons and sorted stratified sediments. Most of the material is believed to have occurred at the surface of the ice. It is in most cases difficult to decide wether the material is a till or not. Most of it may originate from earlier deposited till which was transported by flow or by water from the valley side down on to the ice along the valley bottom.

Most of the active glacial transport of debris seems to have been in an basal position.

The till is generally thicker in the valley than in the mountain areas. Till thickness is greater along the south-western than along the northeastern valley side. A net erosion probably occurred along the northeastern lee-side area when the ice movement was from the north. Some of this material was transported across the valley and deposited along the southwestern valley side. The bedrock structures promoted lee-side plucking and a stoss-side abrasion and deposition. Significant amounts of the till and glacial drift along the northeastern valley side was eroded by melt-water during the deglaciation phase.

Most of the till was probably formed after the Weichselian maximum. Deposition of the lower till took place during an early phase when the ice movement was from the north. This deposition may have continued until the glacial movement changed to a northwest - southeast flow direction. No great discontinuity is necessary between the deposition of the lower and the upper till.

The main deposition of lodgement till probably occurred during the early phase and the first part of the late phase. The glacier then slid uniformly along the undulating valley floor. Local deposition of subglacial melt-out till may have been related to the last part of the deglaciation.

The formation of the transverse ridges may have taken place during the last part of the active phase. No reactivation of the ice seems to have occurred after that their formation

The hummocks were probably formed after the mountains and the upper part of the eastern valley side was free of ice. The hummocks represents the last formation of till in Åstadalen.

Aknowledgements. Professor Dave M. Mickelson and Professor John Shaw visited the field area and initiated inspiring discussions. The final draft of the paper was commented by Professor Aleksis Dreimanis, Professor John Shaw and Professor Tore O. Vorren. Grete Bloch and Åslaug Borgan assisted in the field. Marie-Louise Falch has type-written the manuscript and Åslaug Borgan drafted the figures. Data analysis of fabric measurements was performed at the Univ. of Alberta by John Shaw. To all these persons I tender my sincere thanks. Financial support was provided by the Norwegian Council for Science and the Humanities.

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PAPER 6

MELT-OUT TILL AND THE PROBLEM OF RECOGNISING GENETIC VARIETIES OF TILL

SYLVI HALDORSEN & JOHN SHAW

Haldorsen, Sylvi & Shaw, John : Melt-out till and the problem of recognising genetic varieties of till.

Deposition of till by melt-out was described already hundred years ago, and today the criteria which provide evidence to support an interpretation of melt-out till are available. The most important criteria are (P_1) the presence of unlithified, sorted and stratified sediments within or interstratified with the till(s) , (P_2) the presence of a statistically preferred orientation of stone axes closely related to ice flow condition, and (P_3) a configuration of till with a recognisable textural or lithological property closely related to the configuration of englacial debris with the same property. The Omnsbreen Glacier in central Norway provides an important evidence in regard with P_1. Based on P_1 and P_2, and on regional aspects, tills composing ridges transverse to the direction of ice flow are interpreted as melt-out till and flow till. The interpretation of till genesis must be based on the balance of probability as an absolute proof in most cases is unrealistic.

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Introduction

The most popular approach to till classification is genetic so the commonly used names for tills, lodgement, melt-out, flow, basal, all include genetic connotations. Many early glacial sedimentologists held fixed ideas about processes, which were, nonetheless, hypothetical and sought to relate till properties to these processes.

A major concern is: what is sufficient evidence for an interpretation of till genesis? Absolute proof is unrealistic as is the requirement that all other hypotheses be falsified. We suggest that sufficiency exists when the evidence supports an interpretation above all other known, relevant interpretations. Thus the inevitability of uncertainty in any interpretation is acknowledged.

Direct observation on glaciers has increased our understanding of processes of till formation to the extent that lodgement, melt-out, flow, and deformation are no longer hypothetical processes. Nevertheless, despite improved understanding of process, great uncertainty remains regarding the association of properties and process. We consider the present confusion on the correspondence between properties of till and their genesis to be a major stumbling block to progress in glacial sedimentology. In this paper, we will discuss the problems involved with particular reference to melt-out tills.

A historical review of the melt-out concept

Goodchild (1875) held that *moraine profonde* resulted from a process of fragmented rock being dragged and internally deformed near the base of a glacier. His original view of *moraine profonde* corresponds in many respects to the comminution till of Elson (1962), the deformation of a subglacial slurry (Smalley and Unwin, 1968) and perhaps even to lodgement till where this is restricted to a plastering process at the base of active ice. The putative process involves wholesale internal deformation or dislocation. However, he observed intimately interbedded tills and undisturbed stratified sediments in the Eden Valley which could not have been produced in this way.

Goodchild's reasons for rejecting the *moraine profonde* hypothesis are clear and remain valid. As an alternative, he suggested that the drifts originated by direct deposition of till upon the melting of extensive bodies of stagnant ice. He described the processes which are now called regional stagnation and till deposition by melt-out. We should carefully consider his reasoning. For regional stagnation he wrote (p. 93-94):

> Most persons who have lately written on glacial subjects have remarked how suddenly the great ice period was brought to a close. So little modification have the striae undergone at almost all elevations that it is no uncommon thing to find striae going right across the bed of a considerable valley in such a way as to show that, had the ice dwindled away by slow degrees, and passed back through all stages of glacier development to the tiny glaciers of the later period, all traces of the former existence of the great ice sheet must have been obliterated from the low ground. Everywhere the ice appears as if, after it had reached its maximum thickness, it had quietly melted away, without the lower part, at any stage of its liquefaction, ever again advancing over the rock.

In support of melt-out he concentrated on the importance of interbedding of till and stratified material:

> The upper part of the till exhibits more distinct lamination, which is well shown by the presence of thin lines of sand and fine gravel (p. 80).
>
> Here and there in the country below Brough, a section shows that seams of sand and gravel are interstratified with beds resembling the till.... On the whole, however, it is tolerably clear that in the low ground the proportion of washed detritus associated with the clay-

> drifts is greater, and the signs of lamination in the clay drifts more marked and more widely spread, in proportion to the distance from the head of the main valley (p. 81).
>
> The stiff clay full of blunted and scratched stones of all sizes up to 4 feet, disposed without any regard to form or size, cannot be anything else than the work of ice: but when we try to explain the presence of seven or eight, or, in some cases, as many as eleven such beds of till interstratified with undisturbed beds of sand and finely laminated clays by the *moraine profonde* theory, ..., we meet with complete failure (p. 92-93).

Goodchild (1875) went on to paint a vivid picture depicting the formation of these sequences of till and stratified materials (p. 95):

> When the great ice-sheet began to melt, the stones that were nearest the bottom of the ice, ..., began to be deposited on the floor of the glaciated rock, or on patches of the true *moraine profonde* where these existed. The water resulting from the melting of the bottom ice would find its way here and there towards the sea along channels in the slowly thickening deposit of till.... As the currents shifted they must have allowed till to accumulate in parts where nothing but sand and gravel had been laid down; while on the other hand, they must frequently have cut into banks of till and afterwards filled the denuded hollows with waterworn materials as their course slowly changed.

Goodchild's rejection of the *moraine profonde* hypothesis is a benchmark in the evolution of glacial sedimentology.

With the advantage of hindsight we can commend Goodchild for this but, at the same time, criticise his ready acceptance of melt-out. The diagnostic criteria he used for melt-out, diamicton with glaciated stones and interstratified sorted sediment, are common properties of till flow deposits. Furthermore, both melt-out tills and till flows are expected in the postulated environment of regional stagnation. Goodchild was correct in his interpretation insofar as the flow hypothesis was not available to him. The validity of an interpretation is, therefore, conditioned by the state of contemporary knowledge. As knowledge increases the number of relevant interpretations increases accordingly and discrimination between them becomes increasingly difficult.

Goodchild's opinions were enthusiastically endorsed by Garwood and Gregory (1898) who wrote (p. 222):

> We were constantly reminded during our study of the Spitsbergen glaciers of his protest against regarding Glacial Drifts as a ground moraine and his explanation of their deposition by the quiet melting away of an ice sheet charged with rock fragments.

Unfortunately, Garwood and Gregory (1898) did not document the direct observations at these processes; rather their specific, relevant observations are on the resultant sediments (p. 209):

> Sections cut by streams through the deposits showed them to be laminated with remarkable regularity, forming clays of the type named by Goodchild "gutta percha clays".

Crosby (1896) arrived independently at similar conclusions to those of Goodchild. He also broached controversies which continue today (p. 229-230):

> The real problem appears, then, to be as to the relative efficiency of subglacial and superglacial streams. Upham, the foremost advocate of the efficiency and sufficiency of superglacial streams, holds that the englacial drift became superglacial, bv surface ablation of the ice, in sufficient volume to account for practically all types of modified drift.... That this must be the history of part of the modified drift is obvious from the fact that these conditions are realized in modern ice sheets; but they are only realized it must be added to a limited extent....
>
> Assuming, as I think we must, that the englacial drift is crowded in the basal layers of the ice, enormous wastage of the ice must occur before it becomes superglacial.
>
> It seems to be very probable, however, that when considerable sections or areas of the Pleistocene ice-sheet were so far wasted as to be absolutely stagnant, and when superglacial drift covered its surface and checked the melting of the ice.... Meanwhile, however, or before these conditions are realised, the water resulting from the melting of thousands of feet of ice has escaped from the ice through subglacial channels; and during its entire subglacial course the main body of the englacial drift has been within its reach and undergoing modification.

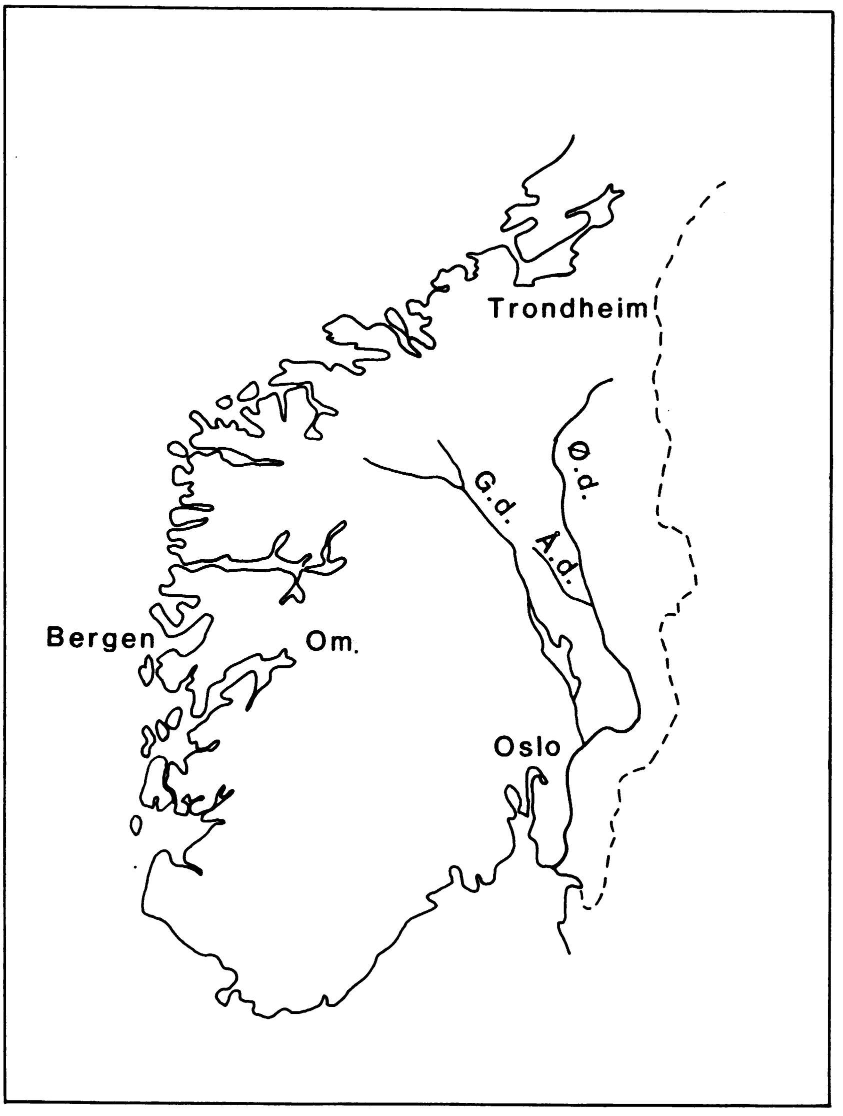

Fig.1 Location map.
Om = Omnsbreen, Å.d. = Åstadalen.
G.d. = Gudbrandsdalen
Ø.d. = Østerdalen

With respect to Goodchild's hypothesis Crosby's contribution does not give additional criteria by which tills deposited by melt-out may be recognised. Crosby clearly showed, however, that we should be concerned with the relative importance of processes rather than the acceptance of one to the exclusion of all others. He was aware of the restricted applicability of processes observed directly at the ice surface and argues persuasively for the relative importance of subglacial melt-out together with considerable syndepositional modification.

G. Lundqvist (1940, p. 29) wrote that sand lenses form a normal part of till sections and postulated that dead ice bodies can occur under active ice, stagnation resulting from a high debris concentration in the basal zone (p. 38). Lundqvist has thus reiterated the conclusions of Goodchild with regard to sand lenses and was, at that point, open to the same criticism. He also follows Crosby but, by invoking debris-charged ice, makes an additional theoretical justification for basal stagnation (see also Russel, 1895). Lundqvist (1951) subsequently introduced the fabric of the till as an argument in favour of melt-out (p. 55);

> However, the till material which melted out seems to have retained its internal fabric. This indicates a slow and careful melting, and the ice may have remained in the valley moraines long into postglacial time.

There can be little doubt that the emphasis on slow and careful melting is specifically to rule out the possibility of flow subsequent to the release of debris. By considering fabric in addition to stratification Lundqvist greatly improved the quality of interpretation.

A further complication was introduced shortly after Lundqvist's publication. Jarnefors (1952) and Virkkala (1952) noted tills with preferred orientation of stone long axes and with relatively well sorted layers or "bed limits". They both interpreted these to represent some form of shearing. The observations of Lundqvist (1951), Jarnefors (1952) and Virkkala (1952) were very similar but Lundqvist's interpretation was quite unlike that of the other two. Here contention hinges on the origin and history of the sorted materials which cannot be taken for granted. As with the tills themselves, the theoretical possibilities are clear, but in many cases a single option has been adopted without supporting argument.

Harrison (1957) presented a well documented paper in which several relevant hypotheses were checked carefully against his observations. Relatively undisturbed, unlithified stratified sediments together with a stone fabric pattern closely related to assumed ice flow characteristics led him to reject lodgement, subglacial deformation and flow hypotheses and to favour a hypothesis of melt-out. Elson (1962, p. 9) confidently expressed the melt-out till concept, "An appreciable thickness of englacial drift can be melted out from the base of a till-covered glacier", and more importantly gave a comprehensive set of properties by which what he termed "subglacial ablation till" could be recognised (p. 9):

> In this till certain structures of the glacier may be preserved though distorted because of a reduction in volume of 70 to 90 per cent. The structures include sheets of precompressed till a few inches thick formed in thrust planes that dip upstream near the glacier margin, and the statistically preferred orientations of elongate stones. An orientation transverse to the direction of ice flow develops among particles that are moved isolated from each other for a prolonged period. Preferred orientations parallel to the direction of ice flow develop near the margins of a moving fluid, and where the particles contact each other frequently. This "subglacial ablation till" may be somewhat precompressed by the overlying ice. Some of its constituent particles have been in contact with one another for an appreciable time and the average grain size is much smaller than that of superglacial till. Silt and clay particles expelled by

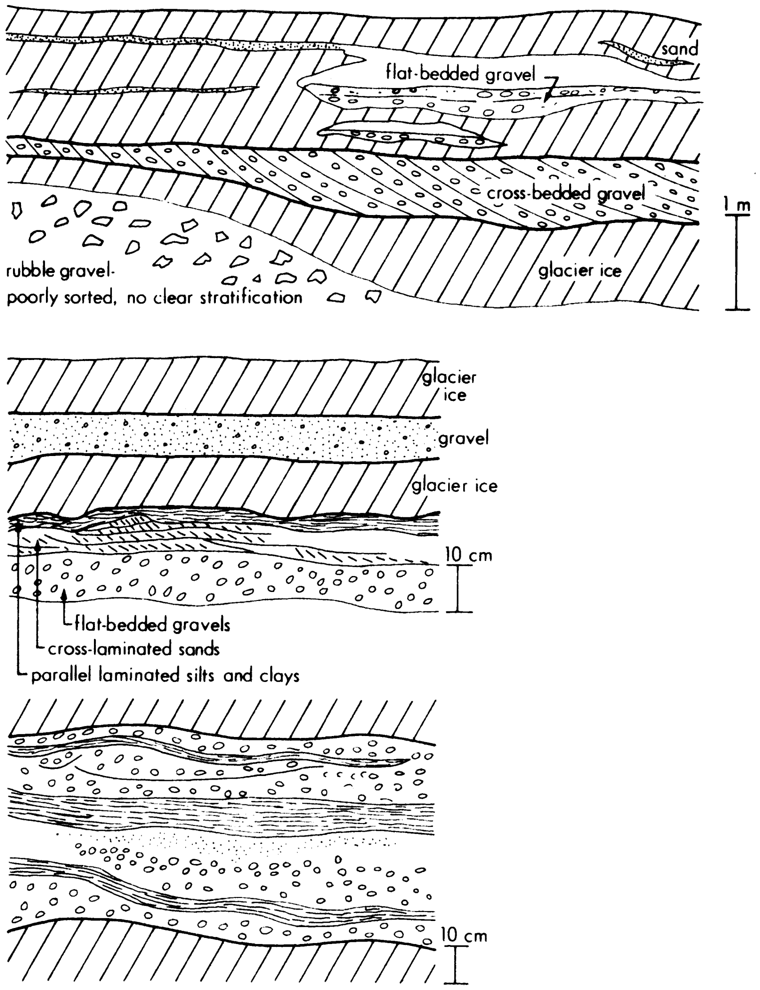

Fig.2 Intercalations of stagnant glacier ice and stratified sediments. Omnsbreen.

> ice crystals form thin coatings around pebbles and larger stones, and voids are abundant among sand-sized particles (Fig. 2). At the base of this till layer striated boulder pavements or thin irregular lenses of sand and pebbles may occur as relicts of the last erosive movement.

One important contribution made by Elson is the recognition that structures of the glacier/debris complex other than just statistically preferred clast orientation may be preserved.

Recent Developments

There has been recently considerable departure from the principles outlined in the review of the historical evolution of the melt-out concept. Early workers such as Goodchild, Crosby, Garwood and Gregory were confident of their interpretations. Lundqvist (1951) introduced fabric as an added criterion. These early workers remained confident that the interbedded stratified sediments were of englacial or subglacial origin. Harrison (1957) argued differently for the origin of the stratified material but his final interpretation was that of these early workers. Perhaps, Hartshorn (1958) sowed the first seeds of doubt with his suggestion that the tills may not be derived directly from glacier ice but may be "flow tills" and the associated stratified sediments need not be of englacial or subglacial origin. However, the major swing against this early interpretation of the stratified sediments came with the application of observations on modern glaciers to the interpretation of ancient glacigenic sediments. In fact, the early interpretation of an englacial or subglacial origin for the sorted sediments was scarcely considered at all, and the major thrust was to discount the view that multiple tills separated by stratified deposits represent multiple ice advances (Boulton, 1972). Dreimanis (1976, p. 28) wrote, "Interbedding with stratified drift, where mudflows from glaciers have moved over proglacial sediments creates situations resembling multiple tills produced by glacial advances". The evidence from modern environments is overwhelmingly in favour of this modern view (Boulton, 1967, 1968, 1972; Lawson, 1979). Lawson (1979, p. 40) estimates only five per cent of the deposits at the terminus of the Matanuska Glacier, Alaska, accumulate as true till, that is as melt-out or lodgement till, and he shows quite convincingly that sediment flow is the dominant process in this modern environment. Careful study of Pleistocene sediments brought several authors to similar conclusions regarding the dominance of sediment flows (Marcussen, 1973; Evenson *et al.*, 1977; Morawski, 1976).

Discussion

The criteria which provide evidence to support an interpretation of melt-out till are available. It is not surprising that no single property gives sufficient evidence and a conjunction of properties is required. No property of melt-out tills which is logically necessary has been identified. However, following Achinstein (1968), those properties which are taken in conjunction to support an interpretation of melt-out may be said to be relevant. Assuming that we can identify tills in themselves and that our only concern is the recognition of genetic sub-classes of till, we might proceed as follows. Using only those properties which have been documented so far, let P_1 be the presence of unlithified, sorted and stratified sediment within or interstratified with the till (or tills), P_2 be the presence of a statistically preferred orientation of stone axes closely related to ice flow conditions, and P_3 be a configuration of till

Fig.3 Extensive planar contact (above the man) between englacial fluvial sediments and overlying ice.

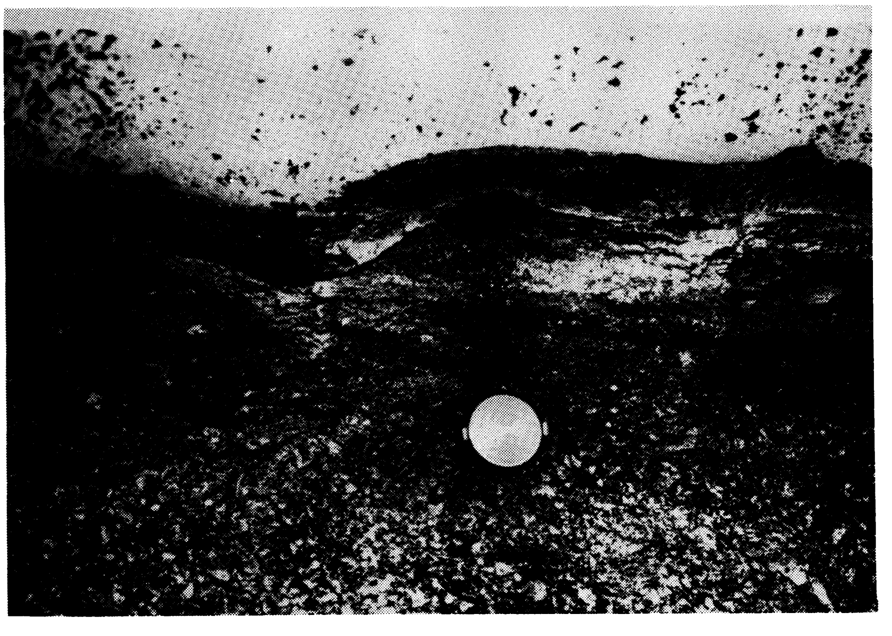

Fig.4 Variable texture and structure of englacial stratified sediments. Flat bedded gravel is seen in the vicinity of the lens cap. The gravel is overlain by small-scale cross-laminated sand which is in turn draped by finely laminated silts. Note that the ice/silt contact undulates in harmony with the bedding surface upon which the silts were deposited.

with a recognisable textural or lithologic property closely related to the configuration of englacial debris with the same property. Some or all of these properties may count in favour of a particular classification, some may count against, and the presence of a particular property may preclude some classifications. These properties in themselves involve some degree of interpretation which adds to the uncertainty of interpretation.

Comparing the approaches of the earlier and later workers, there is agreement on the relevance of property P_2, preferred orientation. Very detailed work by Lawson (1979) confirms the assumption of Lundqvist (1951) and Harrison (1957) that sediment flows do not normally show clast orientations systematically related to ice flow direction whereas melt-out tills do. However, preferred orientations in sediment flows at individual localities may well be those expected of melt-out tills, and there will always be a measure of uncertainty in this respect when fabrics are sampled over small areas. Lawson (1979, p. 93) reports the presence of discontinuous layers, lenses, and pods of texturally distinct material in modern melt-out tills. This corresponds to property P_3 and confirms Elson's (1962) view that englacial distributions of materials may be retained in tills. That this is in itself evidence in favour of melt-out is supported by observations on Pleistocene tills (Moran, 1971; Eyles and Slatt, 1977; Shilts, 1978).

The significance of property P_1, interstratified tills and sorted sediments, remains contentious. Melt-out tills in modern environments have been described as massive and are said not to include interstratified sorted sediments (Boulton, 1976, table 2). Lindner (1976, p. 143) adopts this view when he writes that a till is a melt-out till because it "contains neither streaks of sand nor traces of lamination and nor planes of separation". Thus we see that as a result of observations on modern glaciers the *absence* of property P_1 counts in favour of melt-out whereas formerly the *presence* of this property counted in favour. The confusion is apparent, and yet some authors continue to use interstratified sediments as supporting melt-out (Shaw 1971, 1979; Lundqvist, 1969a; Johansson, 1972; Daniel 1975; May and Thompson, 1978). The confusion is complete with the presence of interstratified sediment being used to reject a melt-out hypothesis in favour of one of lodgement (Kirkby, 1969).

It is clearly of interest to resolve the problems associated with property P_1. What options are available? A till which possesses only P_1 can be ruled not to be a lodgement till but it may be a melt-out or flow till. Yet, some possible alternatives have been omitted. Following Jarnefors (1952) and Virkkala (1952), P_1 might result from subglacial shearing. To deal with this possibility more information on P_1 is required. For instance, if the stratified sediments include primary sedimentary structure such as cross-lamination, the layers cannot represent shear zones. Following West and Donner (1955), the property P_1 might result from multiple advances, but, using the argument of Goodchild (1875), if this hypothesis involves undue complexity it should be rejected as unlikely. For instance, the multiple advance hypothesis should be rejected if P_1 occurs and the stratified deposits are found at numerous stratigraphic levels and are laterally discontinuous. We may accept the weight of evidence from modern glaciers and the probability that interbedding of diamicton and sorted sediment involves sediment flow. Or, we may follow Crosby (1896) and question the wholesale application of observations on modern glaciers, by showing that there are inaccessible

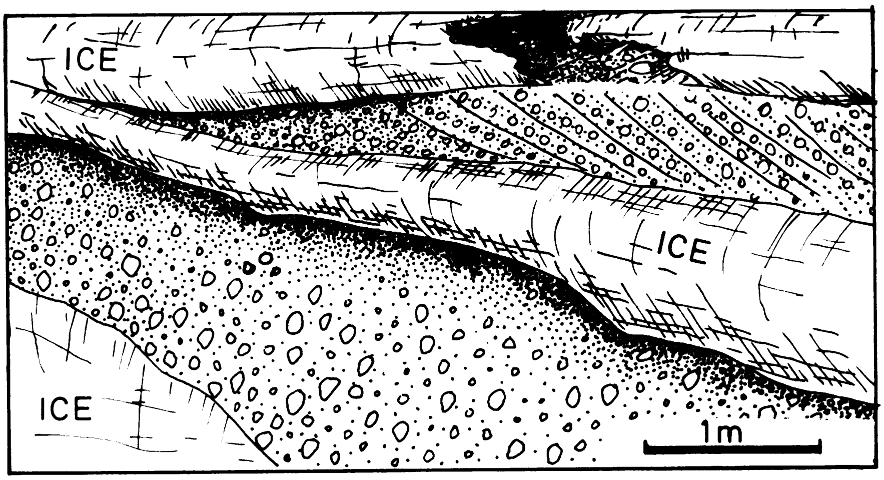

Fig.5 Large scale cross-stratified gravel (maximum thickness about 1 m) intercalated with glacier ice. Note that the cross-stratification is associated with local thickening of the gravels.

parts of modern glaciers in which depositional processes may differ considerably from those at the surface. Direct evidence of such processes would greatly strengthen this case. Finally, we might attempt to show that, despite observations on modern glaciers, the details of some ancient till/stratified sediment complexes are incompatible with a flow origin.

Sorted englacial sediments in modern glaciers

Broad areas of sediment covered stagnant ice, in some cases several square kilometres in extent occur beyond the active margins of many modern glaciers (Gripp, 1929; Okko, 1955; Suprycynski, 1955; Price, 1973; Wronkowski and Olszewski, 1977; Kilger, 1979; and many others). There are arguments as to whether regional stagnation or marginal accretion of stagnant ice occured, but these are not relevant here. The important fact is that ice, which is not moving, is covered by a sediment complex. Also important, is the probability that the stagnant ice includes much of the former basal zone of the glacier in which debris is expected to be concentrated. These ice bodies waste away by melting under the privacy of their overburden and it is only rarely that this process is observed. However, where such ice was open to view, Boulton (1972, p. 374) noted that it was penetrated by complex tunnel systems and a large number of englacial stream segments were to be observed. Okko (1955, p. 83) noted water emerging under hydrostatic pressure from stagnant ice and later wrote (p. 86):

> Thus, the aforementioned opening must in the present author's view be situated here too between two sheets of ice and represent the point of discharge of the englacial flowing stream.

Healy (1975) noted extensive tunnel systems within stagnant ice beyond the active margins of Taylor Glacier, Antarctica, and similar features occur at Wright Lower Glacier in the same general area (Rains and Shaw, in press).

The above observations suggest that englacial stream passages through debris-rich ice should lead to the interbedding of sorted sediment and till as envisioned by Goodchild (1875) and Crosby (1896). A small glacier in central Norway, Omnsbreen (Fig. 1), provides important evidence in this regard. Omnsbreen, which has wasted rapidly in recent years, is said to be climatically dead (Messel, 1971; Liestøl, 1980). Stagnant ice occupying small depressions to the east of the present glacier margin is covered by a variety of sediments and is associated with landforms such as eskers, kames, and kettle holes (Liestøl, 1980). A small westward flowing stream has dissected a portion of this stagnant ice revealing complex intercalations of glacier ice and stratified sediments (Fig. 2). The sediments show a variety of sedimentary structures including large-scale cross-bedding, small-scale cross-lamination and ripple formsets, flat beds, and parallel lamination. Their grain size ranges from gravel to clay.

The sorted sediments are clearly *in situ* as they are seen to be accumulating at present in englacial cavities and the current generated structures are closely related to present drainage directions. Only limited occurrence of such deformation structures as faults and down-warping resulting from subsidence illustrates that deposition is a rapid process relative to melting of underlying ice. However, differential thickness of underlying ice will cause local disruption of the sediments upon final ice melt. The extremely sharp and tight contact between sediment and overlying ice is most striking. This contact undulates in harmony with the bed topography of the fluvial sediments, or, where the bed topography is flat, is extremely planar (Figs. 3 and 4). Sedimentary structure and texture are highly variable over short vertical distances (Fig. 4). Large-scale cross-stratification is associated with local increase in height of passages and appears to be a result of deposition at flow expansions (Fig. 5).

The englacial passages are a form of thermokarst produced by running water. Rapid fluctuations in discharge and the potential for total or partial abandonment of passage segments explain the rapid variations in structure and texture. Passages may remain open because melting occurs more rapidly than closure by ice deformation or because of hydrostatic pressure exerted by the melt water. Once the water is removed, either because of falling discharge or abandonment, ice deformation causes closure and the tightly sealed, conformable contact between ice and stratified sediments.

The ice between the stratified sediments happens to be clear in this example. However, if, as is probable under many circumstances, this ice had been debris rich we can easily predict the sediment sequence. Final melting of the ice bodies would produce interbedded stratified deposits and melt-out till. The contacts between till and sorted sediments are expected to be sharp, and delicate sedimentary structures and bed forms may be preserved at and close to these contacts. Local faulting and warping may occur but these are not inevitable. The tills will retain some properties derived from glacial transport and, in particular, any englacially derived preferred orientation should be preserved. As the meltwaters migrate downwards, interbedding of meltwater and till deposits may be best developed in the lower part of the sequence, although the

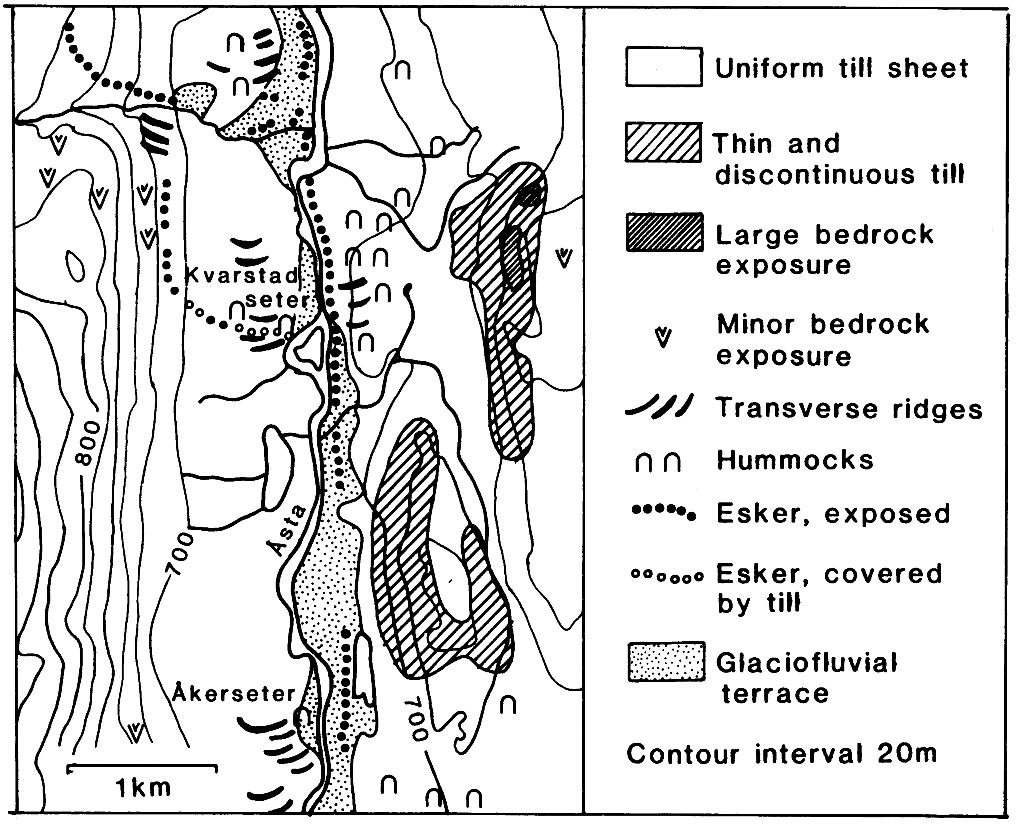

Fig.6 Glacigenic landforms in Åstadalen.
Mainly after Østeraas (in press).

structure of the debris-rich ice may be influential in this respect.

The observations at Omnsbreen show that interstratified sorted sediments and tills may result from contemporaneous deposition of the two components. In addition, Harrison (1957) suggested that interstratification could occur as a result of the englacial transport of sediment "rafts". Direct observations on modern glaciers show that both subglacially and supraglacially derived sediments may be transported englacially with a high degree of preservation of primary structure (Dort, 1967; Shaw, 1977; Boulton, 1979). Given the melt-out process as described from modern glaciers (Boulton, 1971; Lawson, 1979), such sediment rafts should be preserved in melt-out tills.

Discussion

Interstratification of tills and stratified, sorted sediment is produced by the interplay of water transport and sediment flow and/or melt-out processes. Evidently, property P_1 is not in itself diagnostic of either sediment flow or melt-out. The original assertion that interpretation must rest on a conjunction of properties stands. A combination of stratigraphic and fabric analyses is recommended. In addition, the details of the interrelationships between sedimentary units, any associated tectonic features, and landform analysis may add weight to any interpretation of till genesis. We will illustrate this approach using sediments and landforms in Åstadalen, Norway.

Åstadalen

Brief regional description

The Åstadalen area in southeastern Norway is an upland area between the Norwegian main valleys Gudbrandsdalen and Østerdalen (Fig. 1). In a Norwegian context Åstadalen is a broad valley with gentle sides and slopes from 800 m a.s.l. in the northern part to about 600 m a.s.l. 30 km further towards the south, which gives an average gradient of 0.4°. The valley is surrounded by upland areas and mountain plateaus with peaks up to 1100 - 1200 m a.s.l.

The main and last regional direction of ice movement was from the northwest, that is parallel with the valley. Most of the morphological features have a NW-SE extension, which in most cases reflects the bedrock structures rather than accumulation of glacigenic deposits (Haldorsen, in press).

The ice may have been active until the end of the Weichselian and the deglaciation phase was most probably during the mid Preboreal (Haldorsen, in press; Sørensen, 1979). It has been widely accepted that regional ice stagnation occurred in large parts of central Scandinavia during the deglaciation phase (Reusch, 1901, p. 88; Mannerfelt, 1940, 1945; Holtedahl, 1953), and the ice sheet was then supposed to have downwasted so that the mountainous and upland areas first became free of ice. This stagnation model is considered valid for relatively flat inland valleys and depressions, where in the absence of high mountains in the upglacier direction ice supply was severely restricted during deglaciation. These characteristics apply to Åstadalen, and its upland position relative to Gudbrandsdalen and Østerdalen probably caused a rather early stagnation compared with these two neighbouring main valleys (Haldorsen, in prep.). There are no signs of former active glacier fronts in the Åstadalen area.

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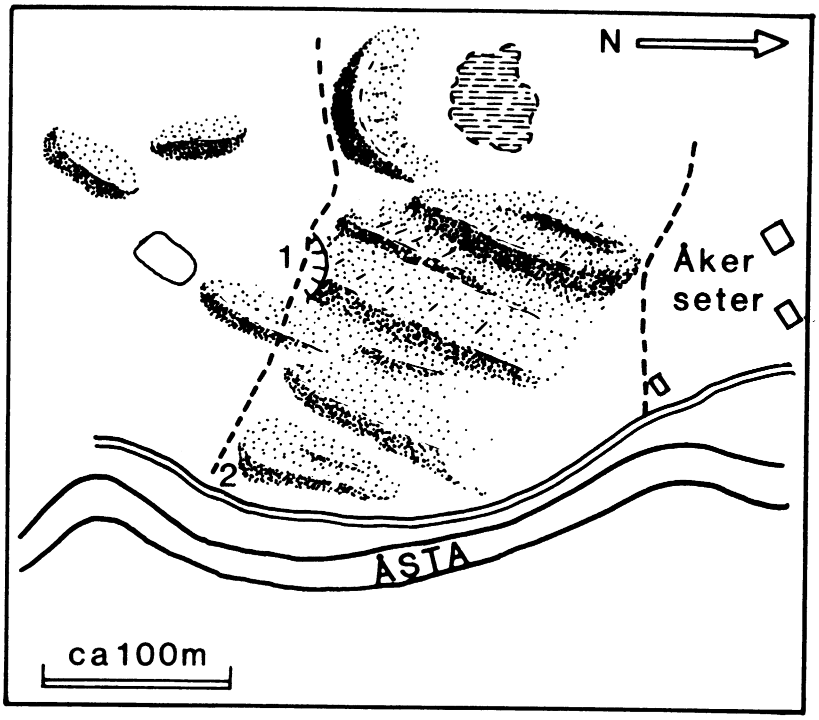

Fig.7 Transverse ridges at Åkerseter.

Glacial sediments and landforms

The main Quaternary deposits in Åstadalen are subglacially deposited tills which form a rather smooth sheet of 1-5 m thickness. Lodgement till dominates and is characterized by a relatively high content of silt and abraded boulders and cobbles (Haldorsen, 1981). This lodgement till seems to rest directly on the bedrock and at most localities is considered to be the oldest Quaternary sediment.

Transverse ridges occur at several places along the western valley side (Fig. 6). They are partly irregular, and partly more regularly arcuate, with the convex side pointing downstream. Their southeastern slopes are usually steeper than the northwestern ones (Fig. 7). They occur in groups forming a fish-scale pattern. The lengths of the ridges is from 50 to 200 m, the height from 2 to 8 m and the width ranges between 20 and 60 m. They occur mainly proximal to, and along valley constrictions and bedrock ridges.

The ridges consist dominantly of diamicton which in most cases contains lenses and bands of sorted sand and silt. The content of silt and clay is generally lower than in the lodgement till (Fig. 8).

The lateral parts of the ridges, i.e. towards the valley side, contain gravel sized material with a degree of roundness comparable with that of the lodgement till (Fig. 9), while towards the center of the valley the ridges include more rounded gravel, comparable with that of glaciofluvial sediments in Åstadalen (Fig. 9).

Hummocks occur along the valley bottom and are most frequent in the east (Fig. 6). They are formed both of glaciofluvial material and of diamicton. This diamicton is generally coarser than that composing the transverse ridges (Fig. 8).

The hummocks are interpreted as supraglacial, with deposition by lowering, debris flow, and water transport (Haldorsen, in prep.). The low content of silt and clay indicates a thorough winnowing of fines by water during the transportation and deposition.

Glaciofluvial sediments also occur as small feeding eskers along both valley sides and as a marked continuous esker along the river Åsta (Fig. 6). Close to the center of the valley there are low terraces of glaciofluvial material. Both the central esker and the terraces contain gravels with a relatively high degree of roundness which have been interpreted as deposits formed in the main drainage channel during the deglaciation phase.

The glacial history of the area is interpreted as follows:

1) An active glacial phase with basal sliding and deposition of lodgement till along large parts of the valley (Haldorsen, in prep.).
2) A more passive glacial phase with sliding in smooth, flat and wide parts of the valley, and stacking or folding of basal ice where bedrock obstacles or valley constrictions retarded the ice flow. Such constrictions are for instance found between Kvarstadseter and Åkerseter. Deposition of glaciofluvial esker material in a subglacial tunnel along the center of the valley. Locally, short melt-water channels with low energy might have flowed underneath and within the ice and formed zones and lenses of sorted sediments.
3) Deglaciation of upland areas to the east, north and west. Lateral drainage channels along the eastern valley side show that the ice surface in the valley was nearly horizontal indicating

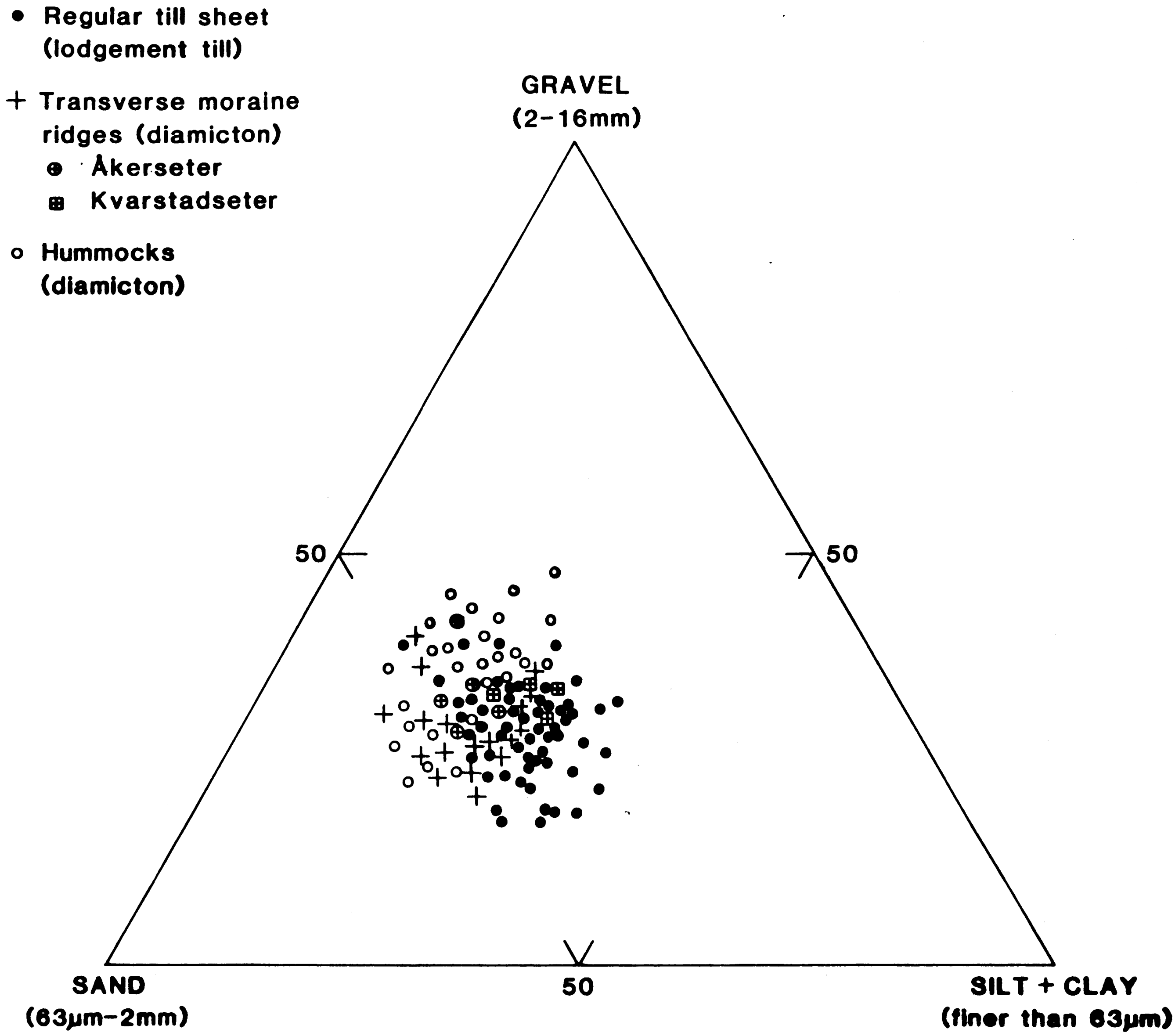

Fig.8 Ternary diagram showing grain sizes of tills and other diamict sediments in Åstadalen.

that the glacier was now nearly stagnant (Østeraas and Haldorsen, in prep.). Feeding eskers show a subglacial penetration of melt-water from ice-free mountain areas down to the central tunnel along the valley bottom. Parts of the originally subglacial till were transported subaerially from the valley sides to the ice surface by mass movement and running water. This is believed to be the main source of supraglacial sediments.

4) Only ice remnants occurring in the valley. A subaerial, ice-walled channel drained most of the melt-water through the valley. Earlier deposits were cut by this stream, and a glaciofluvial plain was formed along the center of the valley (Østeraas and Haldorsen, in prep.). Theoretically phases 3 and 4 should have been the main phases of deposition of melt-out till and flow till, because of great melting from below and above, and the presence of water-saturated debris and till.

Åkerseter

At Åkerseter there is a series of transverse ridges, with a regular fish-scale like morphology (Fig. 7). To the northeast, along the center of the valley the ridges are cut by the central melt-water channel. The ridges are surrounded by a lodgement till sheet (Fig. 6) and drilling indicates that material of the same type underlie the ridges in some places.

Sediments. - A single large exposure in the ridges at Åkerseter reveals a predominantly sandy diamicton in the lower parts with a distinct silt bed occurring towards the top of the section (Fig. 10). The silt bed is

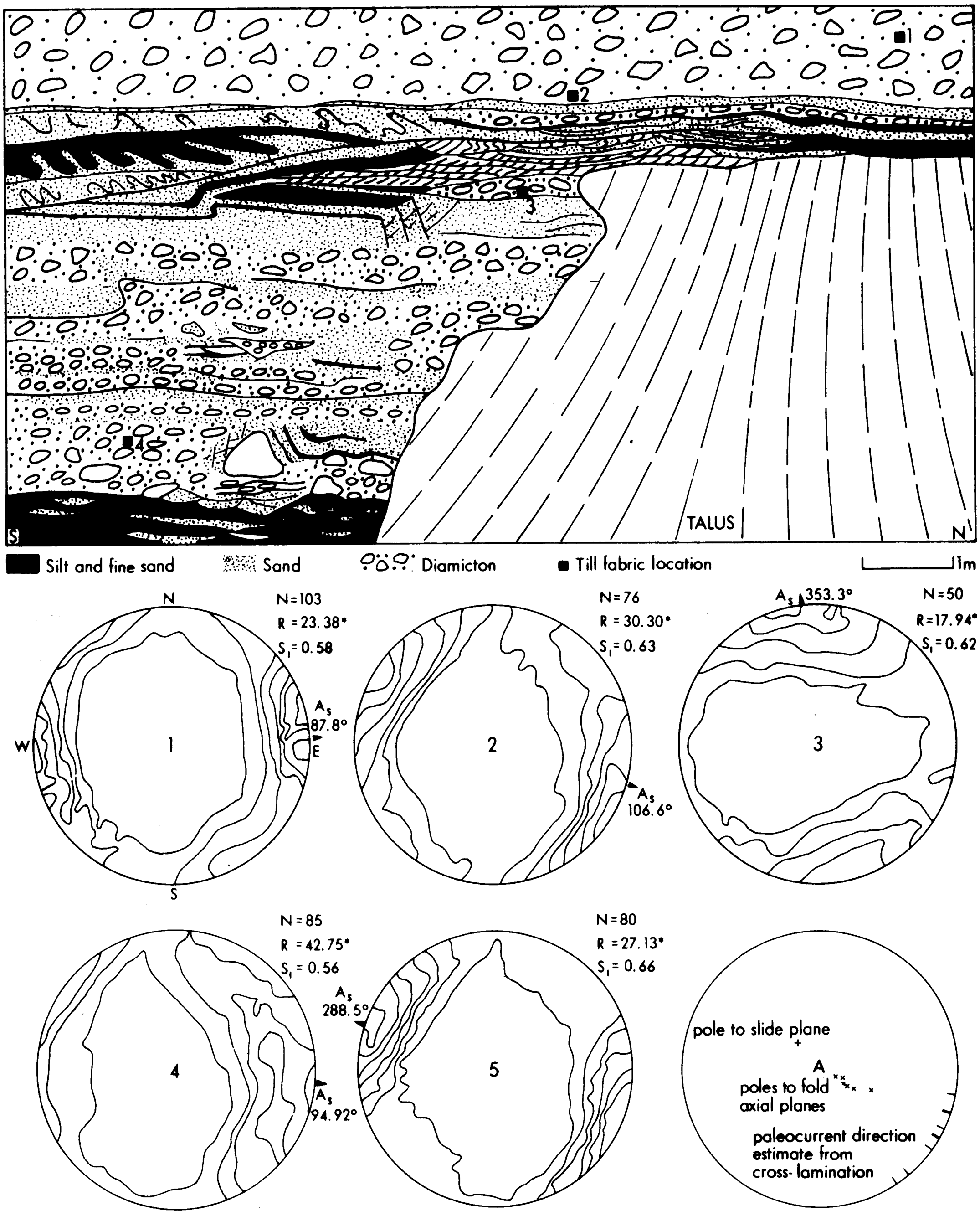

Fig.12 Details of the sedimentary sequence at Kvarstadseter. See Fig.10 for explanation of the fabric diagrams, and Fig.11 for the location of fabric 5. Poles to deformation fold axial planes and slump slide planes. Paleocurrent estimates from cross-stratification.

Stacking of basally transported debris occurred in the Kvarstadseter area. Much of this debris was reworked by englacial and subglacial melt-waters associated with the esker. Thermal erosion, such as is seen in the present day at Omnsbreen, produced cavities and local slumping within these produced the diamictons and the deformation structures in the stratified sediments. Where there was maximum water reworking the resultant melt-out till is expected to be relatively thin. This is seen to be the case (Fig. 11). Interpretation of the fabric pattern is limited by an incomplete knowledge of the processes by which stones become orientated in ice. It is to be expected that, in an area of basal stacking, the stacked zones themselves become obstacles to flow and cause local flow diversion. Mickelson (1973) showed that fabrics are relatively sensitive to subtle changes in ice flow direction. We may conclude that although a systematic pattern of preferred orientations parallel to the regional ice flow direction is evidence in favour of melt-out, the absence of this property need not be evidence against this interpretation. The melt-out interpretation may be sustained by an argument that the consistent preferred orientations reflect late stage ice movements perhaps associated with flow deflection caused by the embryonic ridges. The preservation of the transverse ridges may also be taken in favour of melt-out as ridges formed by redistribution of supraglacial debris are not expected to show close relationships with the characteristics of the glacier in its active phase.

In summary, the case for a melt-out origin for the Åkerseter ridges is confidently presented. The origin of the Kvarstadseter deposits, and the upper diamicton in particular remains problematical. Despite relatively detailed study we have been unable to produce an argument which in balance favours a melt-out or till flow genesis for this upper diamicton. The Åkerseter case is typical of many in which it is not possible to make a confident interpretation of till genesis. The two alternatives must be considered plausible until the appearance of some more sensitive criteria are available to resolve this problem.

Conclusion

The presence of sorted, undisturbed sediments interbedded with till (P_1) indicated that the sequences at Åkerseter and Kvarstadseter were formed in areas of stagnating ice. The problem is to distinguish between melt-out facies and flow facies. At Åkerseter the preferred fabric parallel to the direction of ice flow (P_2) indicated a melt-out genesis. At Kvarstadseter this interpretation may suit the upper, homogeneous part of the section, while the fabric of diamictons interbedded with sorted sediments indicates a deposition by flow. The interpretations have been based bothon observations in sections and on the regional environments of the sediments. No absolute proof can be given, we have argued on the basis of a balance of probability, and we consider the interpretations given above as more probable than other relevant interpretations.

Aknowledgements. The excursion to Omnsbreen was guided by Olav Liestøl. Steinar Skjeseth gave important informations about the esker sediments at Kvarstadseter. Ronald May helped with the statistical analysis of the orientation data. To these persons we tender our sincere thanks.

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PAPER 7

GRAIN-SIZE DISTRIBUTION OF SUBGLACIAL TILL AND ITS RELATION TO GLACIAL CRUSHING AND ABRASION

SYLVI HALDORSEN

Grain-size distribution of subglacial till and its relation to glacial crushing and abrasion

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BOREAS

Haldorsen, Sylvi 1981 03 01: Grain-size distribution of subglacial till and its relation to glacial crushing and abrasion. *Boreas*, Vol. 10, pp. 91–105. Oslo. ISSN 0300-9483.

A subglacial till formed from a sandstone bedrock has a variable grain-size distribution which reflects its variable genesis. Glacial comminution processes were simulated by artificial mill experiments with fragments of the sandstone bedrock. Pure crushing caused disintegration along mineral boundaries into separate minerals, most mineral grains retaining their primary size during the crushing process. Abrasion produced cracks across the minerals and resulted in silt-sized rock flour. The experiments indicate that most of the sand-sized till material formed as a result of crushing, while the silt is mainly the result of abrasion. The sand and silt are both regarded as components resistant to further glacial comminution, but are formed by different comminution processes. By considering also the coarser till material, the general principles of glacial breakdown of resistant rocks from boulders to sand or silt can be illustrated. A matrix index and an abrasion index based on the mill experiments distinguish well between genetically different subglacial till types.

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As pointed out by Dreimanis (1971), Haldorsen (1975), Karrow (1976) and Raukas et al. (1978), grain-size parameters are among the most commonly used in modern classification and description of tills. In Norden, a full classification of till based on such parameters was introduced on Swedish maps as early as 1930 by G. Lundqvist (in Högbom & Lundqvist 1930:70–87). Grain-size studies commonly concern polylithological tills, since a till deposit usually consists of material from different bedrock types. However, grain-size data for tills consisting dominantly or totally of material from one single bedrock type have also been published, e.g. in the works of Granlund (1934), G. Lundqvist (1940:23–28, 1951:27–32), J. Lundqvist (1952) and Dreimanis & Vagners (1971).

The present study concerns the grain-size composition and grain-size variability of a monolithological till from a sandstone bedrock area. The main purpose was to explain the relation between bedrock, glacial comminution processes, and the grain-size composition of the till. The till studied is rather thin and relatively coarse-grained, with the clay content rarely exceeding 4%. Similar tills are characteristic of the greater part of Norway where coarse-grained and/or hard bedrock types dominate. Jørgensen (1977) pointed out that Norwegian tills are texturally very similar to those described from central Finland (see e.g. Kivekäs 1946; Virkkala 1969a) and to till from the Canadian Shield Province (see Scott 1976). Similar till types also dominate in central and northern Sweden (cf. G. Lundqvist 1940, 1943, 1951; J. Lundqvist 1952, 1958, 1969). Much of the following discussion should therefore also apply to tills from many areas outside Norway where resistant bedrock dominates.

Description of the investigated area

Åstadalen valley in southeastern Norway (Fig. 1) was chosen for this investigation because of its rather homogeneous bedrock and continuous till cover. In a Norwegian context this valley is wide with relatively gentle valley slopes and is surrounded by undulating mountain plateaus to the east, north and west. The area is situated some kilometres south of a suggested main ice divide for the Weichselian (P. Holmsen 1951), and thus lay beneath the central part of the Scandinavian ice sheet. Regional investigations of the Quaternary sediments and studies of glacial striae show that an early ice movement was from the north. Later, during the deglaciation phase, the movement was from a more northwesterly direction, parallel to the valley of Åstadalen (Fig. 1).

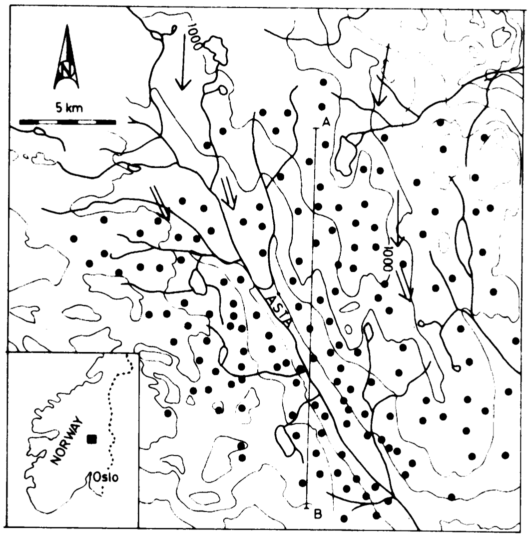

Fig. 1. Location map showing the position of till sample points (dots). The direction of ice movement is given by arrows, oldest movement by single arrows, youngest movement by double arrows. Contour interval 100 metres.

A late Precambrian sandstone formation (greywacke and arkose) makes up the bedrock within the investigated area and extends further northwards to the suggested ice divide. The sandstones are dominated by quartz, microcline, albite and muscovite. Further north, another sandstone formation with similar texture and composition to the bedrock in the investigated area is found.

Description of the till

Samples were collected from subglacial till which forms the main Quaternary deposit within the area. The average till thickness is 3–5 m with the bedrock rarely exposed except at the highest mountain areas. The surface morphology is mainly controlled by the bedrock structures and the till cover is usually not thick enough to create independent landforms. Deep till exposures suitable for fabric analyses are few, but some fabric analyses indicate that part of tne till was transported and even deposited during the early phase when the ice movement was from the north. However, new till material was introduced during this later phase, and a great amount of the material which may have been transported during the earlier phase was then certainly transported parallel to the Åstadalen valley. The total

Table 1. Unnatural variability of two till samples.

	Gravel % (-5Φ to -1Φ)	Sand % (-1Φ to 4Φ)	Silt + clay % (finer than 4Φ)
Sample 1			
$\bar{X}$	35.3	36.7	28
S	2.4	1.3	1.3
Sample 2			
$\bar{X}$	28.2	39.8	32.0
S	3.6	2.0	1.5

till texture is supposed to be mainly dependent on the young ice movement.

Drilling as well as road cuts showed one till bed which is apparently homogeneous vertically; distinct zones with sorted material and boulder or cobble pavement were not observed.

The sand grains of the till appear fresh and unweathered and the gravel clasts are angular to subangular. No inclusions of old soils or water-transported Quaternary sediments were found in the investigated till. The total till material is therefore regarded as glacially comminuted, unweathered bedrock, suitable for studies of the effects of glacial comminution processes.

Sampling and laboratory methods

Till samples were collected from about 150 localities in the main valley and on the surrounding mountain plateaus (Fig. 1). As far as possible, random sampling was carried out and approximately one sample, generally taken at 1 m depth, was collected in each square kilometre. They were treated in random order to avoid systematic error caused by field and laboratory procedures. At some localities, samples were collected from several till depths, but systematic vertical grain-size variation was never observed.

In general, only the material finer than -5Φ (32 mm) was analysed. Samples of 5 kg were sieved in the laboratory and the size-distribution of material finer than 4Φ (63 μm) was determined by hydrometer analysis. Description of boulder and cobble material was done visually in the field. The size grades are classified mainly according to Wentworth (1922), but gravel is used instead of granules and pebbles, and the boundary between silt and clay is placed at 9Φ units (2 μm).

To estimate the variability due to sampling

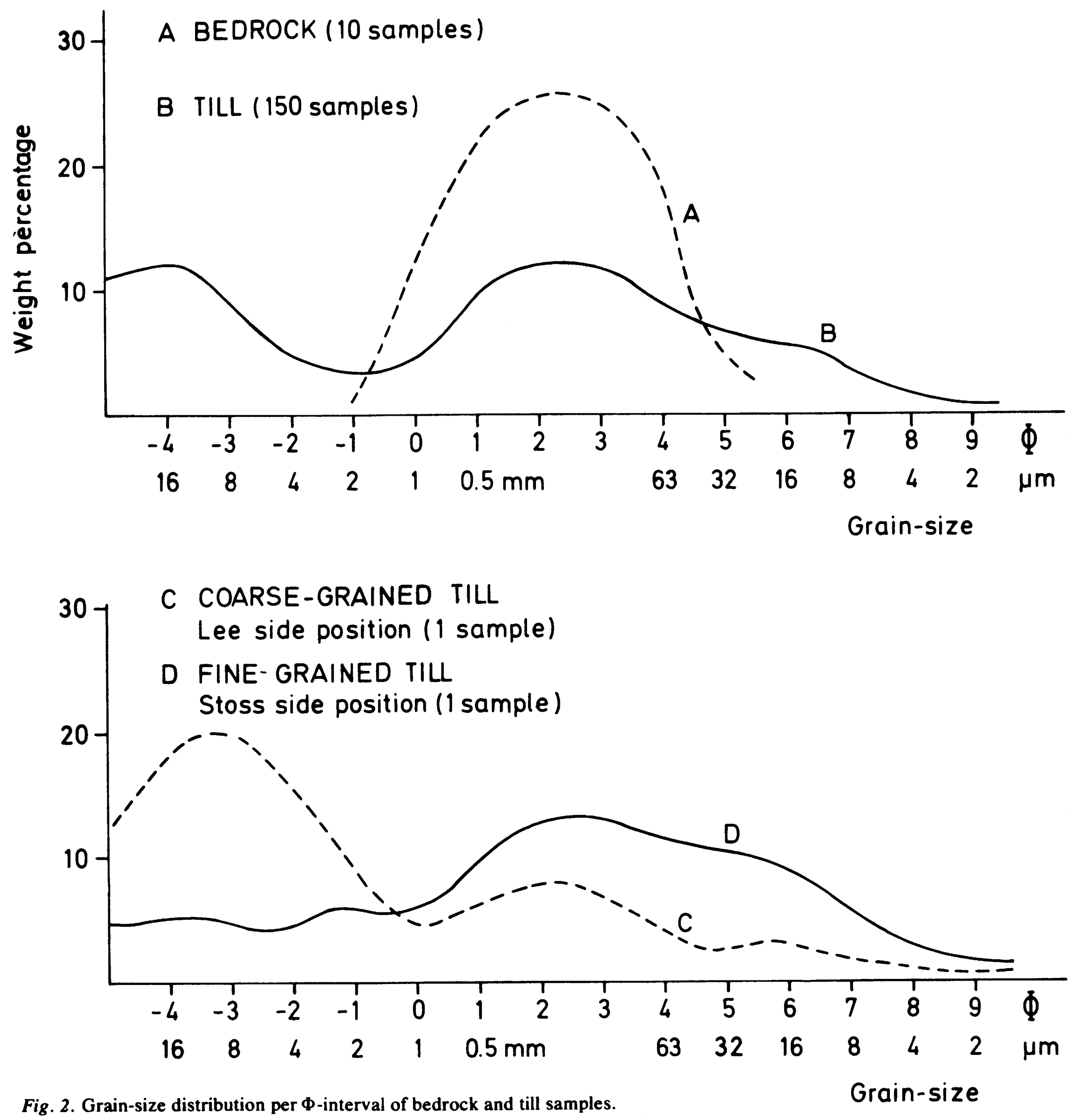

Fig. 2. Grain-size distribution per Φ-interval of bedrock and till samples.

methods and analytical errors, samples from each of two randomly selected localities were split into eight subsamples in the manner described by Koch & Link (1970:326). The results are given in Table 1.

Textural analysis of bedrock samples was carried out on thin section and acetate peels. It is well known that such measurements give smaller grain diameters than obtained by a sieving analysis (e.g. Van der Plas & Tobi 1965). For each i-th Φ-interval of bedrock minerals studied by thin sections, there will be an error X_{i-1} of material which actually belongs to the $(i-1)$th Φ-grade and has to be subtracted, and an error X_i of material which has been measured to the $(i+1)$th interval and which has to be added. Since the shape of minerals varies in different grades, for instance, depending on the distribution of mica, the X_i value will vary from grade to grade. To obtain correction factors well suited for the present study, ten till samples were sieved and thin sections were made of material in each Φ-interval ranging from 2Φ (250 µm) to 5Φ (32 µm). The percentage of material which fell outside its respective Φ-interval by the thin section measurements was regarded as the error

X for this grade. Correction factors were then worked out for each Φ-interval based on the 'average error' of the ten samples. These have been applied for the data presented later in the paper.

Results and discussion

The relation between till matrix and bedrock

The close relation between the grain-size composition of tills and the textural properties of the parent rocks is well known and was clearly pointed out many years ago by Granlund (in Magnusson & Granlund 1928:76–88) and Krumbein (1933). The comminution of mineral grains and rock fragments during glacial transport has been discussed by several authors (e.g. G. Lundqvist 1951:27–32; Hörner 1944, 1946; J. Lundqvist 1952; Virkkala 1969b; Beaumont 1971; Dreimanis & Vagners 1971; Haldorsen 1977, 1978; Boulton 1978).

A very clear relationship between the till matrix and the granulometric composition of the bedrock is shown in Fig. 2. The sandstone bedrock is mainly composed of mineral grains of size −1 to 5Φ units surrounded by a silty matrix (Fig. 2A), and with a mode in the 1–4Φ fraction. In all till samples a fine-grained mode is found in the medium to fine sand fractions, which reflects the primary size distribution of grains in the bedrock. This mode is distinct in coarse-grained samples (Fig. 2C) as well as in fine-grained samples (Fig. 2D). Since the content of rock fragments, that is multimineral grains, relative to separate mineral grains is very small within the till mode fractions, the mode is interpreted as the disintegration of bedrock, mainly along grain boundaries, into uncomminuted, separate mineral grains during glacial transport. The disintegration along grain boundaries and the relatively great resistance of separate mineral grains to glacial comminution have been demonstrated also for till from low metamorphic clastic sedimentary rocks found elsewhere in eastern Norway (Haldorsen 1977) and seem to be commonly associated with such rock types (Haldorsen 1978). This is also indicated by the works of G. Lundqvist (1951:29) and J. Lundqvist (1952:34).

Till matrix composition and its relation to glacial comminution processes

The comminution of subglacial drift along the base of a temperate glacier results from different processes. Cracking of particles along planes of weakness may for instance be caused by percussion, compression, or by frost action. These processes are part of the crushing. In addition, the comminution process in common also includes attrition, which produces a fine-grained rock flour and gives smooth, striated bedrock and boulder surfaces. From the grain-size distribution curves of the tills, it may be very difficult or impossible to determine how much of the comminution is the result of crushing and how much resulted from attrition. This point is further complicated by the fact that the most intensive crushing presumably takes place in the zone of traction at the base of the glacier where the most intensive attrition also occurs. Boulton (1978) concluded that the product of glacial crushing in general is coarser than 1Φ (0.5 mm), while the product of glacial abrasion is dominantly finer than 1Φ. Dreimanis & Vagners (1969, 1971) and Haldorsen (1977) described mineral modes in subglacial till which are finer grained than 1Φ, but did not discuss the process of crushing versus the process of attrition.

To distinguish between different comminution processes, two series of ball mill experiments were carried out, with crushing and abrasion of sandstone bedrock samples. In the first series of experiments several bedrock samples were crushed in wet and dry conditions. The experiment was designed to reduce attrition between grains and between grains and the mill balls to a minimum. A rather moderate speed was chosen, and repeated grinding for five-minute intervals was carried out. After each individual experiment the grain-size distribution of the crushed material was determined; the successive curves for one of the samples are shown in Fig. 3. During the first five grinding intervals, the grains were gradually crushed from size −5Φ (32 mm) to sand. After the fifth time of grinding, repetition of the process did not reduce the grain size significantly, and the sand-sized material seemed to be rather resistant to comminution at this arbitrary mill speed.

The mill speed, the size of the mill balls, and the water content of the material were changed several times, and in each case a certain plateau in the crushing process occurred when the mate-

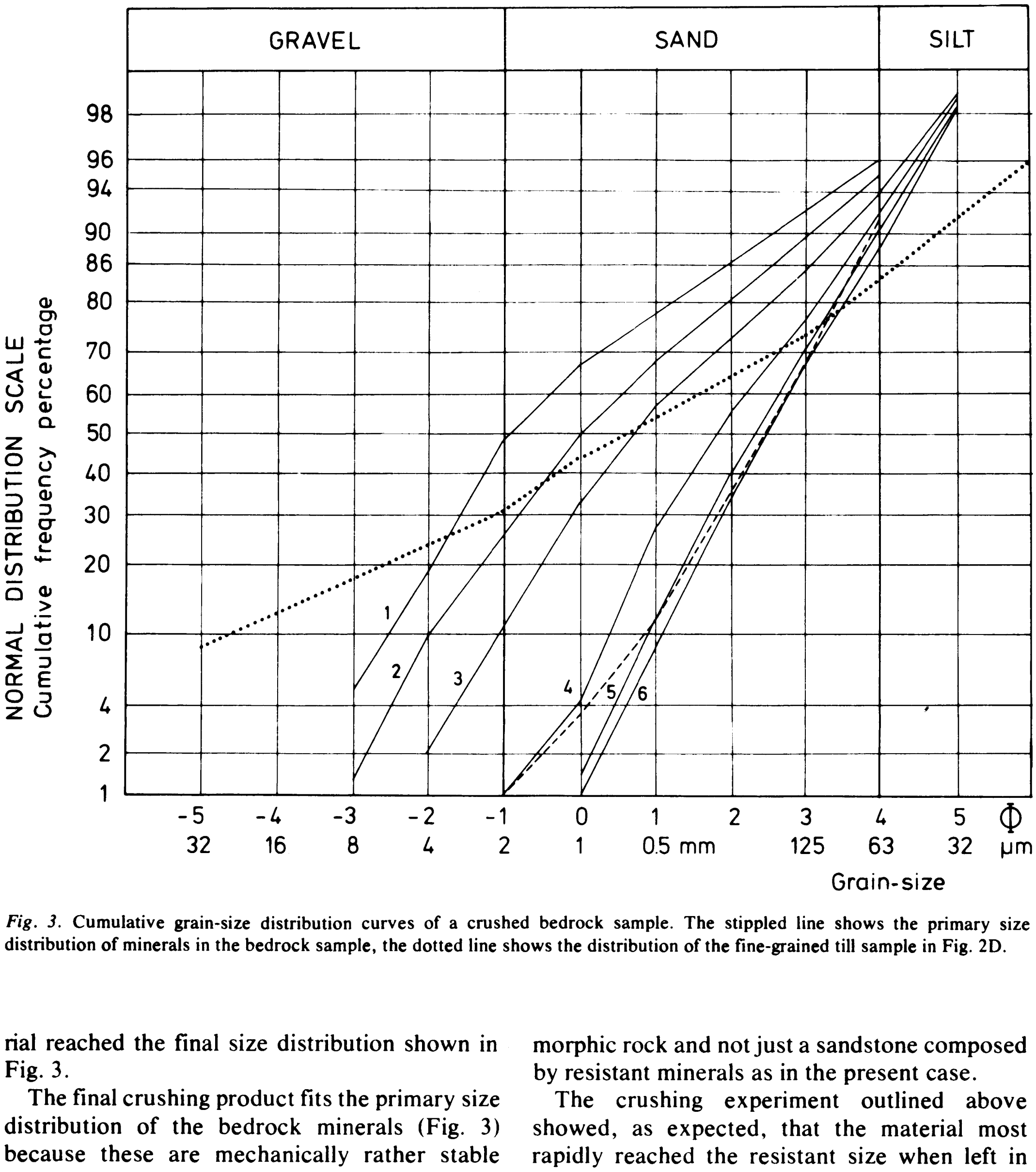

Fig. 3. Cumulative grain-size distribution curves of a crushed bedrock sample. The stippled line shows the primary size distribution of minerals in the bedrock sample, the dotted line shows the distribution of the fine-grained till sample in Fig. 2D.

rial reached the final size distribution shown in Fig. 3.

The final crushing product fits the primary size distribution of the bedrock minerals (Fig. 3) because these are mechanically rather stable constituents from a clastic, sedimentary rock (Haldorsen 1977, 1978). However, for industrial crushing it has been shown that the energy needed to crush a quite homogeneous material beyond a fine sand to coarse silt size is generally very great compared with the crushing of coarser material (Rittinger 1867; Bond 1952). This is certainly the reason why till matrix modes of separate mineral grains are commonly found in sand and coarse silt (Dreimanis & Vagners 1969, 1971), even when the source rock has been a relatively coarse-grained igneous or metamorphic rock and not just a sandstone composed by resistant minerals as in the present case.

The crushing experiment outlined above showed, as expected, that the material most rapidly reached the resistant size when left in water for a couple of days between each separate crushing process. Wet grinding should be most representative of crushing at the base of a temperate glacier where the water present will penetrate all fractures within the rock fragments and mineral grains, and promote disintegration along such planes (Haldorsen 1978). The crushing is here further promoted by the process of freezing and thawing (Dreimanis & Vagners 1969:97). Under such conditions the resistant particle size can obviously be reached even after a short transport distance (Haldorsen 1977:23).

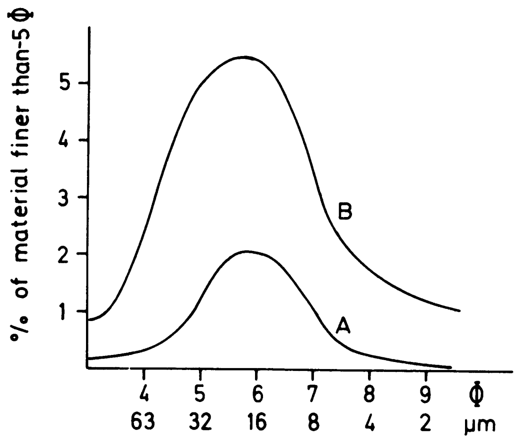

Fig. 4. Size distribution per 1Φ interval of: A. The fine-grained material formed by attrition of sandstone bedrock fragments. B. Calculated fine-grained abrasion material of the till, average of 150 samples.

In the second mill experiment series, sandstone fragments of size −5 to −4Φ (32 to 16 mm) were exposed to attrition. The mill balls were removed and the mill was filled up so much that crushing by percussion did not occur. The comminution process was thus mainly restricted to abrasion along the contact points between particles.

When the fragments had reached the same degree of roundness as the subangular gravel clasts within the till, the grain-size distribution contained 6% of fine-grained rock flour, dominantly of coarse to medium silt size (Fig. 4A). A considerably finer material was therefore formed in this way than by pure crushing (Fig. 3).

The two series of mill experiments show, with great probability, that the mineral mode found in the till (Fig. 2B), which corresponds to that in the crushed material (Fig. 3), is the result of glacial crushing and not attrition. The same may well be the case for many mineral modes described by Dreimanis & Vagners (1969, 1971) and by Haldorsen (1977).

Generally, position of those till matrix modes which are the result of crushing depends on the resistance and primary size of the minerals in the source material. Material from fine-grained source rocks, particularly from easily eroded types, will give matrix modes within much finer grades than those of the material under consideration. The lower boundary at 1Φ (0.5 mm) for the product of crushing estimated by Boulton (1978) can therefore not represent a general lower boundary for glacial crushing.

Most subglacial tills, even those from coarse-grained Norwegian bedrock, are rather rich in silt-sized material (Jørgensen 1977: fig. 10). The tills under discussion have a silt content which is far too great to be explained only by the process of glacial crushing. The greater part of the silt is probably formed by glacial abrasion. This is indicated by the two series of ball mill experiments (Figs. 3 and 4).

It has been attempted to divide the till material finer than −5Φ into three parts; these are the resistant crushed component, the abraded component and the multimineral component. The first step was to calculate the amount and size distribution of crushed, resistant mineral grains (Fig. 5, area A). This calculation is based on the conclusions earlier in the paper that the minerals are not significantly crushed beyond their primary size during the glacial transport and that the content of multimineral grains in the matrix grades 1 to 4Φ is very low. In addition, the attrition experiment showed that glacial abrasion contributes little material to grades 1 to 3Φ (Fig. 4). The total material within these grades was thus regarded as mineral grains of primary size and the total distribution of such grains (area A) was calculated from the size distribution of bedrock minerals given in Fig. 2A. Area B represents then the 'excess' of fines which is regarded as the product of attrition. Area C represents the coarser, dominantly multimineral grains which could have undergone further glacial comminution and finally become mainly crushed material contributing to area A.

All the till samples contain more resistant crushed material than fine-grained abraded material. The content of abraded material varies from sample to sample. In fine-grained till samples (e.g. Fig. 2D) it may constitute up to 20% of the total material finer than −5Φ, in coarse-grained samples (e.g. Fig. 2C) it can be less than 5%. The size distribution of this material, however, is rather constant. It ranges from coarse silt to clay, but the content of clay is small (Fig. 4B), and there is a distinct mode in the medium to coarse silt class, like that produced by the attrition experiment (Fig. 4A).

The size distribution produced by crushing will obviously in many cases overlap with that from abrasion. When the source rocks are very soft or fine-grained, the final crushing mode may even occur in just the same size class as the

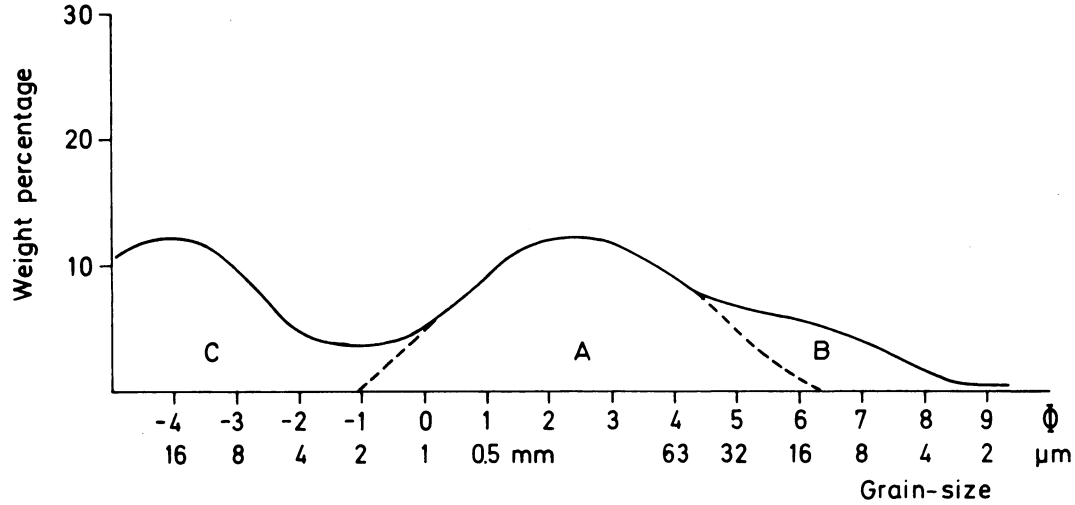

Fig. 5. Grain-size distribution per 1Φ interval of 150 till samples (average value). Area A: Calculated resistant crushed component. Area B: Supposed component from abrasion. Area C: Mainly multimineral grains.

abrasion mode, and it is then quite impossible to distinguish between the two processes. The material finer than 1Φ (0.5 mm), which Boulton (1978) suggested to be the product of abrasion, may then very well be caused by a combination of intensive crushing and attrition, both taking place in the zone of traction at the base of the glacier. The boundary at 1Φ which he supposed differentiates between crushed material and abraded material, may reflect the boundary between the 'clast-sized mode' on the one hand and the 'matrix mode' on the other. A similar bimodality also results from pure crushing processes and has been described in several papers (Dreimanis & Vagners 1969, 1971; Beaumont 1971).

The glacial comminution processes in general

Based on the conclusions in the preceding section and observations by other till investigators (e.g. Dreimanis & Vagners 1971; Virkkala 1961:221–222) the general principles of glacial comminution of hard rocks dominated by sand-sized material are illustrated in Fig. 6. Crushing of boulders and cobbles (Fig. 6A) produces mainly gravel. A part of the gravel is further crushed to dominantly sand and silt. The amount and distribution of sand and silt is dependent on the bedrock type (Dreimanis & Vagners 1971; Haldorsen 1978) and on the intensity of the crushing process. The process of abrasion (Fig. 6B) affects mainly the coarsest clasts and only to a lesser extent the gravel. It gives a little sand, but the matrix material will be dominated by silt (Fig. 4). The combination of crushing and abrasion gives a till rich in both sand and silt (Fig. 6A + B). In time the crushing will affect dominantly the gravel, since coarser clasts which are surrounded by gravel and matrix are then actively abraded but not crushed. The combination of abrasion and crushing will thus give a negative correlation between gravel and sand and between gravel and silt (Fig. 6C) as is commonly observed in Norwegian tills (Jørgensen 1977), even in cases when the crushing from gravel to silt-sized material has been rather unimportant, as in the present case.

For samples from till types where crushing and abrasion have been combined, there is in the present case a positive correlation between sand and silt (Fig. 6A + B), but when crushing has been quite dominant there is no correlation between these two components (Fig. 6A). This is because the transition from sand particles to silt has been unimportant. Both the sand and the silt + clay can be regarded as the final, resistant products of glacial comminution, but formed by different glacial comminution processes. This is a relation which should apply also to other tills from bedrock similar to that described from Norway.

Buller & McManus (1973) studied a large

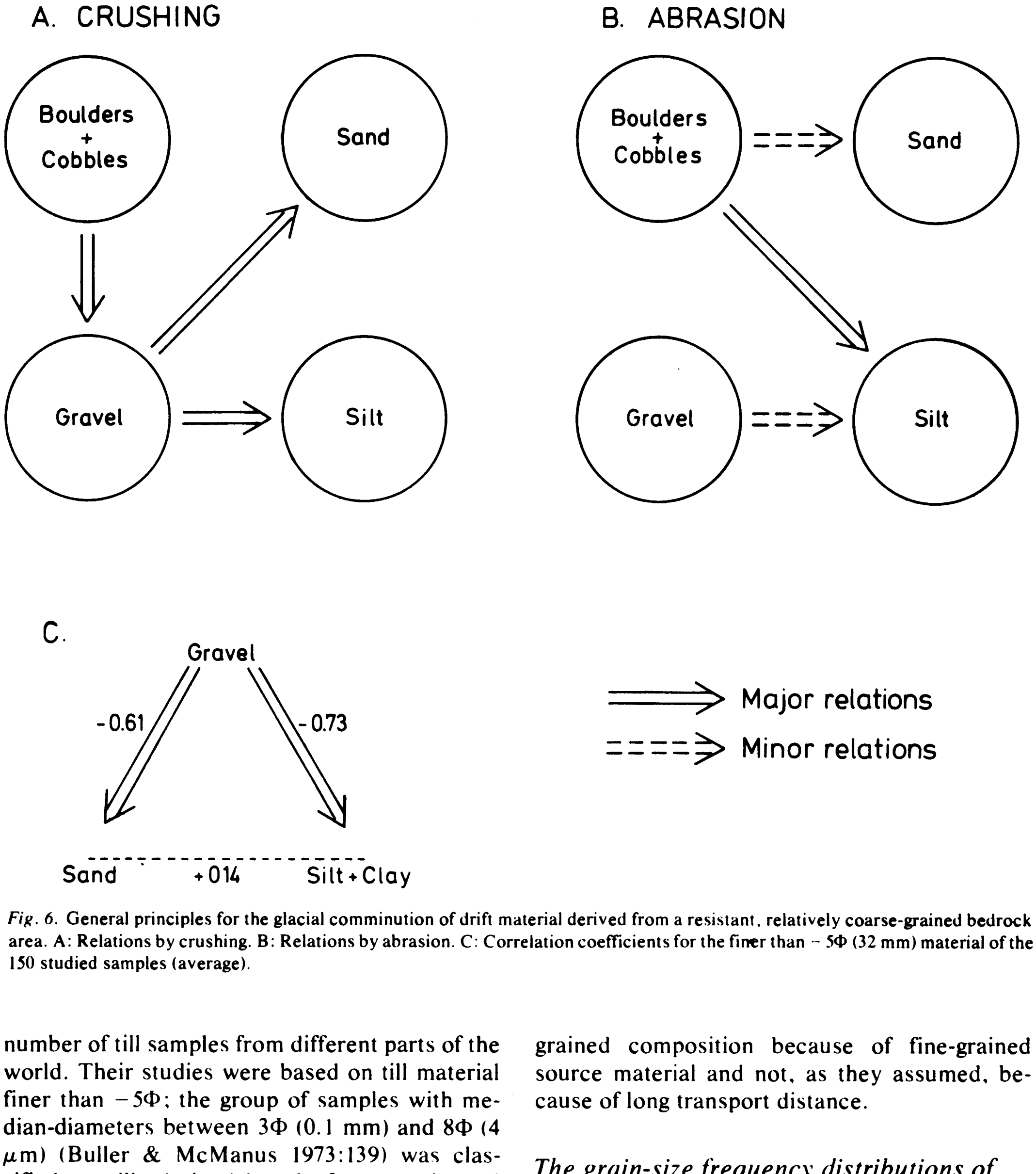

Fig. 6. General principles for the glacial comminution of drift material derived from a resistant, relatively coarse-grained bedrock area. A: Relations by crushing. B: Relations by abrasion. C: Correlation coefficients for the finer than -5Φ (32 mm) material of the 150 studied samples (average).

number of till samples from different parts of the world. Their studies were based on till material finer than -5Φ; the group of samples with median-diameters between 3Φ (0.1 mm) and 8Φ (4 μm) (Buller & McManus 1973:139) was classified as 'tills derived largely from continental ice sheets often some distance from their mountain sources'. The conclusions presented here, the works of Dreimanis & Vagners (1969, 1971) as well as many general till descriptions (e.g. G. Lundqvist 1951:27–32; J. Lundqvist 1958:50–57; Virkkala 1969a) indicate, however, that coarse mineral material is commonly not crushed or even abraded so much that the median value of the respective tills occurs in the fine silt grades. The fine-grained material described by Buller & McManus (1973) therefore probably has a fine-grained composition because of fine-grained source material and not, as they assumed, because of long transport distance.

The grain-size frequency distributions of subglacial till

The grain-size frequency distributions of tills may in some cases be better described by a Rosin–Rammler distribution than by a log-normal distribution (Krumbein & Tisdel 1940; Kittleman 1964). However, as the Rosin–Rammler distribution is calculated for uniform material, a subglacial till may consist of two different Rosin–Rammler distributions; one for 'clast-sized' material, and one for monomineralic material (Dreimanis & Vagners 1969:97). Buller &

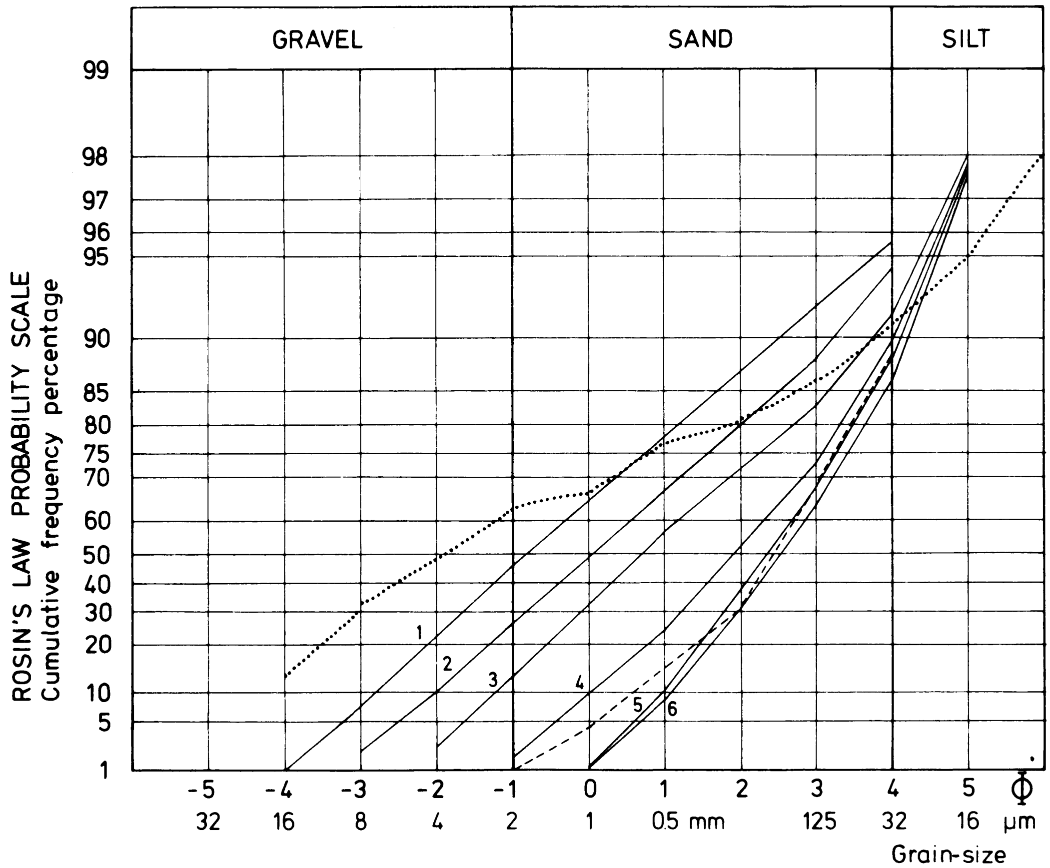

Fig. 7. Cumulative grain-size distribution curves of a crushed bedrock sample on Rosin's law probability paper. The stippled line shows the primary size distribution of minerals in the bedrock sample. The dotted line shows the distribution of the coarse-grained till sample in Fig. 2C.

McManus (1973:140) supposed that short transported debris agrees well with Rosin's law of crushing, but they found that deposited till deviated much from this distribution, and everywhere approached a log-normality.

The grain-size distribution curves of the crushed sandstone bedrock sample from Åstadalen are shown on Rosin's law paper in Fig. 7 and on normal distribution paper in Fig. 3. After each of the first three individual crushing experiments the distributions agreed well with Rosin's law of crushing; shown by the straight lines in Fig. 7 and the more curved lines in Fig. 3. However, the 'goodness of fit' to Rosin's law was best for the coarse material, and the final resistant material obtained a more log-normal distribution corresponding closely to the log-normal distribution of the grains in the bedrock (Figs. 2A & 7). This and the results of Haldorsen (1977, 1978) indicate that final grain-size distributions of tills should be similar to those of associated clastic sedimentary source rocks.

However, only a few of the till samples studied here agreed as a whole with either of the two distribution types discussed above. Till samples dominated by coarse-grained material deviated much from the Rosin–Rammler distribution (Fig. 7), while fine-grained till samples (e.g. Fig. 2D) deviated much from the log-normal distribution of the bedrock minerals (Fig. 3). Each till sample consisted of different subpopulations, as was also observed by Vagners (1969) for till from a homogeneous bedrock area in Ontario, Canada.

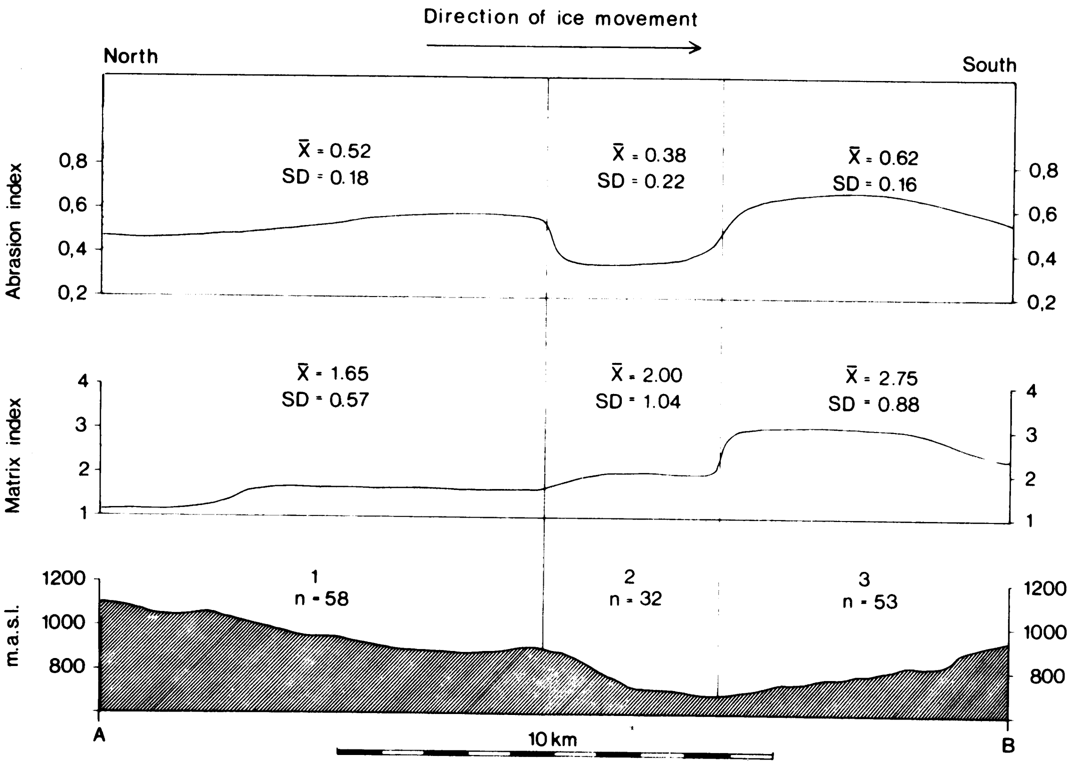

Fig. 8. Schematic N–S topographical profile (A–B in Fig. 1) showing the variation of the matrix index = (A + B)/C in Fig. 5 and the abrasion index = B/A in Fig. 5. $\bar{X}$ = average value, SD = standard deviation, *n* = number of samples in each subpopulation.

Such complex distributions are the result of different factors, for instance the gradual supply of coarse and recently eroded material during glacial transport, the loss of particles from the system by deposition, and what is probably most important for the matrix composition – the combination of glacial crushing and abrasion (Dreimanis & Vagners 1969:97). Other factors which in this study only play a minor role but which in general are important for complex till distributions, are textural and lithological inhomogeneities of the source rocks, and erosion of weathered soil material and soft Quaternary sediments. As pointed out by Dreimanis (1970) such lithologically inhomogeneous tills will only in a few cases obtain a log-normal grain-size frequency distribution.

For most tills, including those from a homogeneous bedrock area, one should thus expect much more complex grain-size frequency distributions than supposed by Krumbein & Tisdel (1940), Kittleman (1964) and Buller & McManus (1973).

The granulometric composition of the till and its relation to topography and till genesis

The amount of matrix material relative to the amount of 'clast-sized' material in tills may be an expression of the intensity of glacial comminution. In the present case, the limit between the 'clast-sized' material and the matrix can be placed at -1Φ (2 mm) (see Fig. 5). The ratio between the matrix and the clast material finer than -5Φ (32 mm) may be regarded as a resistance index or a matrix index for the till, expressed by the ratio of area A + B and C, where the meaning of A, B and C is shown in Fig. 5.

The amount of material formed by attrition relatively to the resistant material formed by crushing can give information about the glacial erosion processes. It may also indicate whether or not the material has been glacially transported in the zone of traction. An abrasion index has been calculated for each till sample as the ratio between areas B and A, and also in this case the meaning of A and B is the same as in Fig. 5.

Fig. 8 shows the variation of the matrix index and the abrasion index along a profile A-B parallel to the early glacial movement. The position of the profile is shown in Fig. 1. The data given in the figure are based on the total number of samples with the same general topograhical position and not just on those positioned directly on the profile. Based on these two indices the till can be divided into three significantly different subtypes, each with a characteristic topographic position (Fig. 8 and Table 2).

The matrix index is lower in till type 1 than in other subglacial till types from Åstadalen (Fig. 8), and the difference between this and other types is even greater if the till material coarser than -5Φ (32 mm) is considered. This type is found on the highland plateaus situated in the northeast and east (Figs. 1 and 8). Here the till cover is generally very thin, and the bedrock is frequently exposed on the highest upland elevations where there is an irregular topography on stoss as well as lee sides. The till has a great frequency of cobbles and boulders which are mainly angular or subangular. Such till types frequently occur in mountainous areas in the central part of the former Scandinavian ice sheet (see e.g. G. Holmsen 1956:38–40, 1960:46–49; J. Lundqvist 1969:129); their formation has been described as the result of extending glacial flow (Minell 1978, 1979) which has resulted in glacial erosion rather than deposition. It has been supposed that the rate of basal sliding of the glacier was small within such areas and that the deposition was mainly by a melt-out process (Minell 1979).

Important components during the formation of this till were certainly the large fields of boulders formed by frost weathering in the highest mountain areas (see J. Lundqvist 1969:53). Boulders from such fields were frequently incorporated into the glacier by overriding and during the short transport crushed to cobbles and gravel. The result is a till in which the coarsest clast component is usually dominating and where the matrix index is low.

The abrasion index is not particularly low in till type 1 (Fig. 8). A certain amount of abrasion occurred in the area which is also shown by the presence of abraded and striated clast material in the till. Even though only a small amount of material was formed by abrasion it has a significant influence on the abrasion index in this area where the matrix content is so small.

Till type 2 is found on the eastern valley side (Fig. 8). The thickness is variable, and on the upper slopes of the valley it rarely exceeds 3m. The bedrock exposures are few, however. The till has a rather complex genesis which may result from different subglacial processes during the two glacial phases. This is reflected by the great standard deviation of both the matrix index and the abrasion index (Fig. 8). Till with a low abrasion index may have been formed during the early phase when this area had a lee-side position relative to the ice movement. During the late glacial phase, the material was more abraded. However, the typical lee side till which is of a subglacial melt-out type occurs particularly at localities in a lee-side position relatively to the late ice movement. The 'lee-side till' in Table 2 mainly includes samples from such localities. Some of these samples are rich in sand relative to gravel, giving a rather high matrix index. The abrasion index for lee-side samples, however, is significantly lower than for other till types (Table 2), reflecting that, even when an intensive crushing occurred, the glacial attrition was unimportant. Similar properties could be associated also with other subglacial melt-out tills.

Complex till populations with great variation in the content and composition of the matrix material, like the till along the eastern valley side, should be commonly associated with areas where the direction of ice movement and the conditions along the base of the glacier have changed from time to time. During the deglaciation phase in Norway, as well as other places, the water present along the base of glaciers promoted high rates of basal sliding and thereby also great abrasion. This is certainly one of the main reasons why the subglacial till in Norway is so commonly characterized by abraded boulders and a considerable amount of silt-sized material.

Table 2. Student's *t*-test values for the matrix index and abrasion index of different subglacial till types in the Åstadalen sandstone area.

		Matrix index	Abrasion index
Type 1 $n = 58$	Type 2[a] $n = 14$	0.95	5.24**
Type 1 $n = 58$	Type 3 $n = 53$	9.86**	3.40**
Type 2 $n = 14$	Type 3 $n = 53$	4.32**	8.41**

[a] Only samples in lee-side position.
** Significant difference at a 1% level of significance.

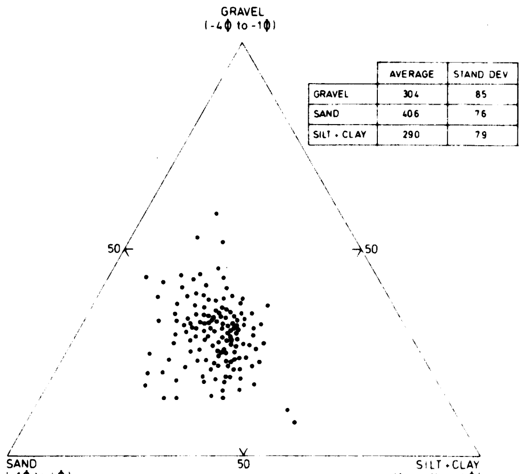

Fig. 9. The distribution of till samples in a triangular diagram.

Till type 3, which is found along the western valley side, is significantly richer in resistant material than till type 2. Till type 3 is positioned on stoss sides relative to the early N–S direction of glacial movement.

The matrix index of till type 3 is significantly higher than that for other till types (Fig. 8 and Table 2). The abrasion index is also rather high, and when the entire till is considered the amount of material formed by attrition is significantly greater here than elsewhere in the area. The rate of transport in the zone of traction was considerable and caused both strong crushing and attrition. Also the dominance of striated boulders and the great compactness and fissility of the till show that the material has been transported and comminuted at the base of an active temperate glacier and mainly deposited by a lodgement process.

Any stoss-lee-side effect relative to the late ice movement was not observed along this valley side. It may be that the main glacial process then was a transport, without any strong comminution, of material formed in stoss-side position during the early glacial phase (Fig. 8). This is also indicated by the very uniform vertical matrix composition, even at the few localities where the fabric reflects both the early and the late glacial movement.

Throughout the investigated area, the values of the matrix index and the abrasion index are strongly dependent on the main topographical features which have determined the intensity of glacial erosion, transport, crushing and abrasion as well as the mode of deposition. The small scale topography, on the other hand, appears to have had no great effect on the till texture. There is, however, not always a positive correlation between the matrix index and the abrasion index since an increased matrix content is not always combined with an increase of abrasion relative to crushing, and vice versa. This is well demonstrated by the mountain plateau till and by the lee-side till.

The matrix index and the abrasion index are parameters designed just to fit the till material studied here. They give a clearer differentiation between the different subglacial till types than many other parameters, as for instance the mean size, sorting, kurtosis and skewness parameters of Folk & Ward (1957), the median diameter-quartile deviation relationship of Krumbein (1939) and three-component systems of gravel–sand–silt + clay and sand–silt–clay. However, to interpret the genesis of tills it is, in most cases, necessary to study also the coarsest till material in addition to the fine-grained part of it, and also other textural properties than the grain-size composition. The present investigation is no exception in this connection.

Comparison with tills derived from other Norwegian bedrock types

Jørgensen (1977) found that tills derived from different types of typical Norwegian resistant Precambrian bedrock can hardly be distinguished by means of grain-size parameters, because the granulometric variation of each such till type is too great. His data were based on a great number of till samples collected from various parts of Norway, and his conclusions were expressed in terms of three-component parameters.

Fig. 9 shows the position of the samples studied here in a triangular diagram with the components gravel, sand, and silt + clay. An upper gravel limit of -4Φ is applied to compare the data with those of Jørgensen (1977). The regional till variation is not seen from this diagram because it is not so marked when the gravel fraction -5 to -4Φ is not included, and because the three-component parameters in the present case do not distinguish so well between different till types as the matrix index and the abrasion index.

The standard deviations of the three grain-size components are shown in Fig. 9. The variability caused by sampling and laboratory procedures is small compared with the natural till variability (Table 1 and Fig. 9). Even though the present samples represent a till population with a minimum variability due to lithology of the source rocks, the natural variability is nevertheless considerable (Fig. 9). It is therefore to be expected that such tills as those commonly found in Norway have a regional variation which is at least as great as that of the present studied till.

This is also demonstrated by a comparison with subglacial tills from each of four coarse-grained bedrock areas studied by Jørgensen (1977). Those four till types were regionally sampled from different topographical positions in rather inhomogeneous bedrock areas in the central part of south Norway. F-test values show that those vary more than the till from Åstadalen; the differences are in most cases significant at a 5% level of significance (Table 3).

The Åstadalen till has average proportions of gravel, sand, and silt + clay which are 30, 41, and 29% respectively (Fig. 9). The silt and clay content is significantly greater than the average of tills from Norwegian Precambrian bedrock areas (Jørgensen 1977: fig. 10). This was also shown by Student's t-test values for each of the till populations listed in Table 3. However, this does not necessarily indicate that the sandstone bedrock in Åstadalen produced more fine-grained material by glacial erosion than the average of Norwegian Precambrian rocks. Differences in till genesis may be at least as important as the source rock variations. When some samples from supraglacial till were included in the present case, the average grain-size composition tended to be like the average of coarse-grained tills from Norwegian, Precambrian bedrock areas (Jørgensen 1977: fig. 10). In the case of such till types the variability is certainly more dependent on genesis than on lithology. Similar results have also been obtained by Slatt (1971) from Alaska, Mills (1977) from the Cordillera of Western North America and by Vagners (1969) from the Canadian Precambrian Shield.

On the other hand, the grain-size composition of the tills studied here (Fig. 9) differs very much from tills related to fine-grained Norwegian bedrock (Jørgensen 1977: fig. 10). In this respect the lithology is more important than the genesis. This clearly demonstrates how difficult it is to compare grain-size data from different tills when their exact genesis and source lithology are unknown, as for instance was attempted by Buller & McManus (1973).

Table 3. Comparison of the gravel, sand and silt + clay contents of subglacial till from the Åstadalen sandstone area and some other subglacial tills from coarse-grained crystalline bedrock areas. The comparison uses data from Jørgensen (1977). Upper numbers give the F-values, lower numbers give the t-values.

	Gravel (−4Φ to −1Φ)	Sand (−1Φ to 4Φ)	Silt + clay (finer than 4Φ)
Tunhovd	1.90*	1.08	2.04*
(N = 271)	4.40**	4.60**	0.15
Førsvatn	2.01*	1.16	2.30*
(N = 281)	2.20*	2.43**	2.55**
Rauddalsvatn	3.09*	1.52*	1.91*
(N = 232)	6.41**	1.08	19.25**
Flatstøldal	2.10*	1.62*	1.95*
(N = 400)	3.50**	18.39**	15.24**

* Significant difference at a 5% level of significance.
** Significant difference at a 1% level of significance.

To be sure that, an observed granulometric variation is really the result of a variable bedrock lithology, the following assumptions have to be satisfied.

(1) The texture and mineralogy of the source rocks have to be so different that the mineral modes, when the rocks are glacially crushed, are found in different size intervals.

(2) The source rocks of each till type have to be lithologically homogeneous or consist of closely related rock types. For the till populations listed in Table 3 this condition is not satisfied.

(3) The samples should be collected from genetically related till types. It is probably best to use samples from zones of lodgement till since the matrix modes are commonly better developed there than in melt-out types.

(4) Because of the great variability within each till type, a great number of samples and systematic sampling is needed. This is demonstrated by the present work and the work of Jørgensen (1977).

If these conditions are not satisfied, it is very difficult on the basis of granulometric data only, to decide whether the observed differences are the product of bedrock lithology, or for instance, of factors related to till genesis. And even when they are satisfied, the result may depend very much on the choice of significant parameters. Since the final differences in most cases are reflected in the till matrix mode; parameters based on the fine-grained till component are expected to be the best ones for such distinctions.

Many of the most frequently used grain-size parameters, as for instance the mean size, sorting, kurtosis and skewness parameters of Folk & Ward (1957), are worked out to fit sediments other than tills. It can, therefore, hardly be expected that they will in every case express the most important characteristics of a till material. More work is certainly needed to develop parameters which are specially designed to give information about tills. This was the case for the matrix and abrasion index in the present study.

Conclusion

Subglacial tills from a coarse-grained sandstone area have been studied. Crushing of the bedrock samples in a ball mill is assumed to represent glacial crushing. Initially, the grains were gradually reduced in size, and the size distribution corresponded to Rosin's law of crushing. Finally, the material became rather resistant to crushing and obtained a log-normal size distribution similar to that of the grains within the original bedrock sample. Mineral modes of the till material are found in the same size class as the mineral modes of the bedrock. The 'excess' of fine-grained material in the till, mainly silt, is considered to be the result of attrition. The transition of sand grains to silt or clay seems to have been insignificant. The resistant, crushed material and the abraded material are therefore regarded as independent components, and they compose the resistant part of the till. The grain-size distribution of the till material finer than -5Φ (32 mm) is rather complex, largely because of the gain and loss of particles during glacial transport and because glacial comminution processes include both crushing and abrasion.

Based on the ball mill experiment and the grain-size distribution of the till, two granulometric parameters are developed. The matrix index is the relation between the resistant till component (resistant crushed + abraded material) and the 'clast-sized' component finer than -5Φ (32 mm). The abrasion index is expressed as the relation between the abraded component and the resistant, crushed component. Variations of these parameters illustrate the difference between melt-out till, represented by mountain plateau till or lee-side till and lodgement till. The mountain plateau till is characterized by a low matrix index. This is mainly the result of a high supply of coarse bedrock material during glacial overriding. The typical lee-side till is characterized by a very low abrasion index, showing that the resistant part of the till material is formed here by the crushing of rock particles into separate mineral grains. The till is mainly rich in clasts, but some localities with a more sandy type occur, showing that the glacial crushing in cases has been intensive. In the lodgement till the matrix index is high and even though the abrasion index is not particularly high, the total amount of abraded material is considerably greater than in the other two till types.

Acknowledgements. – Tore Østeraas kindly placed a lot of grain-size distribution data at my disposal. Aleksis Dreimanis, Per Jørgensen, Jan Lundqvist and John Shaw gave constructive criticism of the manuscript. Grete Bloch and Jens Chr. Køhler carried out the laboratory work, Åslaug Borgan drafted the figures and Marie-Louise Falch has typewritten the manuscript. To all these persons I tender my sincere thanks. Financial support was provided by the Norwegian Research Council for Science and the Humanities (NAVF).

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PAPER 8

GEOCHEMISTRY OF SUBGLACIAL TILL MATRIX MATERIAL

SYLVI HALDORSEN

Haldorsen, S: Geochemistry of subglacial till matrix material.

The variation of main elements in subglacial till matrix material from Åstadalen, southeastern Norway is dependent on the source rocks and till genesis. In the north the bedrock consists of sandstones with some silty shale horizons and in the south and east of more homogeneous sandstones. In the north the ratio between sandstone and shale components in the silt+clay fraction was estimated from the grain-size distribution and the Al_2O_3: SiO_2 ratio of the till. The northern till is divided into two types which are partly related to different genesis.

A coarse melt-out till in the northeast has a matrix dominated by sandstone material while the lodgement till in the northwest contains more shale in the silt+clay and thus more Al_2O_3, K_2O and MgO. In the south the till is again divided into two types related to genesis. A sandy melt-out till in the southeast is dominated by crushed material. The material within each size grade has a composition similar to the corresponding grade in the bedrock and the silt + clay is relatively rich in SiO_2. The lodgement till in the southwest contains more silt + clay formed by abrasion. This is particularly enriched in feldspar and concequently contains more Al_2O_3 and Na_2O. Normal distributions of elements are expected in the lodgement till from the uniform southwestern sandstone area. In other parts of the area skewed or bimodal distributions occur, due to variable bedrock composition or variable till genesis.

Southeastwards from the sandstone/shale boundary a gradual dilution of shale fragments occurs roughly in the form of a negative exponential curve while the decrease of the Al_2O_3:SiO_2-ratio deviates much from an exponential curve because of the high background value of Al_2O_3:SiO_2. Lognormal distributions of the Al_2O_3:SiO_2-ratio can be expected near the bedrock boundary only.

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CONTENTS

INTRODUCTION

The geochemistry of tills is of interest for instance in agriculture and forestry, and the contents of heavy metals in tills have been widely applied in ore prospecting (see Jones 1973, 1975, Bradshaw 1975, Shilts 1976, Davis 1977). Based upon questionnaires with 150 questions concerning methods of till investigations, which was replied to by about 750 till investigators, Raukas et al. (1978) concluded that geochemical studies were rarely included in regular, regional till investigations.

The till geochemistry is dependent on both syngenetic and epigenetic factors (Fig.1) (Shilts 1976, Bølviken & Gleeson 1979). The syngenetic factors include:

1. the composition of the bedrock
2. the till forming processes, which involve glacial comminution (crushing and abrasion, Fig.1 factors A & B) and meltwater activity (Fig.1 factor C).

The epigenetic factors include the secondary water activity and soil weathering (Fig.1).

The aim of the study presented here has been to discuss the relations between the syngenetic factors mentioned above, and the till geochemistry. Based on these relations the geochemical variation in the total till and in separate grain-size fractions are explained, and the regional frequency distribution of elements in glacial till is discussed.

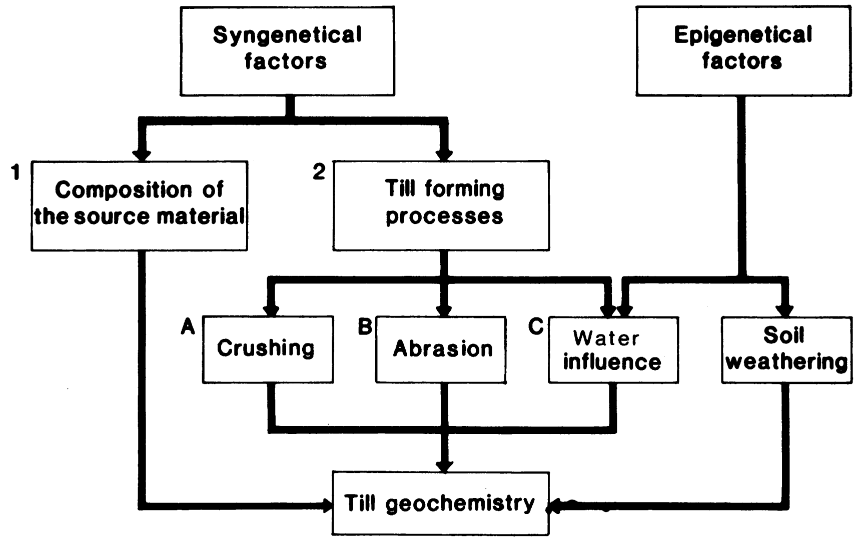

Fig.1 Factors influencing the geochemistry of tills.

THE STUDIED TILL TYPE

The till material was collected from the Åstadalen area in southeastern Norway (Figs. 2 & 3), where the bedrock consists of low metamorphic sedimentary rocks belonging to the Late Precambrian Brøttum Formation (Englund 1972, Fig.17). Detailed maps of the Quaternary geology (Østeraas 1978, 1981) as well as of the bedrock (Englund in press; Englund & Kirkhusmo in press) and detailed studies of genesis and grain-size distribution of tills (Haldorsen 1981, and in prep.) makes the area well suited for detailed studies of till geochemistry.

The material was collected from a reasonably continuous cover of till which in most cases is too thin to form independent landforms. Most of the till was deposited from the basal layers of the ice. Typical lodgement till as well as subglacial melt-out till occur. A more detailed discussion of the till genesis is given elsewhere (Haldorsen in prep).

The average grain-size distribution of 210 till samples is shown in Fig.4. The till is rather rich in coarse clast material and the matrix material (finer than -1 Φ (2 mm)) is dominated by medium sand and coarse silt. The clay content is below 4 %.

The till population in Åstadalen is typical for the upland parts of central Scandinavia (Holmsen 1963, Lundqvist 1977). Such tills are relatively thin (1-5 m) and dominated by coarse and rather shortly transported material (<5 km) (Jørgensen 1977, Lundqvist 1977). The following discussions

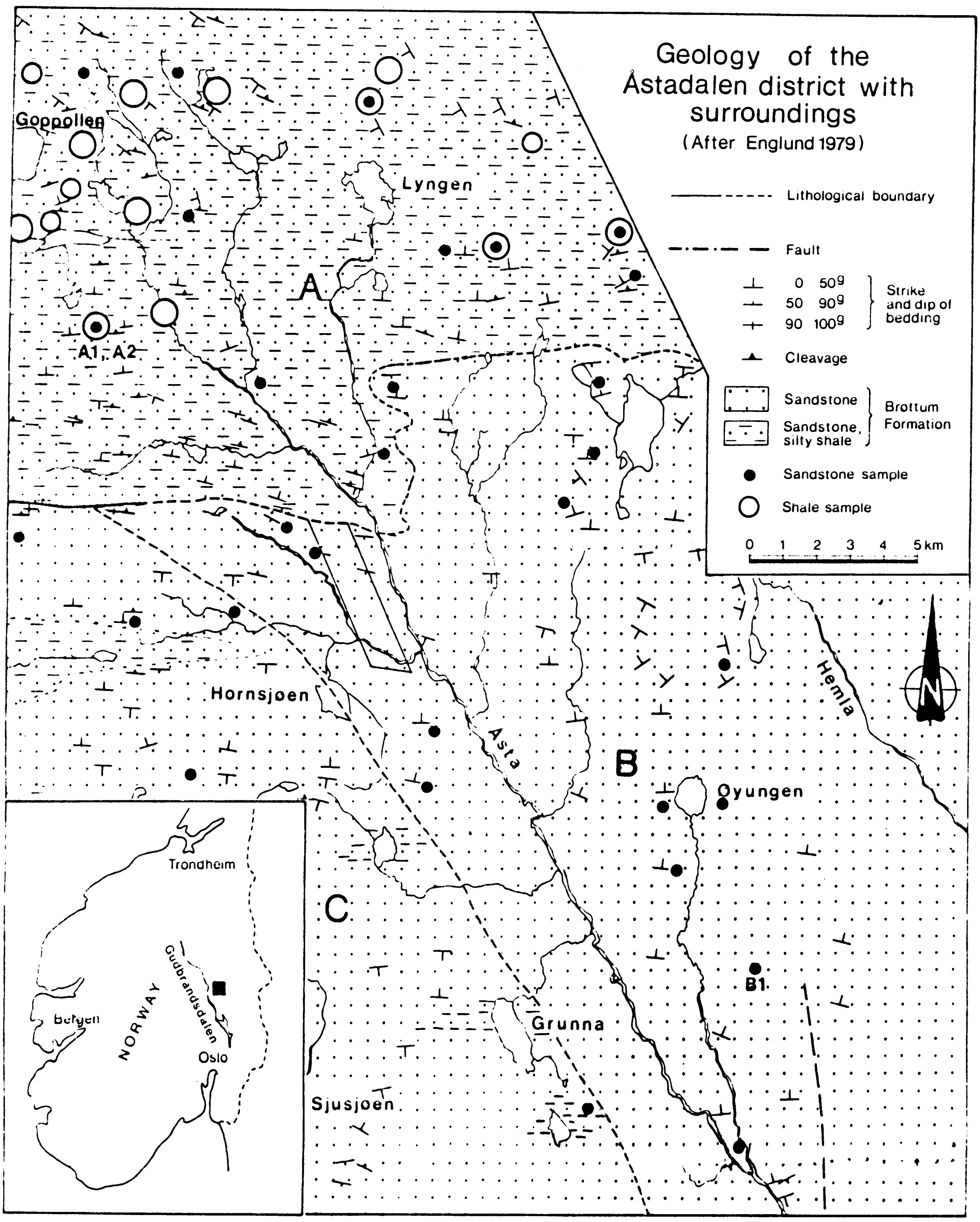

Fig.2 Bedrock map of the Åstadalen area, showing the sampling sites of analysed bedrock samples. A-C give the different regional lithofacies described in the text Framed: The area shown in Fig.23.

apply mainly to these types of till as opposed to those deposited closer to the margins of former continental ice sheets.

SAMPLING AND LABORATORY METHODS

The till samples were collected mainly at 1-2 m depth from sample sites shown in Fig.3. Normally one sample was taken, but at some localities additional samples were collected at distances of a few metres. Vertical sampling at each meter to maximum 5 m depth was carried out at 54 localities (Fig.3). For this, motor driven drilling equipment was used. Otherwise sample pits were hand-dug. All together 436 samples from the area have been analysed.

4 Φ (63 µm) was used as the upper particle size boundary for the routine samples, because the silt + clay is commonly used in geochemical studies (Shilts 1973, 1975; A.Bjørklund pers.comm. 1980). In addition several samples were fractionated at one Φ intervals from -1 to 9 Φ (2 mm to 2 µm). 40 samples were split into two subsamples for analyses in order to estimate the laboratory error. This error, which has been compared with the regional variability by variance analysis, was found to be negligible.

Bedrock samples were collected from most of the main exposures (53 samples, see Fig.2).

Before chemical analysis of the till, amorphous iron oxides were removed by the dithionite - citrate method (Mehra & Jackson 1960). The chemical Composition was

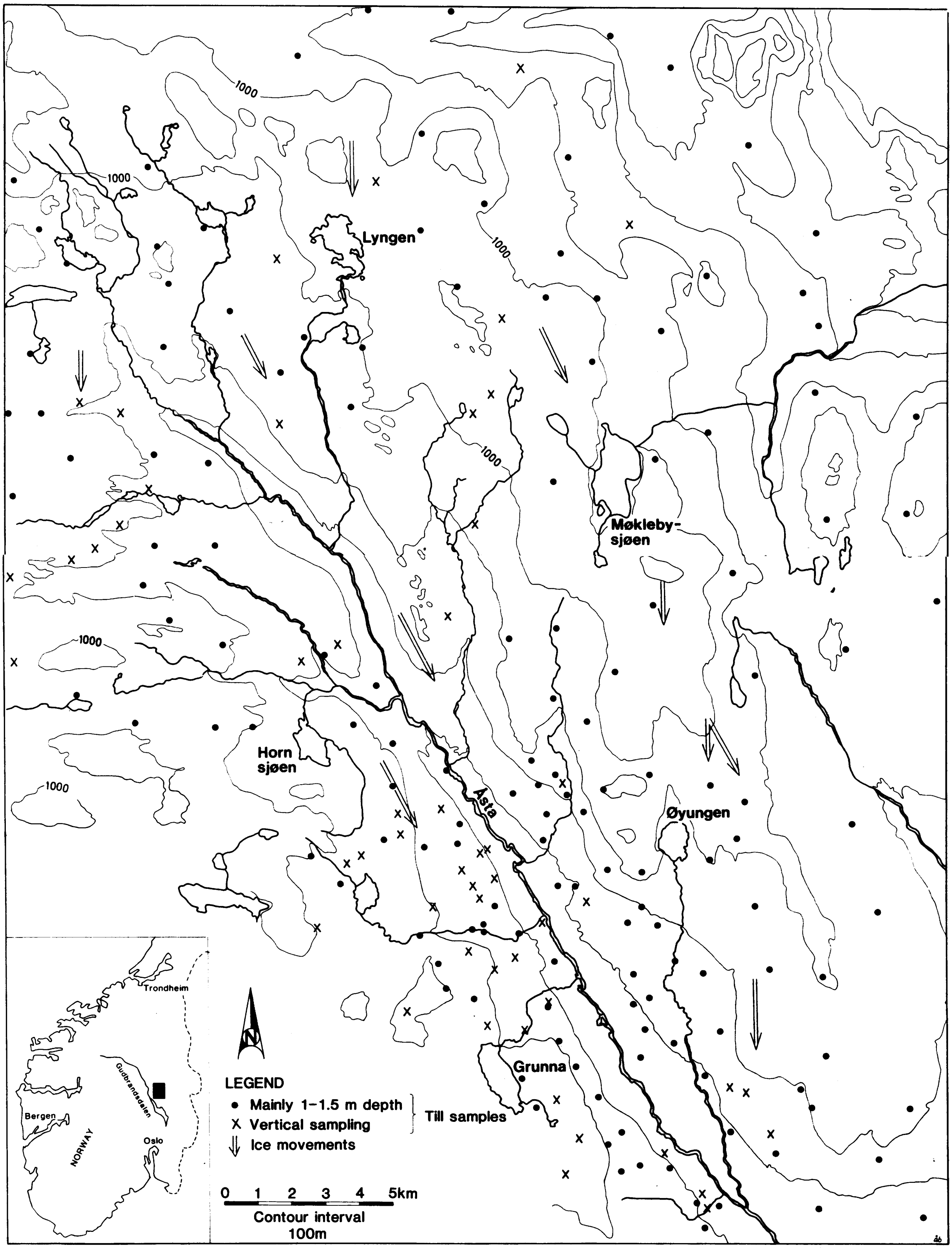

Fig.3 Map showing sampling sites of till samples, type of sampling and different directions of ice movements.

determined by atomic adsorption spectrophotometry, flame photometry and X-ray fluorescence spectrophotometry. The geochemical values are given as weight percentages of oxides, the iron as Fe_2O_3.

The granulometric classification follows the system of Wentworth (1922), but with the boundary between silt and clay placed at 9 Φ. Granulometric measurements of the total till were carried out in road cuttings.

The petrography of the sand and coarse silt was studied under a microscope. Thin sections and unmounted grains as well as grains mounted on acetate peels, have been used. Silt, clay and in some cases also coarser fractions were studied by X-ray diffractometry. Quantitative mineralogical analysis is based on the methods described by Rueslåtten (1976) and Augedal (1978, p.45).
The measured intensities were divided by the following numbers to give an approximation to weight percentage frequencies: Albite (3.19 Å) 2, microcline (3.24 Å) 2, quartz (4.25 Å) 1, chlorite (7 Å) 2, illite (10 Å) 1.

Methods of statistical treatment are taken from Davis (1973). Terms like 'significantly different' used later in the text refer to a 5 % level of significance, tested by Student's t-test or by F-tests.

SOURCE ROCKS

GENERAL DESCRIPTION

The till contains more than 99 % material from the local

Brøttum Formation in the boulder, cobble and gravel fractions. Also the finer fractions, therefore, are believed to be dominated by locally derived material. The rock types are described below. Reference is made to Englund (1972, 1973 a, 1973 b, pers.comm. 1976-1980).

Sandstones

The Brøttum Formation in Åstadalen is dominated by sandstones, viz. arkose and greywacke of varying texture (Fig.4). Quartz, albite, microcline and muscovite usually constitute more than 90 % of the total sandstone (Fig.5). The Na_2O (Table 1) is, therefore, dominantly a constituent of the albite while the contents of K_2O reflect the presence of both microcline and muscovite. Fe_2O_3 and MgO are partly bound in the muscovite.

Calcite, biotite, chlorite and sericite occur in subordinate amounts, the three latter constituting the sandstone matrix. The amounts are sufficient to account for the bulk of the CaO, Fe_2O_3 and MgO (Table 1). In addition, hydroxides of iron and manganese form coatings on mineral grains. TiO_2 (Table 1) most probably occurs in sheet silicate minerals.

The sandstones can be divided into two types (Fig.5 and Table 1), with types 1 and 2 dominating in the north and south, respectively. Type 1 is somewhat richer in muscovite than type 2 (Fig.5) but has on average

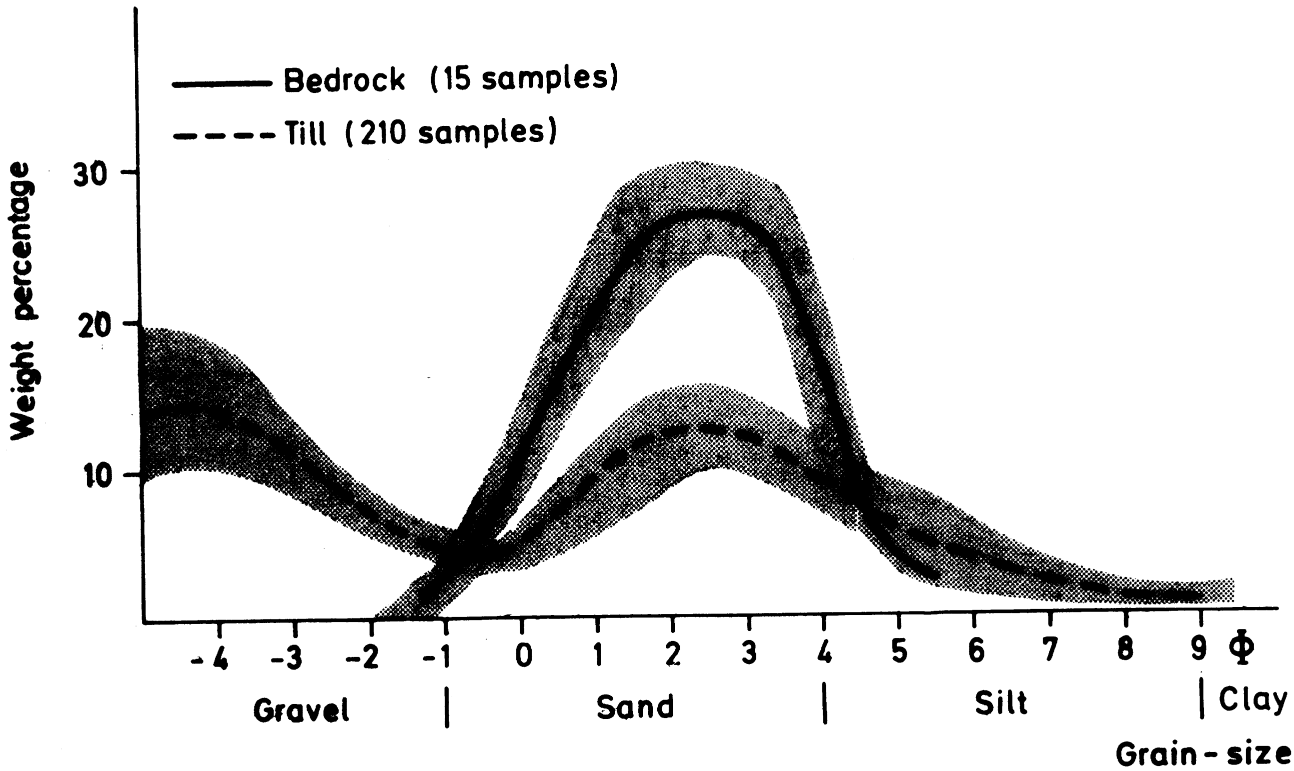

Fig.4 Average grain-size distribution and standard deviation (shaded) for bedrock and till samples from Åstadalen.

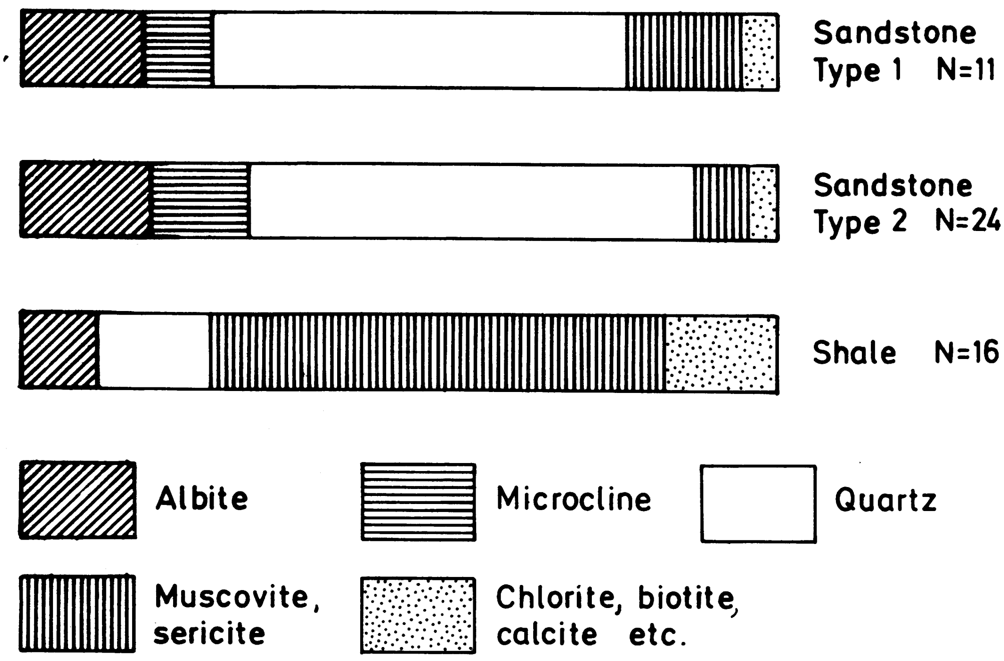

Fig.5 Mineralogical composition of the bedrock types in Åstadalen (after J.-O. Englund, pers.comm. 1979).

a lower content of microcline. The albite is fresher and less sericitised in type 2 than in type 1.

Shale

In the north and west there are some rather thin beds of silty shale (Fig.2) which on average constitute 5 % of the bedrock volume. Sericite is the dominant shale mineral (Fig.5) and in some cases is almost the only sheet silicate. The sericite is probably mainly clastic, but some recrystallization of original clay illite due to low metamorphism has occurred (J.-O. Englund pers. comm. 1980). The sericite has a higher alumina content than usual for dioctahedral illites (Englund & Jørgensen 1973, Fig. 13). The bulk shale is therefore rich in alumina (Table 1) (see also Englund 1973a, Table 7). In several samples chlorite is the second most important mineral. Quartz has been found in all samples. The only feldspar mineral is albite and the total K_2O-content can therefore be related to the sericite and the Na_2O to the albite. The Fe_2O_3, MgO, CaO, MnO and TiO are constituents of the same minerals as in the sandstones.

It is difficult to estimate the average bedrock composition from analyses of samples taken from exposures. The bedrock exposures are mainly found in the mountain areas and along upland elevations, while they are scarce in the valley. The consequence may be that the sampling is biased towards those parts of the bedrock which are most quartz--rich and therefore resistant. The quartz and SiO_2 contents given in Fig.5 and Table 1 may therefore be too high, as

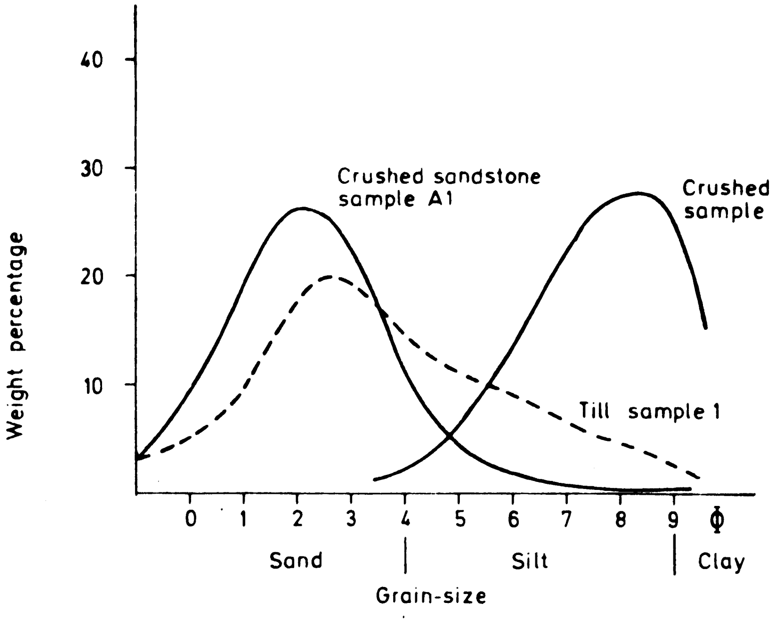

Fig.6 Grain-size distribution per 1 ϕ interval of crushed sandstone sample A1, crushed shale sample A2 and till sample 1 from the northern part of Åstadalen.

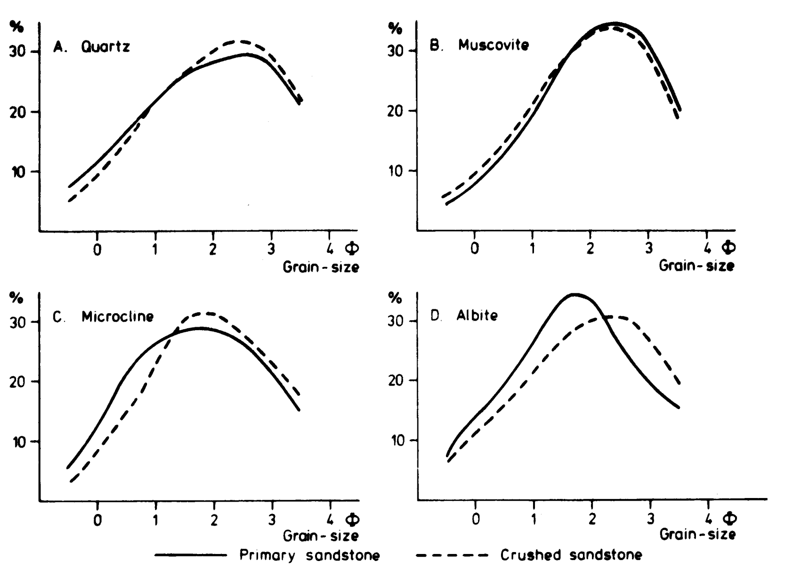

Fig.7 Total distribution of minerals per 1 ϕ interval of original and crushed sandstone sample A1. The total amounts of each respective minerals are here regarded as 100 %. The values shown in the figure were calculated from the grain-size distribution (Fig.6) and the relative mineralogical composition (Fig.8).

will be discussed in a later section.

Bedrock areas , a regional subdivision

Based on the results from field work and from the laboratory work which were given above, the bedrock in Åstadalen can be divided into three regional subareas.

Bedrock area A (Fig.2) forms the northern part of Åstadalen and consists dominantly of sandstone type 1, alternating with 0-10 % of silty shale. This gives on average a bedrock which is relatively rich in Al_2O_3, Fe_2O_3, MgO and K_2O (Table 1).

Bedrock area B forms the southeastern part of the area and is almost entirely composed of sandstone type 2 (Figs.2 & 5), with some conglomeratic beds. This gives a bedrock with a relatively high content of SiO_2 (Table 1).

Bedrock area C in the southwest is a composite group, with parts similar to bedrock group A and parts with a composition like bedrock group B (Fig.5).

RESISTANCE ON MECHANICAL CRUSHING

The till composition is strongly dependent on the mechanical resistance of the source rocks (e.g.Hörner 1944, 1946, Lundqvist 1952). A glacial crushing of rocks from the Brøttum Formation in Åstadalen was simulated by crushing some samples in a ball mill. The crushing process was repeated

Table 1. Chemical composition of the bedrock in Astadalen.

	Sandstone type 1 N = 11			Sandstone type 2 N = 24			Shale N = 16		
	$\bar{X}$	SD	Range	$\bar{X}$	SD	Range	$\bar{X}$	SD	Range
SiO_2	80.1	2.5	74.8-83.2	81.5	4.9	67.5-92.8	58.3	7.3	47.5-69.4
Al_2O_3	9.0	1.4	7.6-12.2	8.4	2.0	4.8-11.8	19.9	4.3	13.8-27.0
Fe_2O_3	2.5	0.7	1.7- 5.9	2.1	1.1	0.5- 4.1	4.7	1.5	3.7- 9.1
TiO_2	0.4	0.1	0.3- 0.6	0.4	0.1	0.1- 0.7	1.0	0.3	0.4- 1.4
MgO	0.8	0.3	0.5- 1.9	0.6	0.4	0.1- 1.5	2.3	0.8	1.5- 4.4
CaO	0.6	0.6	0.2- 2.4	0.5	0.4	0.1- 2.1	0.8	0.4	0.2- 1.7
Na_2O	1.8	0.2	1.3- 2.0	1.8	0.4	0.5- 3.2	1.2	1.0	0.1- 3.0
K_2O	2.9	0.6	1.8- 4.1	3.2	0.5	1.8- 3.9	6.2	2.3	2.5-99.5
MnO	0.03	0.02	0.01-0.63	0.03	0.02	0.01-0.08	0.06	0.03	0.03-0.20
Total	98.1			98.6			94.5		

Table 2. Geochemical composition of subglacial till from Åstadalen. Silt + clay.

	Till group A (northern part of the area) N = 187			Till group B (southern part of the area) N = 195			Till group C (southwestern part of the area) N = 69		
	$\bar{X}$	SD	Range	$\bar{X}$	SD	Range	$\bar{X}$	SD	Range
SiO_2	68.6	4.1	57.0 - 84.0	76.4	4.2	67.0 - 88.0	69.7	4.5	51.0 - 81.0
Al_2O_3	13.9	1.7	8.0 - 15.9	10.5	2.0	6.8 - 15.3	13.4	2.0	8.8 - 17.2
Fe_2O_3	4.8	1.0	0.8 - 7.1	3.3	1.0	1.7 - 6.3	4.6	1.2	1.1 - 7.3
TiO_2	0.9	0.1	0.7 - 1.2	0.8	0.1	0.6 - 1.1	0.9	0.1	0.8 - 1.1
MgO	1.5	0.3	0.5 - 3.9	0.8	0.2	0.4 - 1.9	1.4	0.4	0.8 - 2.4
CaO	0.9	0.2	0.4 - 1.6	0.8	0.2	0.4 - 1.4	1.0	0.2	0.5 - 1.6
Na_2O	2.5	0.3	1.4 - 3.1	2.6	0.3	1.6 - 3.6	2.6	0.3	2.0 - 3.1
K_2O	3.2	0.4	2.0 - 4.4	2.6	0.4	1.7 - 3.7	3.1	0.4	2.5 - 3.7
MnO	0.08	0.02	0.03 - 0.14	0.05	0.01	0.02 - 0.09	0.06	0.01	0.04- 0.07
Totals	96.4			97.9			96.8		

until the grains reached a rather stable size (see Haldorsen 1981). The size distribution of minerals in the original bedrock samples before the crushing was compared with the size distribution of minerals after the crushing.

Figs. 6-9 show the results from the crushing of one sample of sandstone type 1 (sample A1, Fig.2). During this process the rock sample was easily broken down to separate minerals, mainly of sand size (Fig.6). Fig.7 gives the grain-size distribution of quartz, muscovite and feldspars before and after the crushing. The quartz grains retained their size better than the feldspars (Fig.7), supposingly because the original quartz is somewhat more fine-grained without cleavage planes, and more rounded. The muscovite flakes were reduced in thickness by cleavage but resisted breakage across cleavage planes (Fig.7 B) because of the great elasticity Such resistance is well known from industrial crushing (see Mortenson 1968, p.50). Also the microcline mode fell in the same size grade before and after the crushing, but the coarsest grains had become significantly smaller (Fig.7 C). The albite was broken down more than the quartz and microcline and its frequency maximum moved from 1-2 Φ to 2-3 Φ (Fig.7 D).

The relative mineralogical composition of the sand and coarse silt from the crushed sample A1 is shown in Fig.8. The quartz is dominant in all fractions. The relative albite content is higher in the silt than in the sand, while both muscovite and microcline have their modes in the sand.

The relative mineralogical composition of the silt and clay is shown in Fig.9. It should be emphasized that the

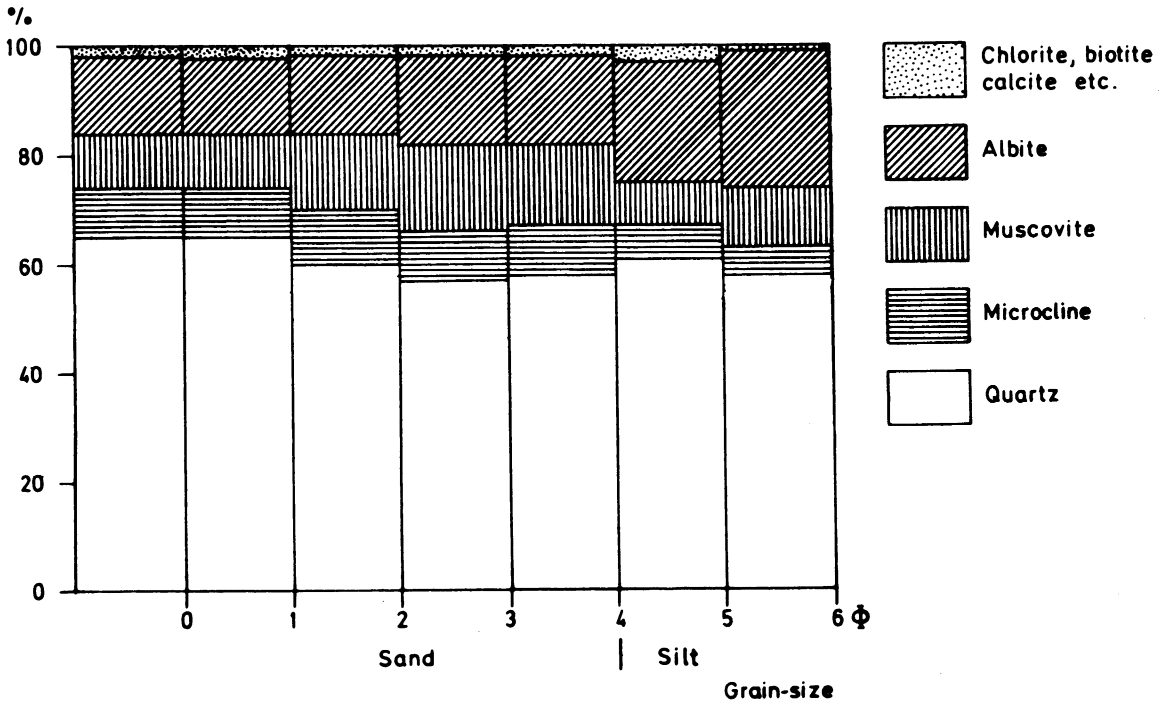

Fig.8 Relative mineralogical composition per 1 Φ interval of crushed sandstone sample A1, sand and silt grades.

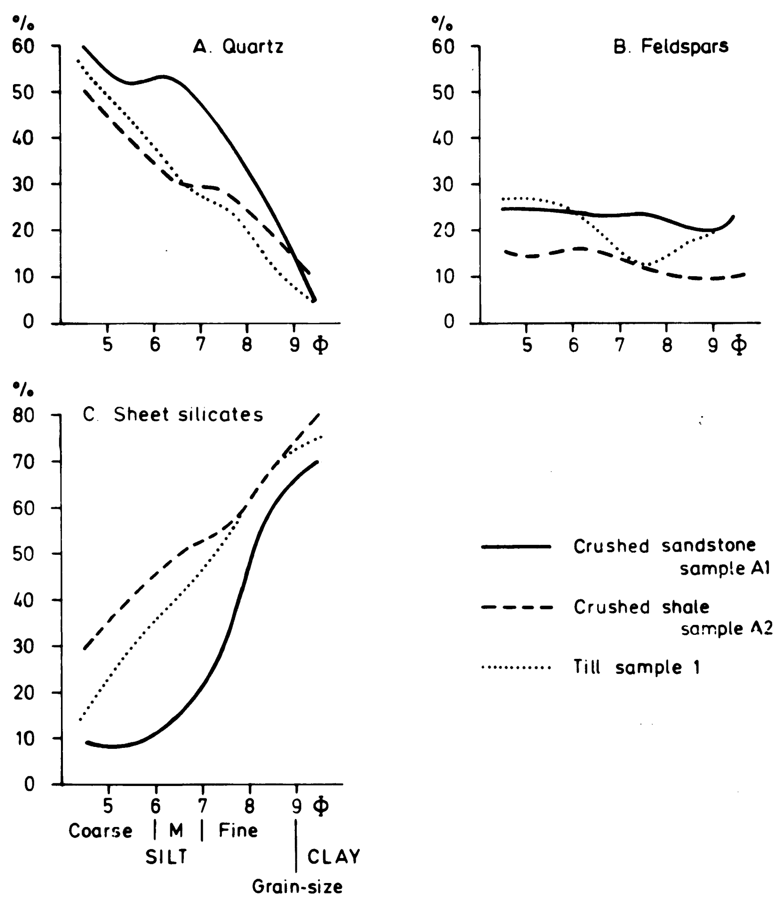

Fig.9 Relative mineralogical composition per 1 Φ interval of crushed sandstone sample A1, crushed shale sample A2 and till sample 1. Silt and clay fractions.

medium silt to clay grades constitute only a minor part of the total crushed sandstone material (Fig.6). In these fractions the relative quartz content is decreasing with decreasing particle sizes, while the relative content of sheet silicates is increasing (Fig.9), reflecting an increasing influence of sericite-chlorite sandstone matrix material. The feldspar content, mainly albite, is rather uniformly distributed in the medium to fine silt and clay (Fig.9 B) because albite occurs both as crushed fragments of original sand particles and as disintegrated matrix constituents.

The analytical values for the crushed sample A1 are shown in Fig.10 and clearly reflect the mineralogical variations. The high content of quartz in the sand and coarse silt grades (Figs.8 & 9 A) gives a low Al_2O_3: SiO_2 ratio (Fig.10 A) and rather low contents of Na_2O, K_2O and Fe_2O_3+ MgO (Fig.10 B-D).

The Al_2O_3:SiO_2 ratio, the K_2O and Fe_2O_3+MgO contents are increasing with decreasing grain-size in the medium silt to clay grades (Fig.10 A, C & D) because of the increased sheet silicate content. The Na_2O-content is higher in the silt and clay than in the sand (Fig.10 B), because the silt and clay fractions are relatively rich in albite.

One sample from the shale (A2, Fig.2) was moderately crushed in the ball mill and produced particles finer than 5 Φ (Fig.6). The Al_2O_3:SiO_2 ratio (Fig.10 A), as well as the content of K_2O and Fe_2O_3+ MgO (Fig.10 C & D) increase with descreasing grain-size while the Na_2O content is decreasing (Fig.10 B). This reflects the decreasing quartz

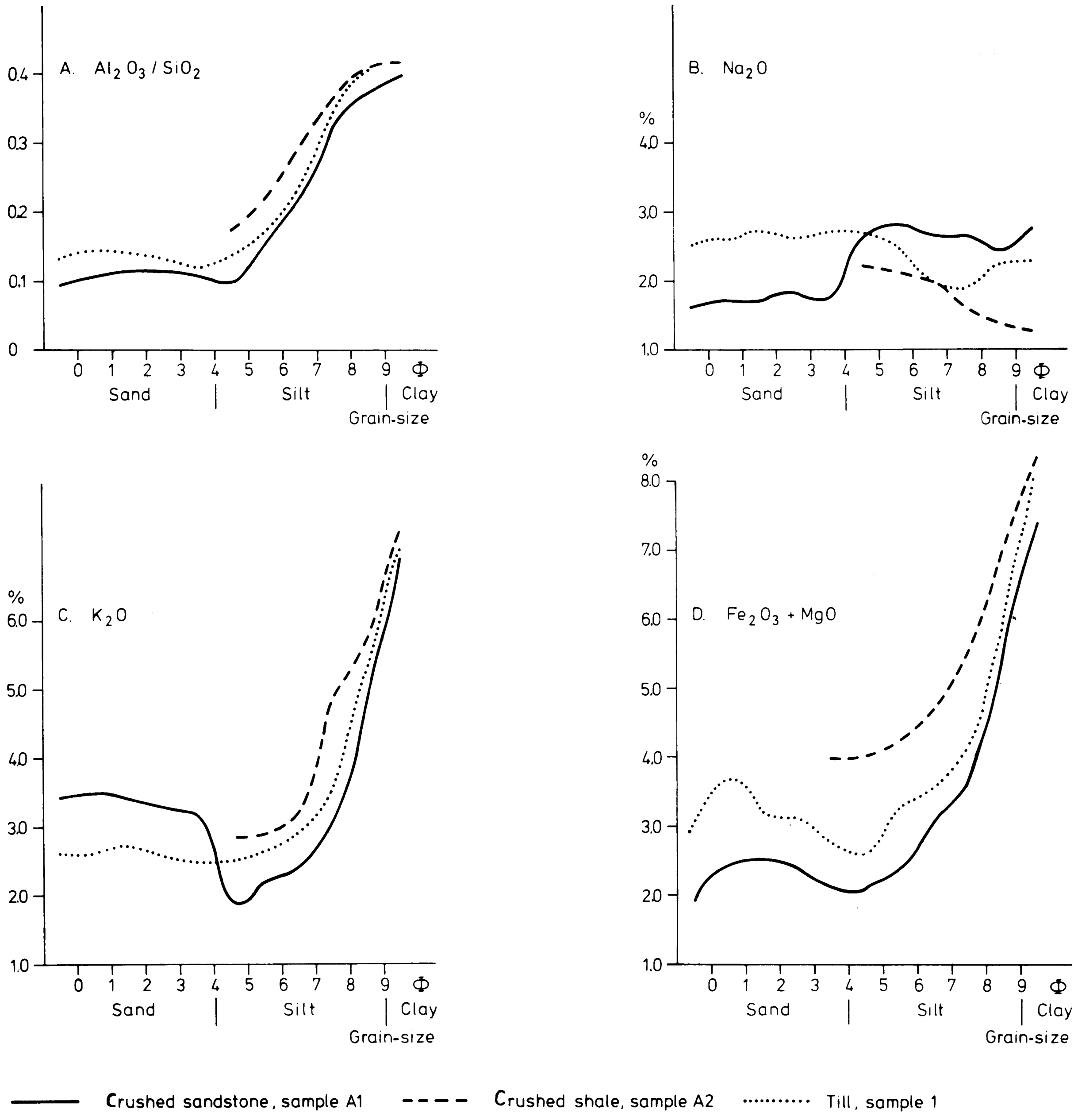

Fig.10 Relative geochemical composition per 1 Φ interval of crushed sandstone sample A1, crushed shale sample A2 and till sample 1.

and albite contents and increasing illite and chlorite contents (Fig.9). These are mineralogical characteristics which may well be related to the uncomminuted shale sample.
which may well be related to the uncomminuted shale sample, but in addition the crushing process may also cause a similar
and albite remain in coarse grades while minerals with low resistance, like chlorite, are very rapidly pulverized and thereby become enriched in the finest silt and clay.

VERTICAL TILL VARIATION

The vertical variations of elements between 1 and 5 m depth in the till were studied at selected localities (Fig.3). Of the elements studied, only iron and manganese showed systematical vertical variations. This variation is the result of postglacial (epigenetical) weathering (Fig.1). The vertical variations of iron, however, were found to be subordinate to the regional variations. The minerals from the sandstone as well as most of the minerals from the shale (Fig.5) are rather resistant to chemical weathering. Except for the iron and manganese, the post-depositional weathering processes have probably had little influence upon the till composition beneath a soil zone of about 50 - 70 cm. The weathering processes are therefore regarded as insignificant for the geochemical variations discussed in this paper.

There are several reasons why most of the geochemical till constituents do not vary with depth. The fact that the bedrock is homogeneous over large areas is certainly important. At most localities the till can be considered as one bed, either deposited by a continuous lodgement process or by a local melt-out process.

Further discussion of syngenetical till variations is based upon all the sample collected, both regionally and from vertical sections.

THE RELATIONSHIP BETWEEN BEDROCK AND TILL MATRIX GEOCHEMISTRY

Based on the silt + clay geochemistry the tills can be divided in three regional groups. These groups show a strong relation to the underlying bedrock types.

The till upon the alternating sandstone/shale bedrock in the north (Figs.2 & 11) forms till group A, which has a relatively high content of Al_2O_3, Fe_2O_3, MgO and K_2O (Table 2). This corresponds to the high contents of such elements in the bedrock (Fig.5, Table 1).

The till from the homogeneous sandstone area in the southeast (Figs.2 & 11) forms till group B, which is richer in SiO_2 than the till in the north (Table 2), due to the more quartz-rich bedrock (Fig.5).

The till in the southwest constitutes group C (Fig.11) which has a variable geochemistry due to the composite nature of the bedrock (Fig.2); on average it is midway between groups A and B (Table 2).

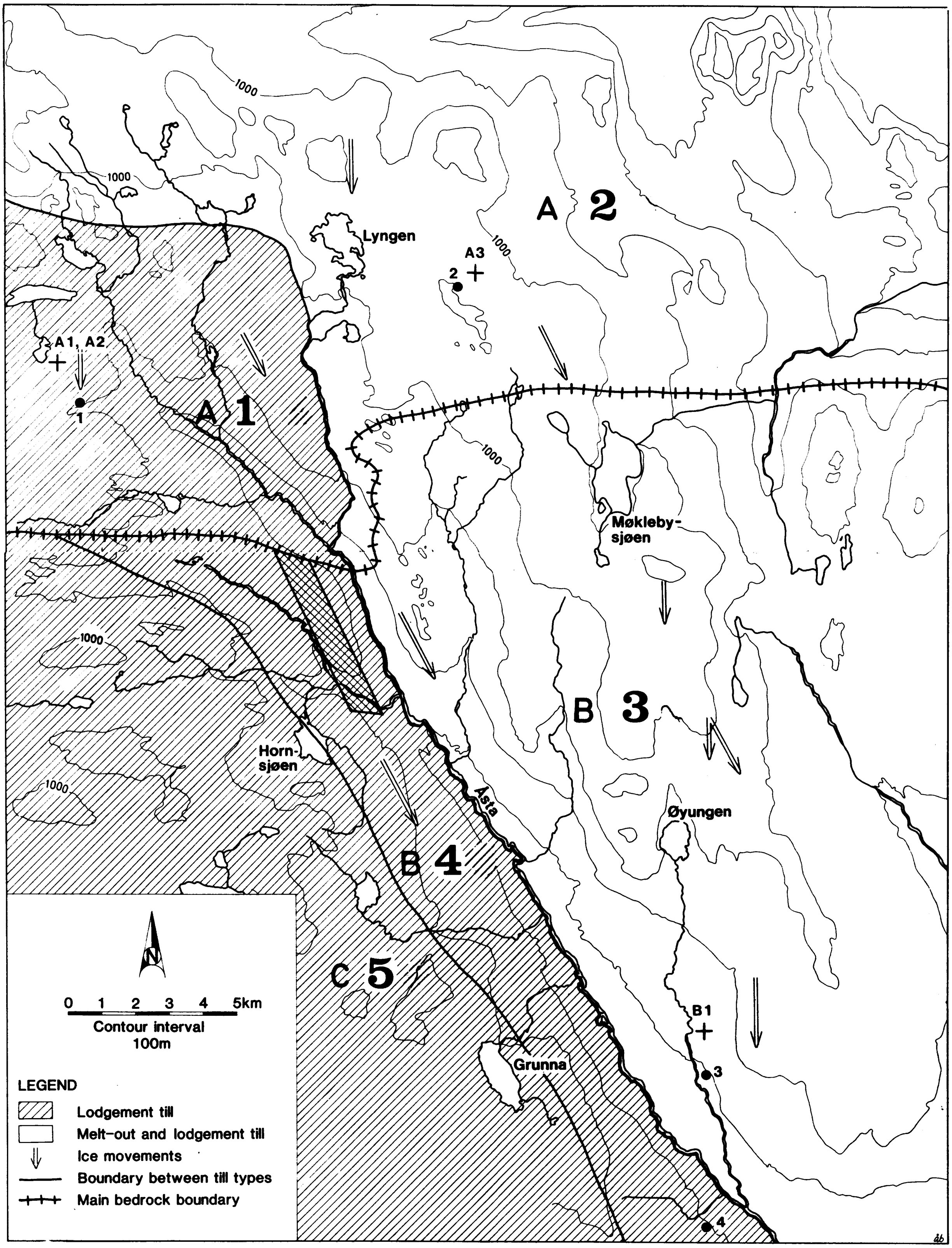

Fig.11 Till genesis, lithological till groups (A-C) and lithological subgroups (till types 1-5) in Åsta-dalen. Framed: the area of Fig.23.

MnO too, shows distinct regional variations (Table 2). However, its content is low and its distribution so much influenced by secondary processes that its variation is not discussed in the following text.

CaO seems to be closely related to the calcite minerals since these are at least as commonly related to bedrock fractures as to the primary sandstone mineralogy (J.-O.Englund pers.comm. 1979), the CaO-variation in the till is hard to explain from the available bedrock data. The following discussion is therefore based on variations in the Al_2O_3: SiO_2 ratio and the varying contents of Fe_2O_3, MgO, Na_2O and K_2O.

TILL GROUP A FROM THE SANDSTONE/SHALE AREA IN THE NORTH

Variations through the matrix fractions

Till group A is formed by glacial comminution of sandstone and shale. The results from the artificial crushing of bedrock samples (Figs.7-10) indicated that a distinct mineralogical and geochemical variation would be found in the till matrix grades.

Figs.9,10 & 12 show the mineralogical and geochemical composition in different parts of the till matrix for one sample from till group A (sample 1, Fig.11). The sand grades are dominated by separate minerals (Fig.12), mainly from the sandstone, as the shale chiefly contains grains of silt and clay size. There is a low content of shale fragments in the sand grades of this till sample (Fig.12), showing that all influences from the shale are small in the sand.

The lithology is reflected in the rather uniform geochemistry of the sand grades, with low Al_2O_3: SiO_2 ratios and low values of K_2O and Fe_2O_3 + MgO (Fig.10).

Since the sandstone contributes most of its material initially to the sand fraction (Fig.6) one would expect the sand grades of the till to be geochemically similar to the bulk sandstone samples. The sand in the till however, contains more Al_2O_3 and Na_2O and less K_2O than the average of the sandstone samples (Fig.10 A-C). This reflects a higher content of albite and lower content of microcline and quartz (Figs.8 & 12) in the till than in the sandstone samples. The Na_2O content is clearly higher than in the sandstone also when the bulk till matrix is considered (Fig.13).

A too high Na_2O-value was found to be a regional characteristic of till group A. The explanation of this probably is that the source rocks on average contains more Na_2O and less SiO_2 and K_2O than the average of the sampled sandstones (Table 1). This indicates a biased bedrock sampling as discussed earlier. However, the difference between the till and the bedrock may result also from the crushing processes (Fig.1, factor A). Mill experiments indicated that the quartz- and microcline-rich sandstone types are more resistant to a thorough glacial comminution than the sericitized albite-rich types. During glacial transport the most resistant material may have been enriched in the boulder, cobble and gravel grades. The albite-rich types have been more easily disintegrated to separate minerals and thereby became over-represented in the matrix grades.

Table 3. Correlation between the Al_2O_3 and the Fe_2O_3, MgO, Na_2O and K_2O for till types from Astadalen. Only silt+clay material.

		Al_2O_3 - Fe_2O_3	Al_2O_3 - MgO	Al_2O_3 - Na_2O	Al_2O_3 - K_2O
TILL GROUP A	Till type 1	0.79	0.86	-0.03	0.36
	Till type 2	0.61	0.88	0.17	0.61
TILL GROUP B	Till type 3	0.56	0.66	0.29	0.53
	Till type 4*	0.26	0.18	0.42	0.85
TILL GROUP C	Till type 5	0.38	0.79	0.03	0.72

*only samples from the southern part of the area of till type 4 are included.

Table 4. Al_2O_3:SiO_2 ratios and source material of two till samples from the northern area. Sample sites are shown in Fig.11.

	Sample 1 (Till type 1)				Sample 2 (Till type 2)			
	Weight %	Al_2O_3:SiO_2	Sandstone %	Shale %	Weight %	Al_2O_3:SiO_2	Sandstone %	Shale %
Total matrix (finer than -1ϕ)	100	0.19[1]	65[2]	35[2]	100	0.14[1]	80[2]	20[2]
Sand (-1 to 4ϕ)	55[1]	0.15[1]	90[1]	10[1]	60[1]	0.12[1]	95[1]	5[1]
Silt + clay (finer than 4ϕ)	45[1]	0.26[1]	40[2]	60[2]	40[1]	0.18[1]	60[2]	40[2]

1) Values obtained directly from analyses

2) Calculated values

A similar 'quartz-deficiency' may also be expected in other areas, since quartz-rich rocks in many cases are the most resistant bedrock types. The opposite result, a quartz enrichment, may certainly occur purely from crushing but it is probably more uncommon than a 'quartz-deficiency'. A quartz-enrichment in tills thus usually has to be explained by factors other than the glacial comminution processes (Rosenqvist 1975, Perttunen 1977, p.59, Gillberg 1977, Haldorsen in prep.).

The ratio of $Al_2O_3:SiO_2$, and values of K_2O and Fe_2O_3+ MgO increase rapidly in the till grades from 4 to 9ϕ (Fig.10), mainly because of the gradual increase of sheet silicates (Fig.9). A similar variation in the silt and clay grades was also found for the crushed sandstone and shale (Figs.9 & 10). The geochemistry within a restricted particle size interval of the crushed sandstone was rather similar to the same size interval of the crushed shale (Fig.10). This results in the characteristic geochemical variation in the different parts of the silt and clay of samples from till group A (Fig.10). The similarity between the shale and sandstone geochemistry shown in Fig.10 makes it extremely difficult to estimate the sandstone and shale ratio in different parts of the silt and clay on the basis of the geochemistry alone.

The ratio of sandstone and shale components in till group A

The bulk silt + clay of the crushed sandstone has a

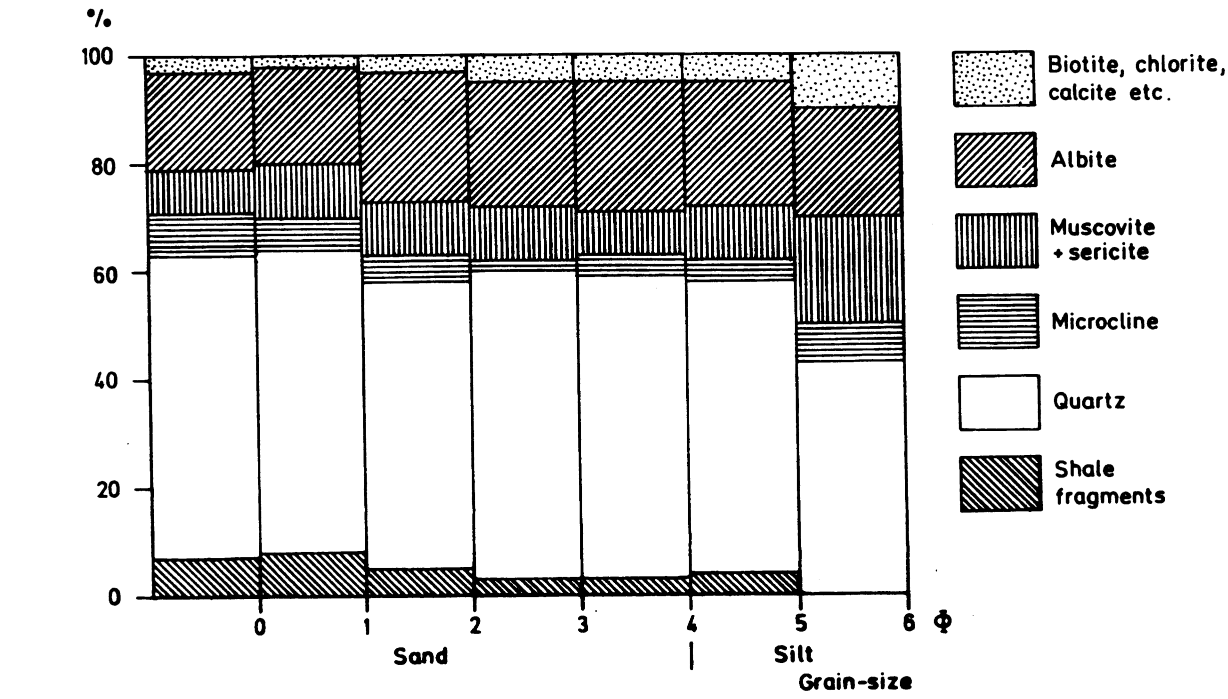

Fig.12 Relative mineralogical composition of till sample 1, sand and coarse silt grades.

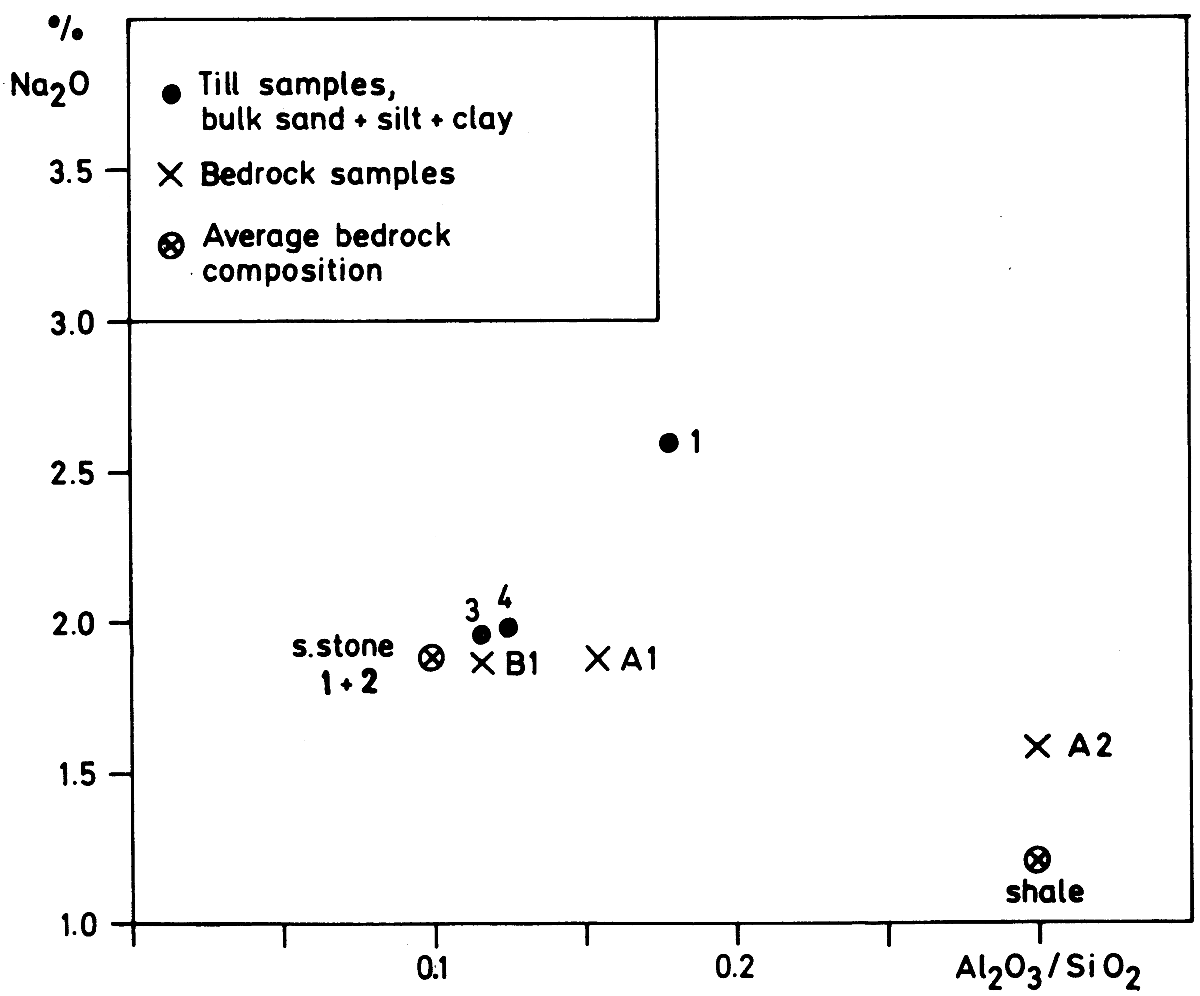

Fig.13 N_2O and Al_2O_3:SiO_2 relationship for bulk bedrock samples, total till matrix and silt+clay of till significantly lower Al_2O_3: SiO_2 ratio and lower K_2O- and Fe_2O_3 + MgO contents than the bulk crushed shale. This is because the crushed sandstone is dominated by the coarse silt fractions which are rich in quartz and feldspar while the crushed chale contains much more medium to fine silt rich in sheet silicates (Figs.6 & 9). The geochemistry of the bulk silt + clay of the till is therefore clearly dependent upon the ratio between sandstone and shale components. The Al_2O_3: SiO_2 ratio can also be regarded as a function of the grain--size distribution, since an increase of shale components relative to sandstone components results in an increase of fine to medium silt relative to coarse silt (Fig. 6).

This is illustrated in Fig.14, where the Al_2O_3:SiO_2--grain-size relationship has been estimated from variable proportions of crushed sandstone material from sample A1 and crushed shale material from A2.

Based on the discussion above, which is summarised in Fig.14, the main geochemical variations in the silt + clay of till group A are believed to be the result of variable sandstone and shale components. This conclusion is supported by the positive correlation which exists between Al_2O_3 on the one hand and the other typical shale parameters, Fe_2O_3, MgO and K_2O, on the other and also by the lack of correlation between Al_2O_3 and the sandstone parameter Na_2O (Table 3).

The sandstone and the shale components in the bulk silt + clay of till sample 1 can be roughly estimated from the calculations given in Fig.14, and the data in Figs.6 & 10 A.

This estimate gives a shale content between 50 and 60 %. Two sources of error involved with this calculation have to be mentioned. The first is that the shale probably also contributes multimineral grains to the coarse silt in addition to its monomineralic material.

The other is that a glacial abrasion of sandstones, in contrast to glacial crushing, certainly has produced considerable amounts of medium silt sized material (Haldorsen 1981).

Another direct quantification of the sandstone and shale components in the silt + clay of the till is based on the total till matrix material (finer than 2 mm). This includes about 90 % of all the separate mineral grains in the till, and the bulk geochemical composition should therefore reflect both the total sandstone composition and the total shale composition.

The sandstone : shale ratio can thus be calculated from the grain-size distribution of the till, the bulk sandstone and shale geochemistry (Fig.13) and the content of shale fragments in the sand. This calculation was carried out for till sample 1, and a till sample 2 from the northeastern part of the area (Fig.11). The calculation is summarised in Table 4 . The applied bedrock data are based on samples from the nearest bedrock localities (Fig.11, samples A1, A2 and A3). The percentage of shale in the silt + clay was by this method found to be approximately 60 % for till sample 1, which is in accordance with the value from the first described calculation method. The percentage of shale in the silt + clay

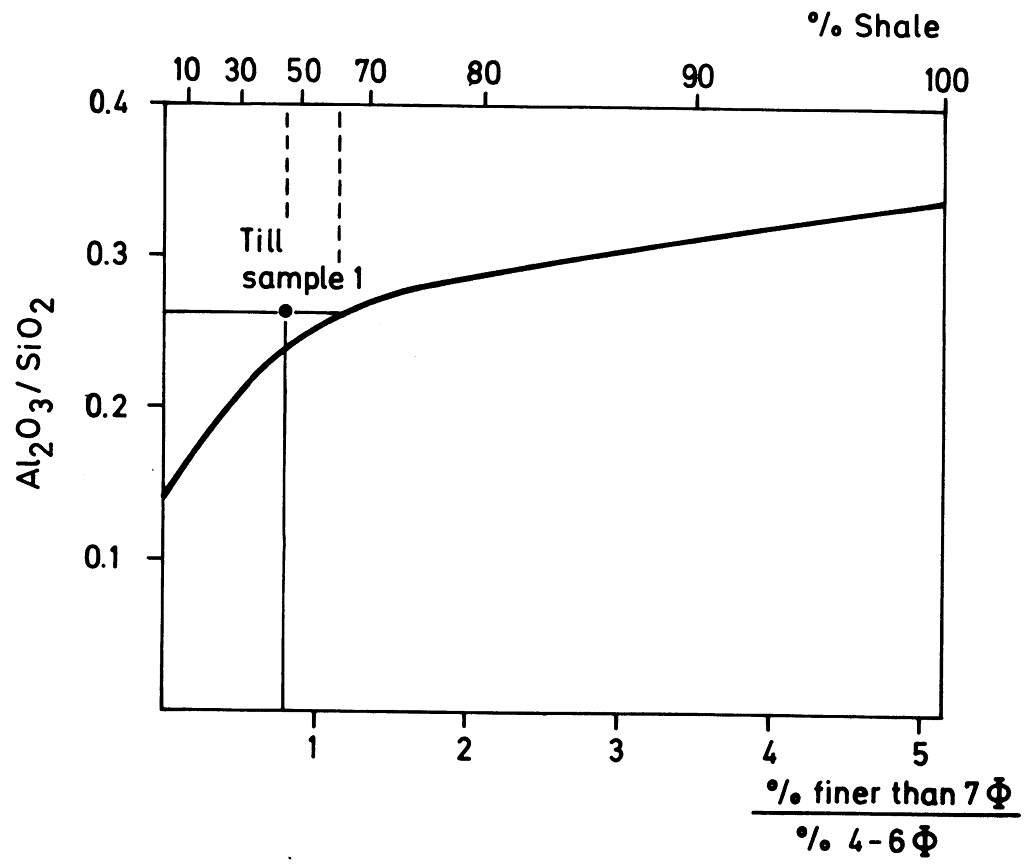

Fig.14 Theoretical relationship between the $Al_2O_3:SiO_2$ ratio in silt+clay, the percentage of shale material in silt+clay and the ratio of coarse to fine silt+clay of till group A. Calculated from data from sandstone sample A1 and shale sample A2, taken from Figs. 6 & 10A.

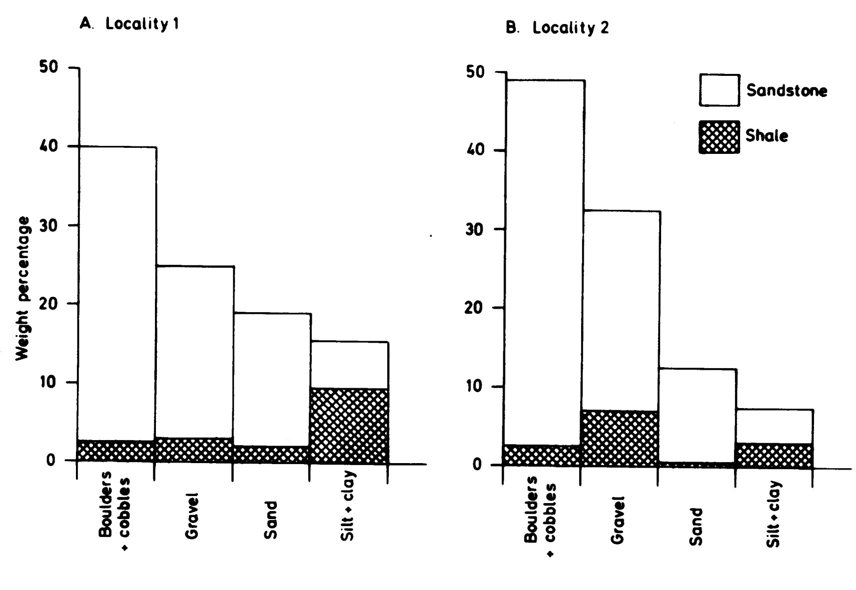

Fig.15 Histogram showing the total grain-size distribution of till at localities 1 and 2 (Fig.11), and the content of shale and sandstone components in each main fraction.

of till sample 2 was estimated to about 40 % (Table 4).

The estimation method based on Fig.14 has the advantage that it is independent of errors involved with the sand grade calculations. In the estimation method based on Table 4 the two sources of errors mentioned for method one are minimised.

Till types 1 and 2

Based on the geochemistry of the bulk + clay, till group A can be divided into two regional subgroups, viz. till types 1 and 2, (Table 5). Till type 1 is found in the northwest and till type 2 in the northeast (Fig.11). Till type 1 has significantly higher contents of Al_2O_3, MgO and K_2O than till type 2 (Table 5).

Till samples 1 and 2 (Table 4 and Fig.11) are typical for till types 1 and 2, respectively. The calculations given in Fig.14 and Table 4 indicate, therefore, that till type 1 has a higher content of shale than till type 2. Based on average geochemistry and grain-size distribution of till types 1 and 2, the shale content in the silt + clay was estimated as 40-60 % for type 1 and 30-50 % for type 2.

Fig.15 shows the grain-size data combined with petrographical data. The sand and silt + clay values are taken from Table 4. By adding together all the shale values for each of the two till samples in Fig.15, the total amount of shale is found to be 16 % in sample 1 and 12 % in sample 2. This may indicate that the total amount of shale is somewhat higher in till type 1 than in till type 2.

Table 5. Geochemistry of subglacial till types from Åstadalen. Silt + clay material.

	Till Group A						Till Group B					
	Till type 1 N = 105			Till type 2 N = 82			Till type 3 N = 57			Till type 4 N = 138		
	$\bar{X}$	SD	Range	$\bar{X}$	SD	Range	$\bar{X}$	SD	Range	$\bar{X}$	SD	Range
SiO_2	65.7	3.2	57.0–73.0	72.3	4.3	64.5–84.0	80.2	4.8	68.0–88.0	74.6	3.0	67.0–83.0
Al_2O_3	15.2	1.1	11.3–18.0	12.2	1.9	8.0–15.9	9.4	2.4	6.8–13.4	11.0	1.3	7.7–15.3
Fe_2O_3	5.3	0.7	3.4– 7.1	4.1	1.1	0.8– 6.3	2.7	0.9	1.7– 6.0	3.5	1.1	1.7– 6.3
TiO_2	0.9	0.1	0.8– 1.2	0.8	0.1	0.7– 1.1	0.8	0.1	0.7– 0.9	0.8	0.1	0.6– 1.1
MgO	1.8	0.3	1.1– 3.9	1.2	0.3	0.5– 2.0	0.7	0.2	0.4– 1.3	0.9	0.2	0.5– 1.9
CaO	1.0	0.2	0.5– 1.5	0.8	0.2	0.4– 1.6	0.7	0.2	0.4– 1.3	0.9	0.2	0.4– 1.4
Na_2O	2.5	0.3	1.4– 3.0	2.4	0.4	1.6– 3.1	2.3	0.2	1.8– 2.9	2.7	0.3	1.6– 3.6
K_2O	3.4	0.3	2.8– 3.6	2.9	0.4	2.0– 4.4	2.3	0.4	1.8– 3.7	2.7	0.3	1.7– 3.6
MnO	0.08	0.02	0.04–0.14	0.07	0.02	0.03–0.12	0.04	0.01	0.02–0.07	0.05	0.01	0.02–0.09
Totals	95.9			96.9			99.1			97.2		

The proportion of shale bedrock horizons, measured perpendicular to the bedding is the same in the eastern and western parts of the area (J.-O.Englund pers.comm.1979). However, in the west where till type 1 is found, the shale beds are more frequently exposed to erosion, because of the rather steep and variable topography. In the east, on the other hand, the gently undulating mountain plateaux commonly represent the surface of resistant sandstone beds under which the shale horizons partly may have been protected against erosion. Therefore, more shale should be expected in till type 1 than in till type 2.

However, the calculated difference in shale content between till sample 1 and 2 is rather small (4 %). The difference between the two samples are much more marked when the distribution pattern of shale in different size fractions (Fig.15) is compared. This may indicate that different shale content in the till matrix is not only the result of differences in the total shale content in the till. In areas where a fine-grained bedrock alternates with a more coarse-grained one, as in the areas of till types 1 and 2, the ratio between the two rock components in the overlying till matrix may be dependent also on the glacial grinding processes (Factors A and B in Fig.1). In that connection, it is important to look at the distribution of shale and sandstone in the total till and not only in the matrix (Fig.15). Some mill experiments indicate that when the sandstone fragments have reached a medium gravel size, they are crushed down to monomineralic grains even more rapidly than the shale.

When the glacial crushing has not been too intensive, the matrix (finer than - 1 ϕ) will be enriched in sandstone material relative to shale. The silt+clay of the till will then be dominated by the coarse silt from the sandstone relative to the fine silt from the shale (Fig.6) and thus have a low Al_2O_3: SiO_2 ratio (Fig.14). These are the characteristics of till sample 2 (Fig.15B and Table 4) as well as of great parts of till type 2. Till type 2 is characterized by a high content of coarse angular clasts and seems to be of very local origin and partly deposited by a melt-out process (Fig.11).

An intensive crushing combined with abrasion will give a thorough comminution of both sandstone and shale down to their separate and resistant mineral grains (Fig.6). Through this comminution there will be a gradual enrichment of shale components in the silt + clay since the total shale material ends up in these grades and because the shale has a greater proportion of soft minerals and therefore is more easily abraded than the sandstone. The intensive grinding which occurs along the base of an active sliding glacier will therefore result in a silt + clay material rich in shale components, and with a high Al_2O_3:SiO_2 ratio. This is the characteristics of sample 1 (Fig.15 A and Table 4) as well as of the average of samples from till type 1. The different till geochemistry of till types 1 and 2 is therefore not only dependent on the bedrock features but also on their different genesis.

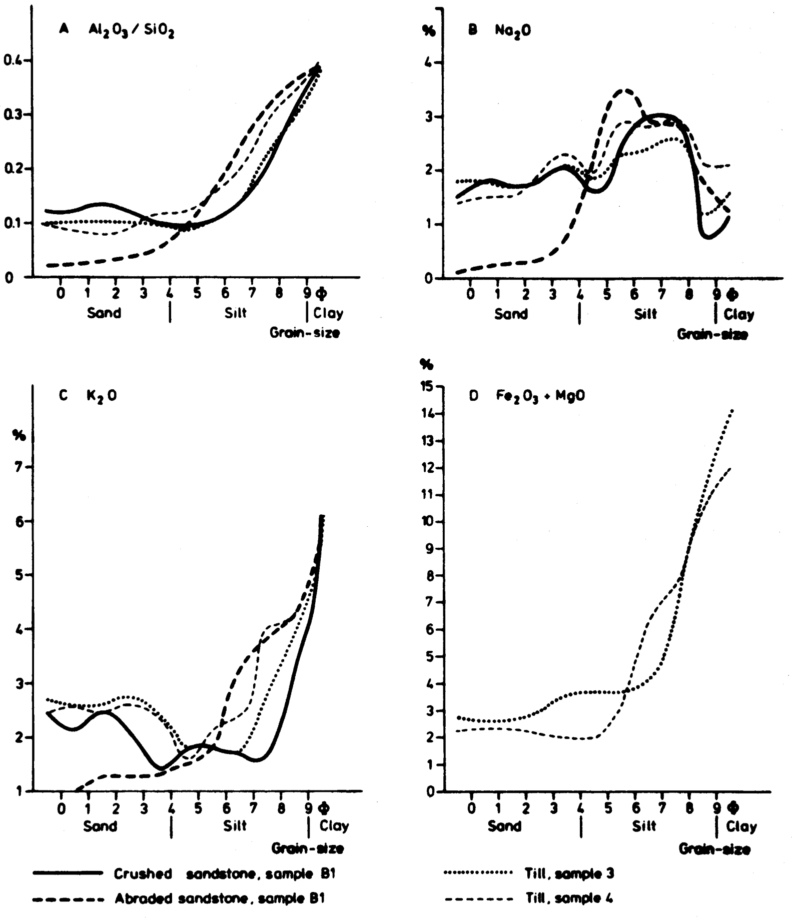

Fig.16 Relative geochemical composition per 1 ϕ interval of till samples 3 and 4 and of crushed and abraded sandstone sample B1 from the southern part of Åstadalen.

TILL GROUP B FORM THE SANDSTONE AREA IN THE SOUTH

In the silt+clay of till group B there is on average a lower positive correlation between Al_2O_3 and Fe_2O_3 and MgO than in till group A while there is a higher positive correlation between Al_2O_3 and Na_2O (Table 3). This reflects that Al_2O_3 in the north is mainly related to sheet silicates from the shale while in the south the Al_2O_3 is more related to the feldspars from the sandstone.

In the eastern mountaineous area there is a distinct boundary between till groups A and B which is closely related to the bedrock boundary because the influence from the shale is very local in the short transported melt-out till which dominates in areas near the bedrock boundary (Fig.11).

In the west the boundary between till groups A and B is more transitional. Till samples from group B positioned close to the shale -

-sandstone bedrock boundary are clearly influenced by shale material. The till has generally undergone a longer distance of glacial transport here than further east.

The variations in geochemistry and mineralogy throughout the different till matrix grades have been studied for samples 3 and 4 from till group B (Figs.11, 16 & 17). The variations follow about the same general trend as for till sample 1 (Figs.9, 10 & 12). Because of the lack of shale influence some characteristics for sample 3 and 4 are like those of the crushed sandstone. A Na_2O-maximum is for instance found in the 5-8 ϕ -grades. (Figs.9 B & 16 B), reflecting the abundance of albite (Fig.7).

The bulk matrix of till sample 3 is similar to bedrock sample B1 (Figs.11 & 13) and the geochemistry of till group 2

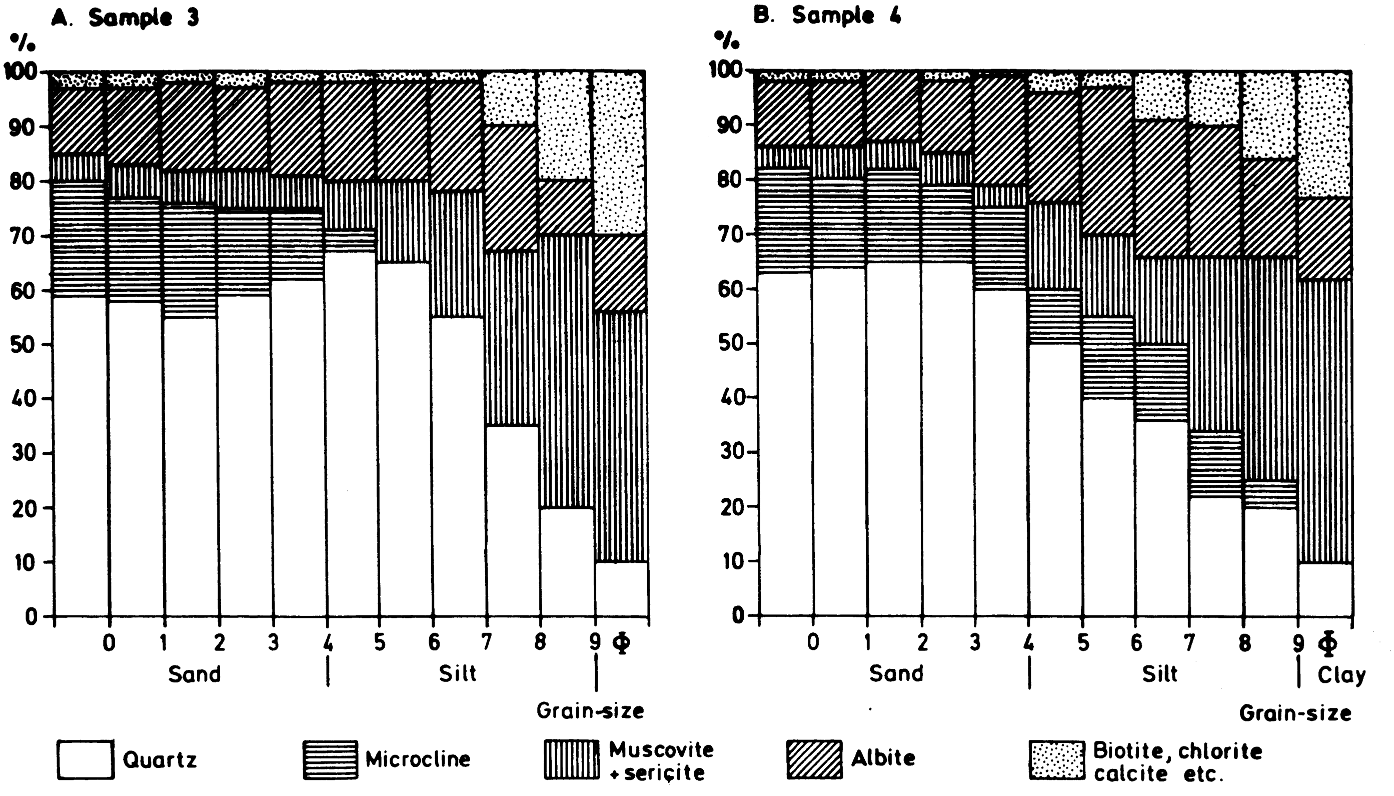

Fig.17 Relative mineralogical composition of till samples 3 and 4.

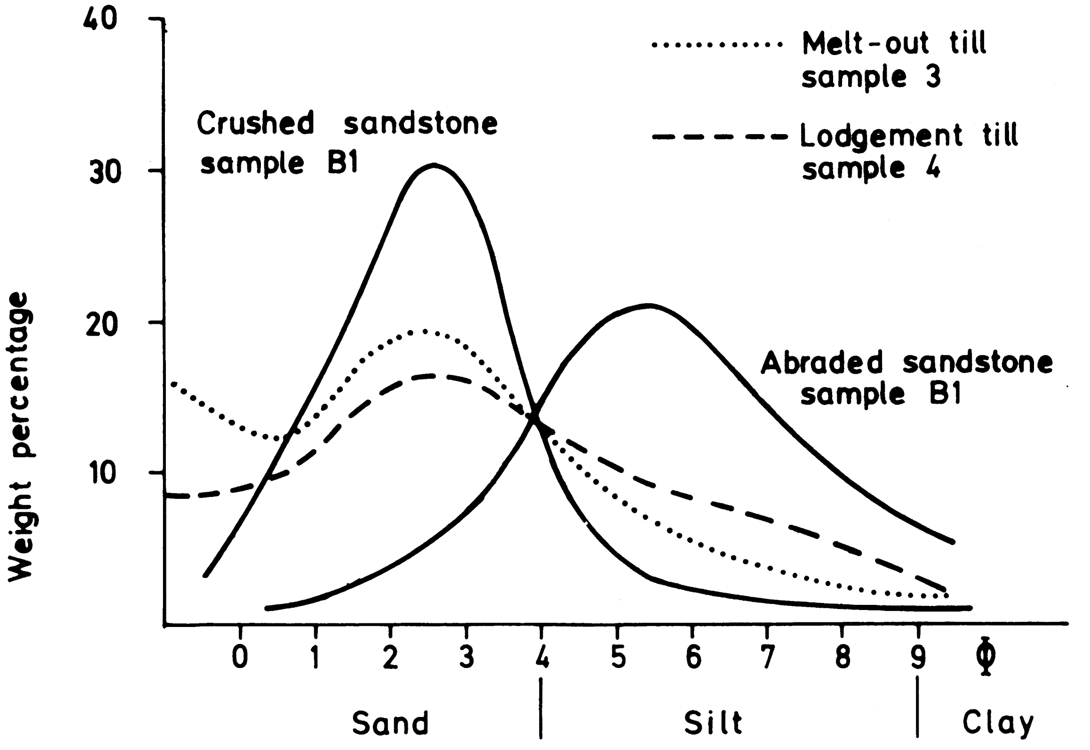

Fig.18 Grain-size distribution per 1 Φ interval of till samples 3 & 4 and of crushed and abraded sandstone sample B1.

seems to be in accordance with the sampled sandstone type 3.

TILL GROUP C FROM THE COMPLEX BEDROCK AREA IN THE SOUTHWEST

Till group C (Table 2) is complex; some samples have a composition close to till group A, others are similar to group B. The geochemical variation shows no relation to specific genetical or topographical features. The variations are explained by local influence from a few, isolated sandstone/shale horizons alternating with the more uniform sandstone bedrock (Fig.2).

RELATIONSHIP BETWEEN TILL MATRIX GEOCHEMISTRY AND TILL GENESIS.

In this section the influence of till forming processes (Fig.1) upon the till geochemistry is discussed.

Haldorsen (1981) showed that glacial crushing may produce another type of till material than that resulting from the glacial abrasion - even in cases where the till is formed from a homogeneous source rock. This is demonstrated for a sandstone sample B1 from the southern homogeneous bedrock area (Fig.2). This sample was moderately crushed in one series of ball mill experiments and abraded in another. The initial size of the sandstone fragments in both cases was -5 to 4 ϕ (32-16 mm). The abrasion process was stopped when the grains obtained the same degree of roundness as the dominating subangular gravel grains in the till.

The difference between the two artificial comminution processes is revealed in the final grain-size distribution. The crushing mainly caused cracks along grain boundaries. The final grain-size distribution was about the same as in the primary rock (Haldorsen 1981). The material was dominated by sand, with a mode in the 2-3 Φ fraction (Fig.18). The abrasion afforded much more cracking across mineral grains and gave mainly a coarse to medium silt (Fig.18).

The difference between the artificial crushing and abrasion is clearly reflected also in the mineralogical composition. During the crushing the different minerals retained their primary size distributions well. During abrasion all the mineral types were significantly comminuted beyond their primary size (Fig.19) and the feldspars and sheet silicate minerals were more comminuted than quartz. The abrasion studied in the laboratory is believed to have occurred in the following way. Initially the edges and corners of the angular sandstone fragments were pressed into cavities and fractures of the other angular sandstone fragments. By the relative movements between the particles, minerals with marked planes of weakness (feldspar, mica) or soft minerals (mica, chlorite) were more exposed to comminution than the more resistant grains (quartz). Feldspar and sheet silicate minerals were thereby selectively abraded from the surface of the gravel grains, until the quartz grains constituted the most exposed parts of the surface. By this time also quartz grains were removed from the gravel surface by abrasion, but the quartz partly avoided breakage because of its resistance. The quartz thereby remained in the sand after the abrasion process was finished. Feldspar grains, particularly albite with marked planes of weakness along interstitial sericite grains, were much more disintegrated and the bulk feldspar in the material formed by abrasion was concentrated in the coarse and medium silt size (Fig.19 B). The soft minerals, mainly mica and chlorite, were grinded by the harder quartz and feldspar minerals and ended up in the fine silt grades (Fig.19 C). The abrasion process as a whole gave a sand fraction enriched in quartz (Fig.20) and silt fraction enriched in feldspar and mica.

The selective mineralogical fractionation produced by the abrasion is reflected in the geochemistry (Fig.16). The enrichment of quartz in the sand is reflected by a low Al_2O_3: SiO_2 ratio. The enrichment of feldspar in the coarse to medium silt and sheet silicates in the fine silt gave high Al_2O_3: SiO_2 ratios (Fig.16 A). The feldspar variation is clearly reflected also in the Na_2O content (Fig.16 B). The K_2O-curve reflects the enrichment of both microcline and muscovite in the silt (Fig.16 C).

TILL TYPES 3 AND 4

Till samples from group B, taken east of Åsta (Fig.3), have on average a significantly higher content of SiO_2 and lower contents of Al_2O_3, Na_2O and K_2O than samples taken west of Åsta. Till group B can thus be divided into two regional subgroups; till type 3 (east of Åsta) and till type 4 (west of Åsta) (Fig.11 & Table 5).

Till type 3 is partly interpreted as a subglacial melt--out till. Such tills are found in the eastern mountainous area, but also in lee-side positions relative to the main directions of ice movements (Fig.11). During a short glacial transport before deposition by a melt-out process, the material was crushed but not significantly abraded. Since the crushing from gravel to sand mainly took place along the grain boundaries, it gave a great proportion of uncomminuted mineral grains (Haldorsen, 1981).

Till type 4 is interpreted as mainly a lodgement till (Fig.11). In addition to the mineral material produced by crushing, this till is significantly enriched in silt which is the result of abrasion (Fig.18) (see also Haldorsen 1981).

Till samples 3 and 4 are taken from till types 3 and 4 respectively (Fig.11). The composition of samples 3 and 4 can be compared with the crushed and abraded sandstone sample B1 from the data given in Figs.16-19.

Sample 3 is taken from a melt-out till in a lee-side position close to the locality of bedrock sample B1 (Fig.11). Since this till sample represents a material which was dominantly formed by crushing, the grain-size distribution, as well as the mineralogy and the geochemistry within each particle size interval, resembles that of the artificially crushed bedrock (Figs.16-19).

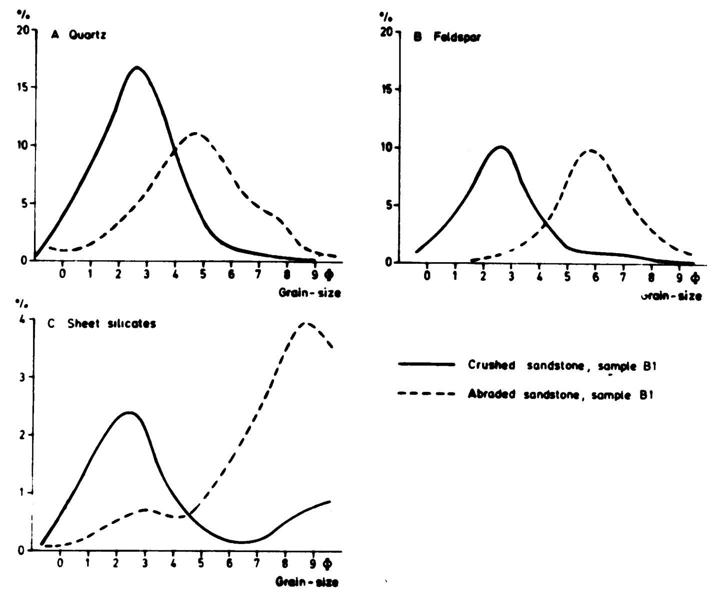

Fig.19 Total mineralogical composition per 1 ϕ interval of crushed and abraded sandstone sample B1. Calculated from grain-size distribution (Fig.18) and relative mineralogy.

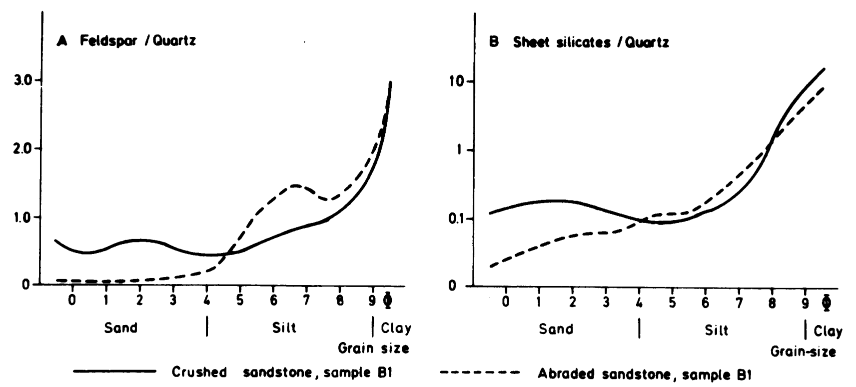

Fig.20 Relative mineralogical variation through different 1 Φ intervals of crushed and abraded sandstone sample B1.

Sample 4 represents a typical lodgement till from the southernmost part of the western valley side. It is collected from a locality so far towards south that any influence from the shale may be excluded. The geochemistry of the sand and very coarse silt resembles that of till sample 3 (Fig.16). The medium silt to clay grades have a higher ratio of Al_2O_3:SiO_2 and higher contents of Na_2O and K_2O than sample 3. This is reflecting that the lodgement till contains more feldspar and mica in the silt + clay than the melt-out sample (Fig.17). As a result of this the bulk silt + clay of sample 4 is enriched in Al_2O_3, Na_2O and K_2O compared with sample 3. This is balanced by a certain deficiency of these components in the sand. Both the Al_2O_3:SiO_2-ratio and the Na_2O content are very much alike for the bulk matrix of till samples 3 and 4 (Fig.13). The variation in geochemistry shown in Fig.16 is therefore interpreted as the result of a mineralogical fractionation, caused by different ratios of crushed and abraded material, like that described from the comminution experiment.

Till samples 3 and 4 reflect characteristic genetical properties of their respective till types. When samples influenced by material from the shale bedrock in north are excluded, there is a more marked positive correlation between Al_2O_3 and Na_2O in till type 4 than in any other till type (Table 3). There is also a marked positive correlation between Al_2O_3 and K_2O while there is only a weak positive correlation between Al_2O_3 and Fe_2O_3 or MgO. This indicates that the geochemical variation is mainly dependent on the variation of feldspars and muscovite resulting from a variable degree of abrasion.

The total number of samples from till type 3 contains on average more Al_2O_3 than sample 3, because till type 3 generally is somewhat more abraded than the material at typical lee-side localities. During the deglaciation phase much of the material along the eastern valley side was transported under temperate conditions along the base of the sliding glacier. Some material was deposited after a rather short transport, the remainder was transported for a greater distance. The result is a variable degree of abrasion and hence a variable silt + clay geochemistry. This is probably the reason why SiO_2 and Al_2O_3 have rather high standard deviations in till type 3 (Table 5).

Another factor which may have influenced the composition of till type 3 is the meltwater (Fig.1 factor C). During the deglaciation much more meltwater drained along the eastern than along the western valley side. Removal of fine silt and clay during or after deposition would give a more SiO_2-rich silt + clay (see Fig.16). Fluvial activity may be responsible for some of the difference between till type 3 and 4 but the geochemical difference between these types cannot be explained only by the removal of fines. The difference is presumedly also the result of different genesis.

The conclusion from the discussion above is that the glacial abrasion has given not only another grain-size distribution than the glacial crushing (Fig.18), as pointed out by Haldorsen (1981), it has in addition resulted in another size distribution of the minerals which is clearly reflected in the bulk silt + clay geochemistry (Table 6) and in the geochemistry of more restricted grain-size intervals (Fig.16).

In the homogeneous sandstone area in the south the conditions are very favourable for studying this mineralogical fractionation. The bedrock is easily crushed to separate minerals and the most resistant mineral, quartz, is originally more abundant than the feldspars and mica in the coarse silt (Fig.20). Since a pure glacial crushing process in many ways differs from a glacial abrasion process, similar lithological variations may also occur in other areas dominated by homogeneous, relatively coarse-grained bedrocks.

When the bedrock is fine-grained, such a differentiation should not be expected. The product of abrasion will then be very similar to the product of crushing. In areas where fine-grained rocks alternate with coarse-grained types, as in the northern part of Åstadalen (Fig.2), the differentiation described above and demonstrated in Figs.19 & 20, will probably be quite subordinate. Variations due to variable ratios of material from the two different bedrock components will then control the variation of the till geochemistry.

FREQUENCY DISTRIBUTIONS OF ELEMENTS IN THE TILL

In this section some aspects of frequency distributions of geochemical parameters in till are discussed. The discussion is based on the conclusions from the preceeding sections.

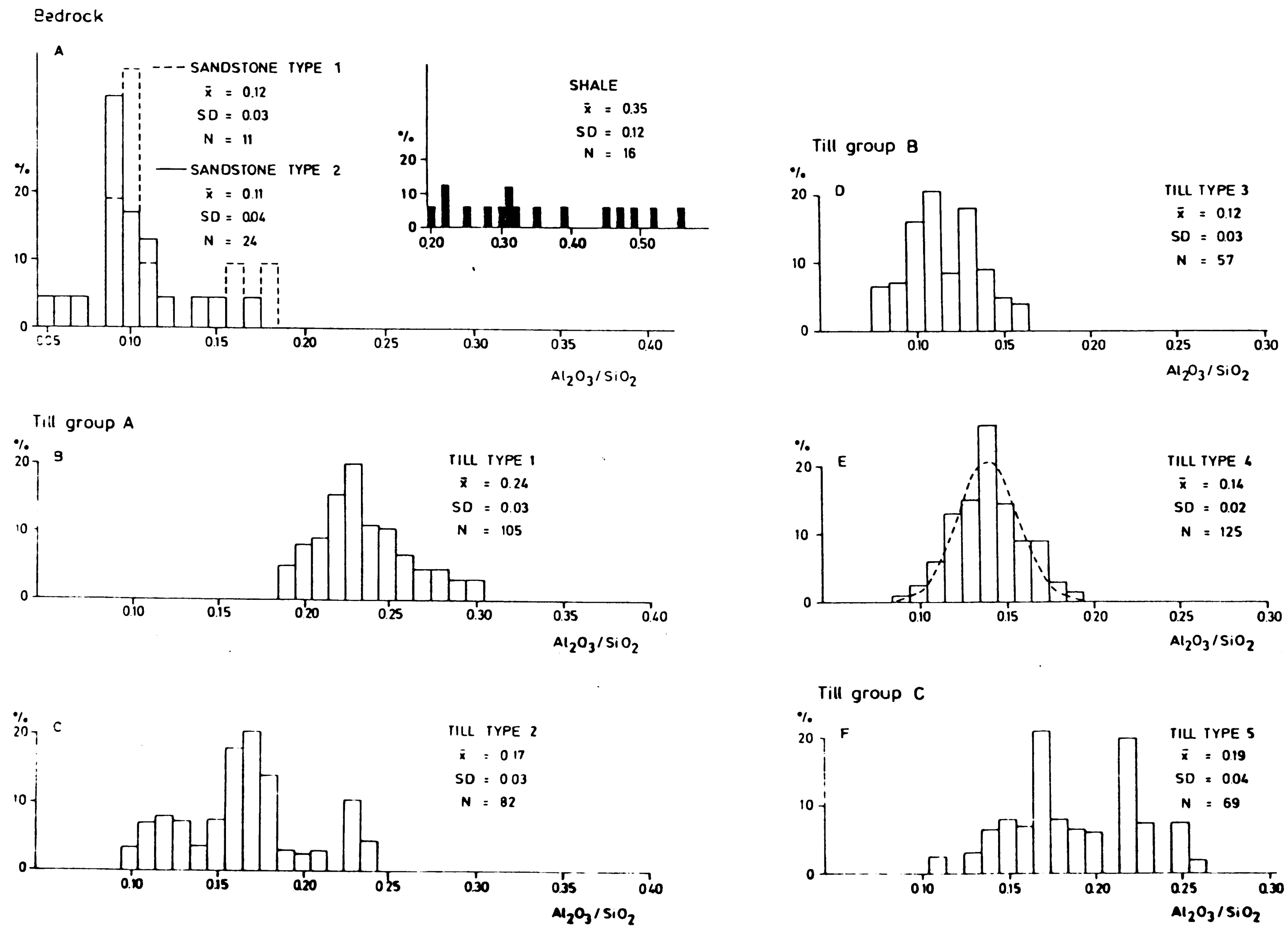

Fig.21 Histograms of the Al_2O_3:SiO_2- ratio frequency distribution of bulk bedrock and the silt+clay of till types 1-5. Stipled curve in E shows the normal distribution curve calculated from the mean value ($\overline{x}$) and standard deviation (SD) of till type 4.

There are many general descriptions of elements in soils. Normal, lognormal as well as more complex distributions are reported (e.g. Govett et al. 1975, Lepeltier 1969, Malmqvist et al. 1968, Sinclair 1974, 1976, Tennant & White 1959 and Bjørklund in press.).

Normal distributions of elements in till are rare in regional surveys, probably because the source rocks are too varied to produce such distributions. In the present case the southern sandstone area (Fig.2, group B) is the only bedrock group which is sufficiently homogeneous.

Another requirement for normal distributions of elements in till is normal distributions of elements in the bedrock. This is rarely the case and distribution patterns of elements in rocks are commonly better described by lognormal distributions (Ahrens 1954, Sinclair 1974). In the present case it is difficult to calculate the distribution types of elements in the source rocks because only a few samples are analysed. Based on the data available one can not exclude, for instance, that the Al_2O_3: SiO_2 ratio forms normal distributions in the sandstone (Fig.21 A). If the Al_2O_3: SiO_2 ratio of the shale and the sandstone form normal distributions and components from the two rock types were uniformly comminuted and sufficiently mixed during glacial transport, then the compound till material of till types 1 and 2 would possess normal distributions of Al_2O_3:SiO_2 ratios. In practice a glacier does not work like an effective mixmaster. Skewed distributions like the Al_2O_3: SiO_2 ratio distribution of till type 1 or different frequency maxima like those of till type 2 (Fig.21 B & C) are to be expected.

Even when some elements within the bedrock satisfy both the conditions above, the distribution within the resultant till material is not necessarily normal. Earlier in the paper it was demonstrated how glacial crushing and abrasion influence the distribution of minerals and geochemical components in different matrix fractions (Figs.16-20). When bulk matrix geochemistry was considered, a crushing versus an abrasion did not make any sense for the geochemistry (Fig.13), since the total matrix in both cases included all the source rock components. The differences in geochemistry were observable only by comparison between limited parts of the matrix. Geochemical analyses are, however, commonly based on the silt and clay material only, and different genesis may then significantly influence the distribution of elements, as shown by the data for till types 3 and 4 (Fig.21 D & E) . Consequently a normal distribution of elements should only be expected in cases of uniform till genesis.

The discussion above leads to the conclusion that till of types 1, 2, 3 and till group C (=till type 5) (Fig.11) will not form normally distributed elements. Till of type 4 is believed to be a lodgement till of which the parent material is a homogeneous sandstone in a northeast-sloping area (Fig.11). This situation should promote normal distributions of geochemical values in the till.

Excluding all samples inside a 5 km zone from the sandstone/shale bedrock boundary the Al_2O_3: SiO_2 ratios of till type 4 are seen to be approximately normally distributed.

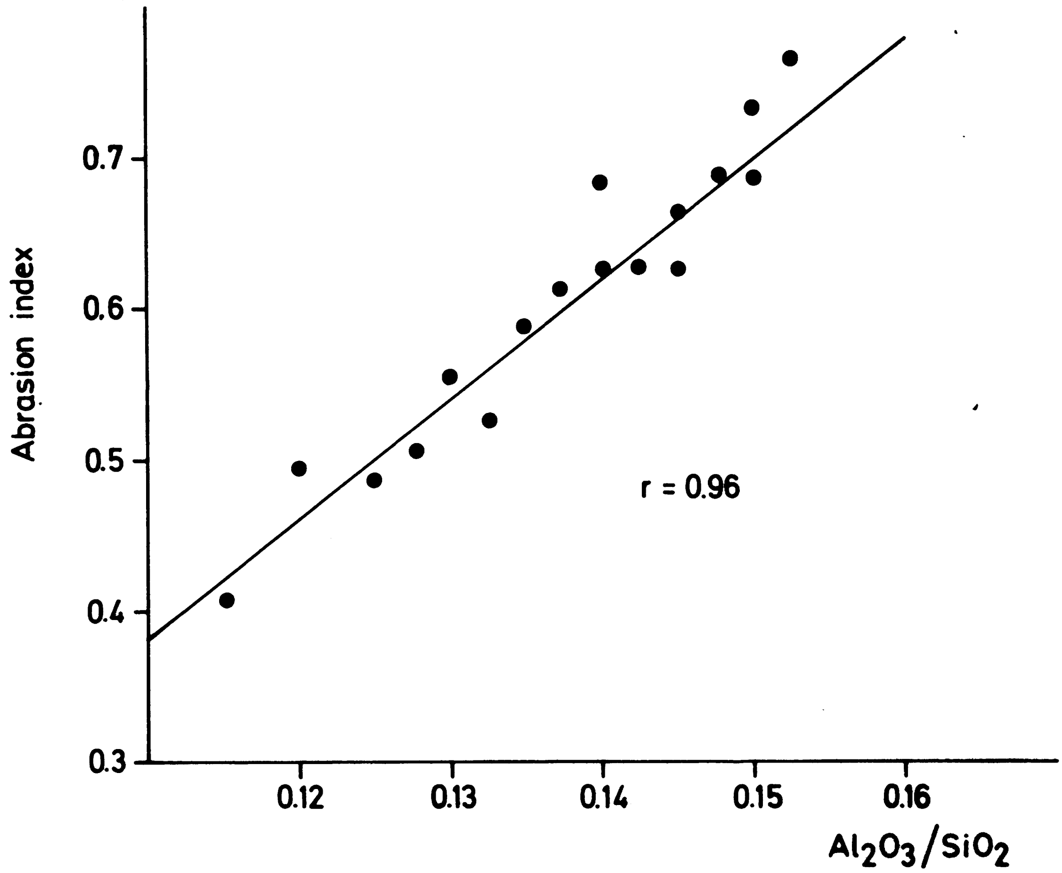

Fig.22 Relationship between the abrasion index and the $Al_2O_3:SiO_2$ ratio of till type 4 (only silt+clay).

A Chi-square test indicated that the hypothesis of normal distribution can not be rejected.

The rate of abrasion in till type 4 can be expressed by an abrasion index which is defined as the ratio between abraded and crushed sandstone in the matrix (Haldorsen 1981). A Chi-square test showed that the abrasion index fits well to a normal distribution. The Al_2O_3: SiO_2 ratio and the abrasion index are positively correlated (Fig.22), supporting the idea of inter-dependence.

The standard deviation of the Al_2O_3: SiO ratio is smaller in till type 4 than in other types (Tables 2 and 5) because of the more nearly uniform genesis and source rock. F-test (N=10) showed that the chemical composition of the total matrix of this till is significantly more homogeneous than that of the underlying sandstone. Local lithological bedrock variations, for instance mineralisation in fractures, were not reflected in the till. A lithological homogenisation is probably one of the most typical results of the process along the base of an active sliding glacier. The camoflaging of local bedrock inhomogenities is therefore a typical lodgement till characteristic.

Homogenisation processes have smoothed out the local alternation between sandstone and shale beds also in the northwestern part of the Åstadalen area where lodgement till dominates (Fig.11). This is the reason why the Al_2O_3: SiO_2 frequency curve of till type 1 (Fig.21 B) is skewed but not bimodal, though the sandstone has an Al_2O_3:SiO_2 ratio mode which is totally separated from that of the shale (Fig.21 A). In the northeastern part of the Åstadalen area, a tendency towards a polymodal distribution is found (Fig.21 C), since the distance between the shale horizons here is greater than further west, and the till material is frequently of a more short transported melt-out type.

The distribution of Al_2O_3: SiO_2 in till type 5 (=till group C) appears to be bimodal (Fig.21 E). One part of the population is probably formed from the alternating sandstone/shale bedrock and the other from the sandstone alone. The glacial homogenisation process seems, in this case, to have been rather incomplete, even though the till is of a lodgement type.

Such composite distributions are probably common in tills from areas with highly variable bedrock composition. In cases of bimodal till populations, two monomodal distributions may be identified by increasing the number of samples in the grid. For till type 5 this was not possible in practice. Even samples taken at distances of 10 metres in some cases differed considerably. Small, isolated inclusions of a shale-rich till seemed to occur within the common sandstone--rich type. There were no boundaries visible in the field or detectable by gravel countings or grain-size analyses.

Another type of bimodal distribution occurs in till type 3 (Fig.21 D), as a result of complex till genesis. Material of subglacial melt-out origin is found at lee--side localities, and as local inclusions in lodged material, without any clear boundary against the latter. This melt-out till is represented by the low-value mode of Al_2O_3:SiO_2 in Fig.21 D. The lodgement till, on the other hand, is represented by the high-value mode. As with till type 5, a regional division into two monomodally distributed subpopulations is difficult, and a certain bimodal trend remained even when all samples from typical lee-side localities were excluded. The explanation may be that local material has been eroded from sandstone beds many places along the northeastern valley side, and deposited together with longer transported lodgement till.

EXPONENTIAL CURVES

Krumbein (1937) found that the dispersion of boulders in a glacial boulder train follows a negative exponential curve. Gillberg (1965) and Perttunen (1977) found similar exponential decreases of many particle sizes of glacially transported clasts from one bedrock, measured in the down-glacier direction from its distal contact. Idealised, one would expect that all particle size intervals from a bedrock form negative exponential curves when they are glacially dispersed into other bedrock types. Shilts (1976) concluded that also the concentration of heavy metals could form such negative exponential curves.

In a small, rather flat area of 1 x 5 km with lodgement till, just south of the boundary for the shale/sandstone bedrock in the northwest (Figs.2, 11 & 23) a detailed investigation was carried out to see if exponential decreases of the shale/sandstone bedrock components could be traced. A rapid but regular southwards decrease of shale in the -4 to -3ϕ (16-8 mm) fraction was observed with a

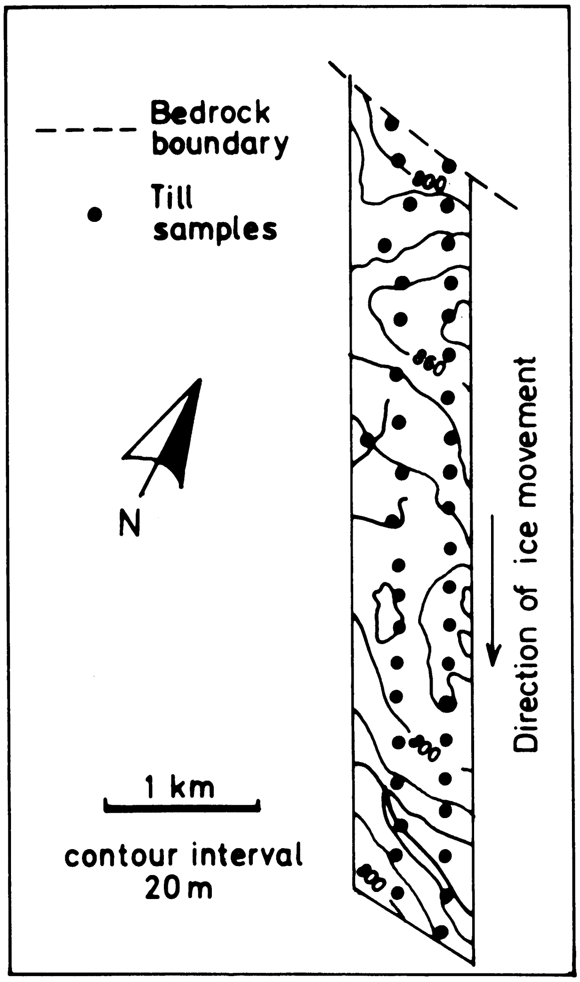

Fig.23 Sampling localities for till samples in the transitional zone between till types 1 and 4. Situation of the area: see Figs.2 & 11.

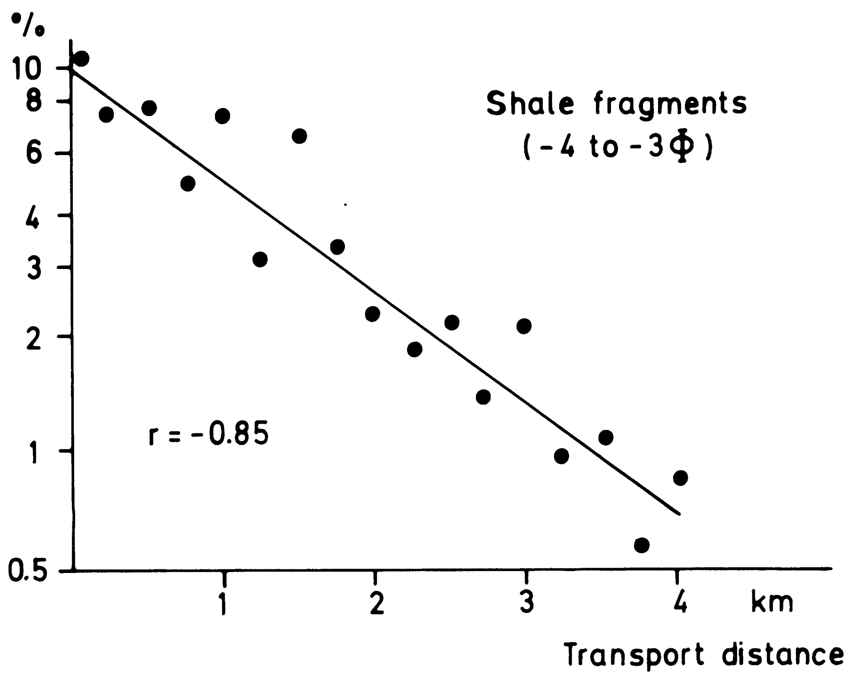

Fig.24 Distribution line of shale gravel fragments in down-glacier direction from the bedrock boundary in the area shown in Fig.23. Semilogarithmic scale.

good approximation to an exponential curve (Fig.24). The requirement for obtaining exponential decreases of till components from the northwest was satisfied.

A dense sampling for geochemical analyses was carried out from 2 m depth across the limited area of Fig.23. Fig.25 shows the Al_2O_3: SiO_2 ratio measured along the direction of late ice movement (Fig.11). The deviation from an exponential curve is significant. The decrease is apparently more rapid than for the shale fragments (Fig.24), because of the high background values of Al_2O_3: SiO_2 in the sandstone.

The theory of an exponential dilution proposed by Krumbein (1937) was worked out for rock fragments in tills and not for single chemical constituents.

Deviations from exponential curves, as in the present case, should be expected when elements, or ratio of elements are most abundant in the proximal bedrock type but are also significant in the distal bedrock (c.f. Bjørklund in press). The higher the background value in the distal rock type the more rapid is the decrease to the background value.

An approximation to the theoretical exponential curve is given in Fig.26. The average value of Al_2O_3:SiO_2 for till type 1, (0.24, see Fig.21 B), minus the average of till type 4, (0.14, see Fig.21 E) is regarded as 100 %. The distance from the bedrock boundary to the area where the till on average has an Al_2O_3: SiO_2 ratio of 0.14 is about 5 km. This was the transport distance needed to deposit the total component from the sandstone/shale bedrock.

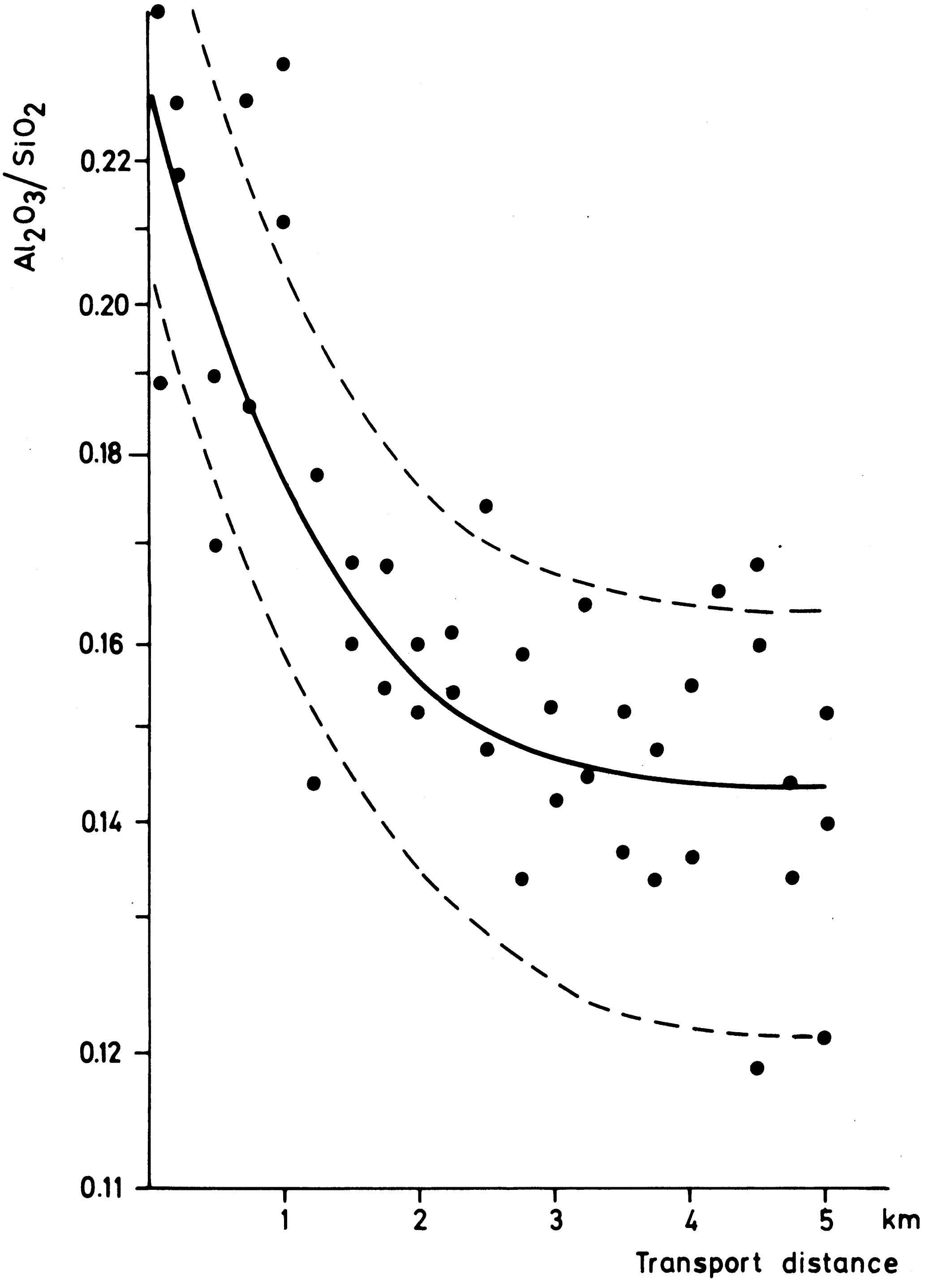

Fig.25 Distribution of Al_2O_3:SiO_2 ratios of the silt+clay in down-glacier direction from the shale/sandstone bedrock boundary (see Fig.23). Theoretical mean value curve is given with one standard deviation denoted by dashed lines. Semilogarithmic scale.

The values plotted in Fig.26 are the measured values of $Al_2O_3:SiO_2$ minus the background value (0.14). The approximation to the exponential curve is fairly good within a transport distance of 3 km. Outside this distance the difference between the observed values and the background is too small compared with the accuracy of the analysis.

The theoretical curve in Fig.25 was constructed from mean values of Al_2O_3: SiO_2 for till types 1 and 4. In reality each of the two components belongs to the respective frequency distributions shown in Fig.21 B & E. The value of each composite sample may differ considerably from the mean value curve in Fig.25. Most of the samples are within one standard deviation of the mean value (Fig.25) and all samples are inside a confidence interval of 95 %. The hypothesis of an exponential dilution of components from the sandstone/ shale bedrock is therefore not rejected.

Composite geochemical populations formed by exponential dilutions have recently been described by Bjørklund (in press). Based on the ideas from that study and the observed distributions in Åstadalen, three different frequency distributions of $Al_2O_3:SiO_2$ have been simulated. The basis is an exponential dilution down to the background value in a 5 km distance, as in the area of Fig.23.

1. Till type 1 is dispersed into a till with an insignificant amount of Al_2O_3.

The Al_2O_3: SiO_2 value for each 0.25 km of transport was calculated from the exponential curve and samples drawn randomly from the frequency distribution of till type 1 (Fig.21 B). When presented in a histogram, the distribution

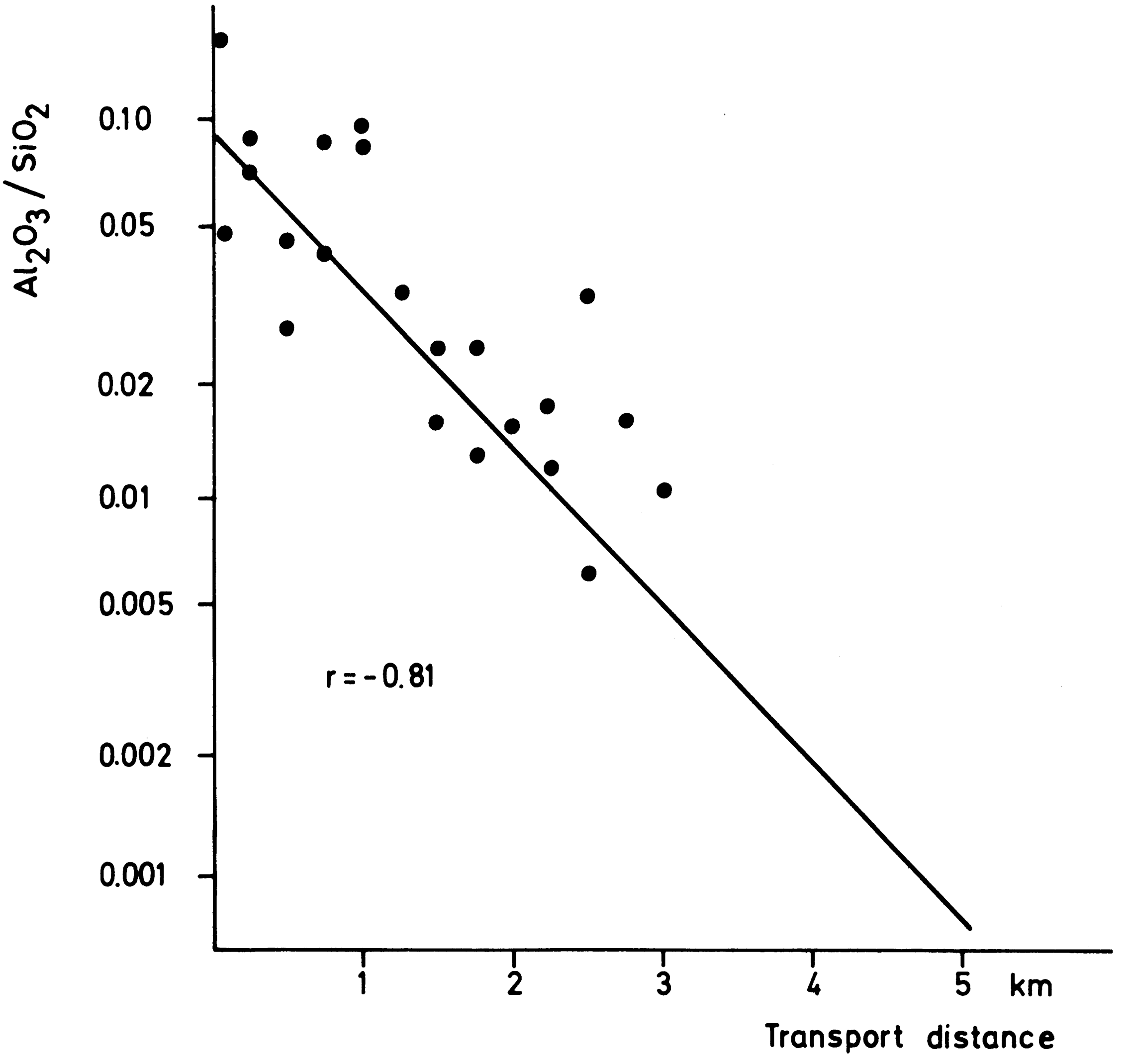

Fig.26 Distribution of Al_2O_3:SiO_2 ratios given in Fig.25 when the background value of till type 4 has been subtracted. Theoretical line is given. Semilogarithmic scale.

is distinctly skewed (Fig.27 A). The cumulative curve shows that the distribution deviates much from a lognormal distribution, even in its central part (Fig.28, curve A).

2. A till material with insignificant amounts of Al_2O_3 is dispersed into a till of type 4.

The calculations are performed in the same way as for model 1. There is a distinct deviation from both a normal and a lognormal distribution (Figs.27 B & 28, curve B).

These two models are hypothetical since almost all tills contain significant amounts of Al_2O_3. The models may illustrate the distribution of more rare chemical components.

3. Material of till type 1 is dispersed into material of till type 4. This is the actual model for the composite till in the area of Fig.23. The approximation to a lognormal distribution is good (Fig.29). In Fig.27 C this and the observed distribution of samples from the area of Fig.23 are shown. The observed distribution deviates much from the expected lognormal distribution. On the basis of these few samples it would be impossible to determine whether they belong to a lognormal distribution, to distributions like those of models 1 and 2 (Figs.27 & 28) or other, more complex distributions.

As shown in Figs.27 & 29, lognormal distributions may occur in areas where there is a completely regular dilution of one till component in the manner of a negative exponential curve. This requires uniform topography and a genetically uniform till preferably of a lodgement type. When the till is of a local melt-out type, as in the northeastern part of

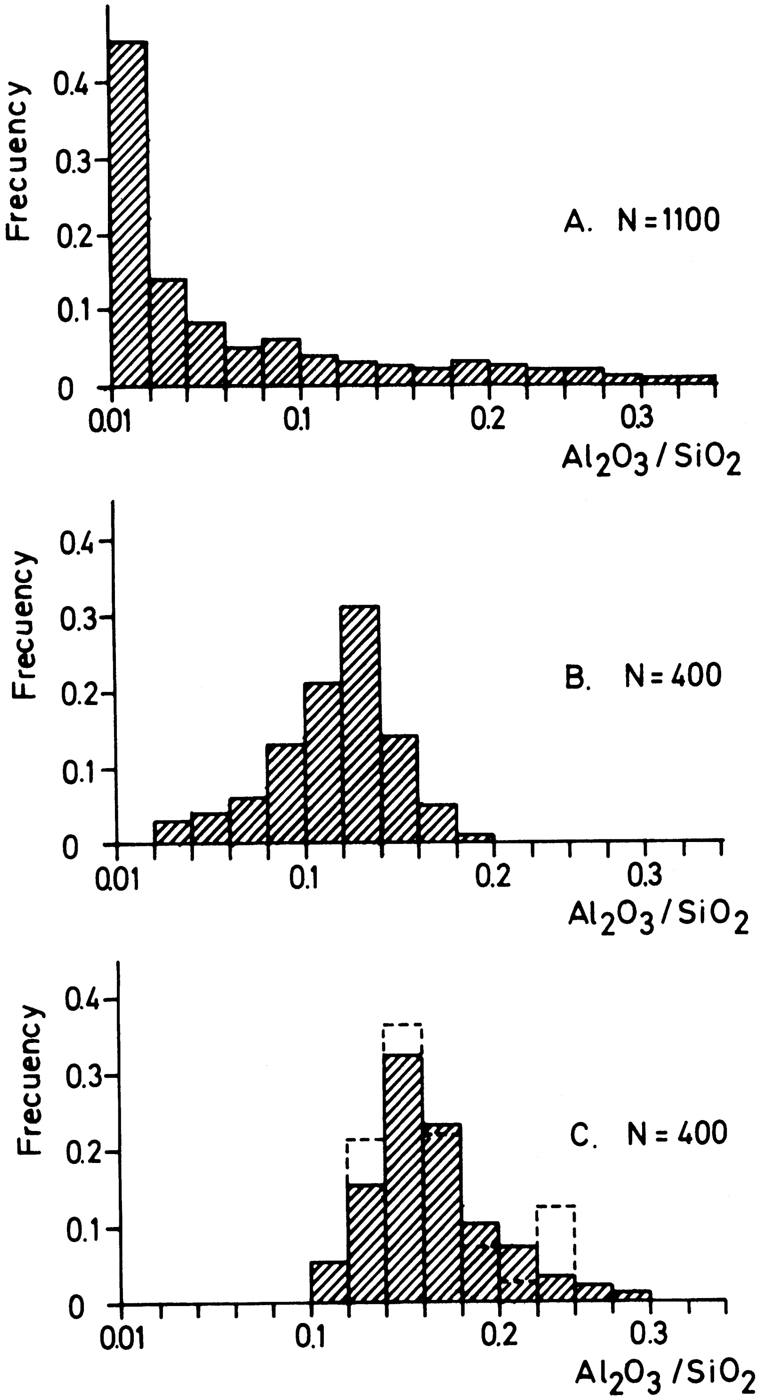

Fig.27 Histograms of simulated Al_2O_3:SiO_2 ratio distributions.
A: Till type 1 diluted according to a theoretical exponential curve into a till with a background value of Al_2O_3 approximately zero.
B: A till with Al_2O_3 value of approximately zero, diluted into a till type 4 according to an exponential curve.
C: Till type 1 diluted into till type 4 according to an exponential curve. The observed distribution of the compound population of Fig.23 is shown by dashed lines.

Åstadalen (Fig.11), the transport has been very short. Exponential curves and lognormal distributions of elements can then scarcely be observed without an extremely dense sampling grid. If topography and till genesis is variable, as in great parts of Norway, exponential dilution of till components will not occur (Shilts 1976) since the erosion, transport and deposition of debris will have changed frequently along the direction of ice movement (Minell 1978).

The frequency distributions of elements in natural till populations are usually skewed but are probably only exceptionally lognormal. This principle was in general realized by Sinclair (1976, p.12) who wrote that 'no fundamental "lognormal law" has been stated or should be implied'.

CONCLUSION

The studied subglacial till was in the north derived from an alternating sandstone/shale bedrock and in the south from a pure sandstone. The relation between shale and sandstone components in the silt + clay can be calculated roughly, for instance by means of the Al_2O_3: SiO_2 ratio. The variation of Al_2O_3:SiO_2 is dependent both on bedrock features and till genesis. In the northeastern part of the area, less shale has been eroded than in the northwestern part, because the shale horizons in the east have been more protected. However, the shale to sandstone ratio in the silt

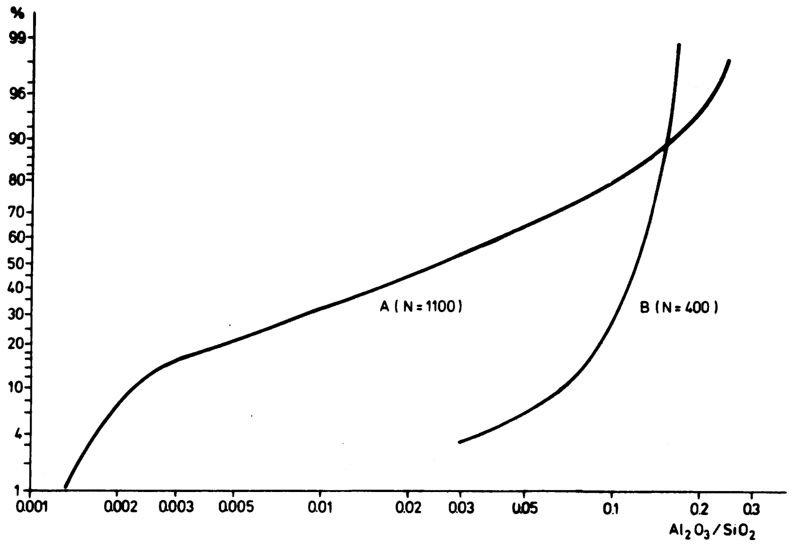

Fig.28 The cumulative frequency distribution of Al_2O_3:SiO_2 for the population of Fig.27 A & B. Abcissa: logarithmic scale, ordiate : normal distribution probability scale. A & B: Information given in Fig.27.

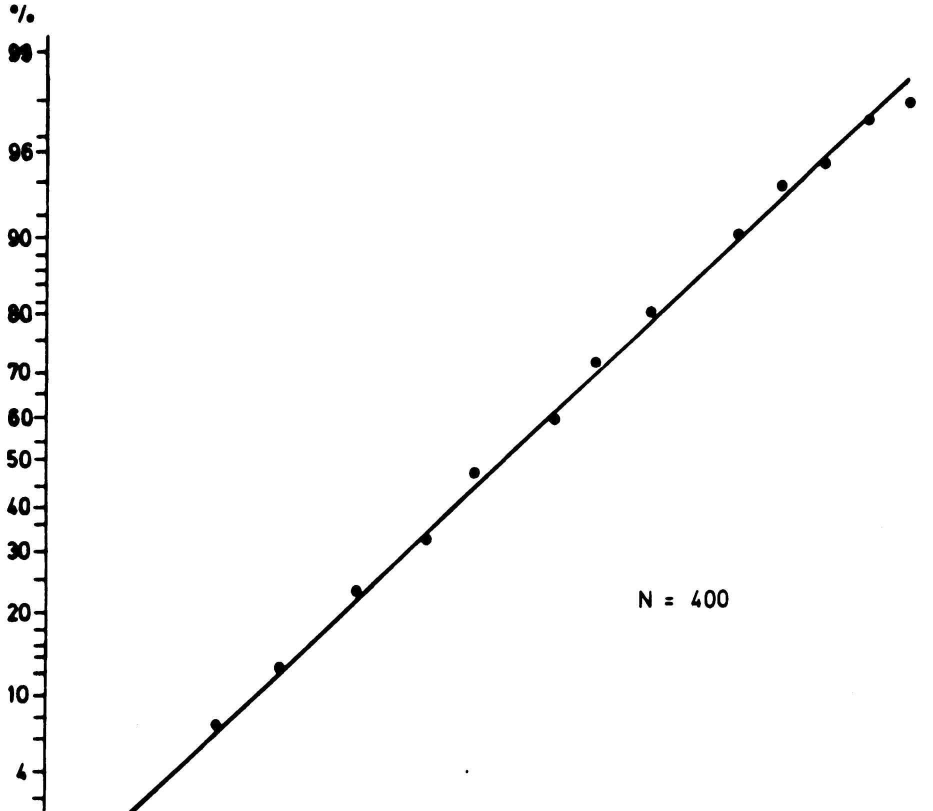

Fig.29 Theoretical cumulative frequency distribution of Al_2O_3:SiO_2 for the compound till material in the area of Fig.23. Calculated for a 0 to 5 km distance.

+ clay is also dependent on the glacial comminution processes. By moderate crushing, the tills obtain a silt material which is dominated by sandstone components. By a combination of intensive crushing and abrasion, the finer-grained till material is successively enriched by shale components, because the soft and fine-grained shale minerals are more exposed to abrasion than the sandstone. The silt + clay of a lodgement till is therefore more rich in shale than the silt + clay of a melt-out till.

The till overlying the homogeneous sandstone in the south can be regionally divided into two subtypes related to its genesis. In a melt-out till a crushing process has dominated and each particle size interval has a composition very similar to the respective particle interval in the sandstone bedrock. The coarse silt is most dominated by quartz, and has a low Al_2O_3: SiO_2 ratio. In the lodgement till the silt is more enriched in feldspar and mica, giving a higher Al_2O_3: SiO_2 ratio. The abrasive grinding caused more disintegrations along cleavage planes across mineral boundaries, and a selective grinding of soft minerals like mica. It is supposed that a similar lithological fractionation may also occur in other tills from areas of homogeneous bedrock.

The frequency distribution of geochemical components in the till showed a close connection to the bedrock and to the till genesis. The study is concentrated on the Al_2O_3: SiO_2 ratio.

Normal distributions were assumed for tills from the southwestern part of the area. Here the bedrock is uniform, the till genesis uniform and there is a smooth northeast--sloping topography.

The approximation to a normal distribution was here very good.

A sliding glacier can be regarded as a lithological homogeniser which causes local bedrock inhomogeneties to disappear. In some cases this process may be quite incomplete as for instance after a very short transport before deposition by a melt-out process. In areas with variable bedrock the melt-out till has a distinct bimodal distribution of Al_2O_3: SiO_2 ratios. A bimodal distribution was found also in the homogeneous southeastern bedrock area, where the till genesis is variable and the geochemistry was studied only in a certain part of the matrix fraction.

Exponentially decreasing contents of shale gravel material in the direction of ice movement were observed just south of the sandstone/shale bedrock. The Al_2O_3: SiO_2 ratios within the same area deviated much from an exponential curve because of the high background ratios of Al_2O_3: SiO_2 in the sandstone. By subtracting this background value from the observed values, a certain approximation to the exponential curve was obtained. This till material forms a composite population. Separately, the sandstone/shale component transported from north has a distinctly skewed frequency distribution of Al_2O_3: SiO_2. When this material is mixed with the normally distributed Al_2O_3:SiO_2 population in the south, the compound Al_2O_3:SiO_2 population is approximately lognormal. It is suggested that many of the previously reported lognormal or normal frequency distributions in tills may likewise be more complex.

Acknowledgements.

Jens-Olaf Englund kindly placed detailed bedrock data at my disposal. Bjørn Bølviken and Per Jørgensen have given constructive critism of the manuscript. Adrian Read kindly corrected the English manuscript and suggested some alternations of the text. Grete Bloch performed most of the laboratory analysis, the reamining analyses were performed at The Geological Survey of Norway. Åslaug Borgan drafted the figures and Marie-Louise Falch has type-written the manuscript. Financial support was provided by the Norwegian Research Council for Science and the Humanities (NAVF). To all these persons and institutions I tender my sincere thanks.

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PAPER 9

THE ENRICHMENT OF QUARTZ IN TILLS

SYLVI HALDORSEN

The enrichment of quartz in tills

SYLVI HALDORSEN

Haldorsen, S. : The enrichment of quartz in tills.

In Åstadalen, southeastern Norway an abrasion of bedrock fragments in glacial environments has produced a material mainly composed by silt. Feldspar, mica and other minerals with a relatively low resistance on mechanical comminution were grinded down to silt size while the sand was enriched by quartz. A removal of silt and clay by subglacial meltwater resulted in a bulk enrichment of quartz in the remaining sediment. In some places such quartz-rich sediments were incorporated into the glacial ice and mixed with ordinary glacial debris. A subglacial melt-out till with an enrichment of quartz in the sand as well as in the bulk matrix (material finer than 2 mm) was formed. Similar processes may explain why a certain enrichment of quartz is found in tills several places in Scandinavia.

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During a glacial phase the sedimentological processes result in a mechanical comminution, and the rate of comminution depends on the mechanical resistance of the rocks and their constituent minerals and on the types of comminution processes involved, as discussed by for instance Dreimanis & Vagners (1971), Haldorsen (1977, 1978, 1981) and Slatt & Eyles (1981) The purpose of the present work is to study if this comminution may result in a mineralogical fractionation and in combination with other glacigenic processes may produce glacial sediments with a bulk petrographical composition differing significantly from that of the source rocks.

Methods

Major elemental analyses were performed by atomic absorption spectrometry. The mineralogical analyses were carried out by microscopy of thin sections. The fractionation in different particle size intervals was performed in settling tubes and the grain-size analysis was carried out by sieving and hydrometer method.

Source rocks

The investigation was carried out in Åstadalen in southeastern Norway (Fig. 1). This area was chosen because the bedrock is homogeneous and detailed information about its composition is available. The bedrock consists of Late Precambrian sedimentary rocks of the Brøttum Formation (Fig. 1). In the northern part there are

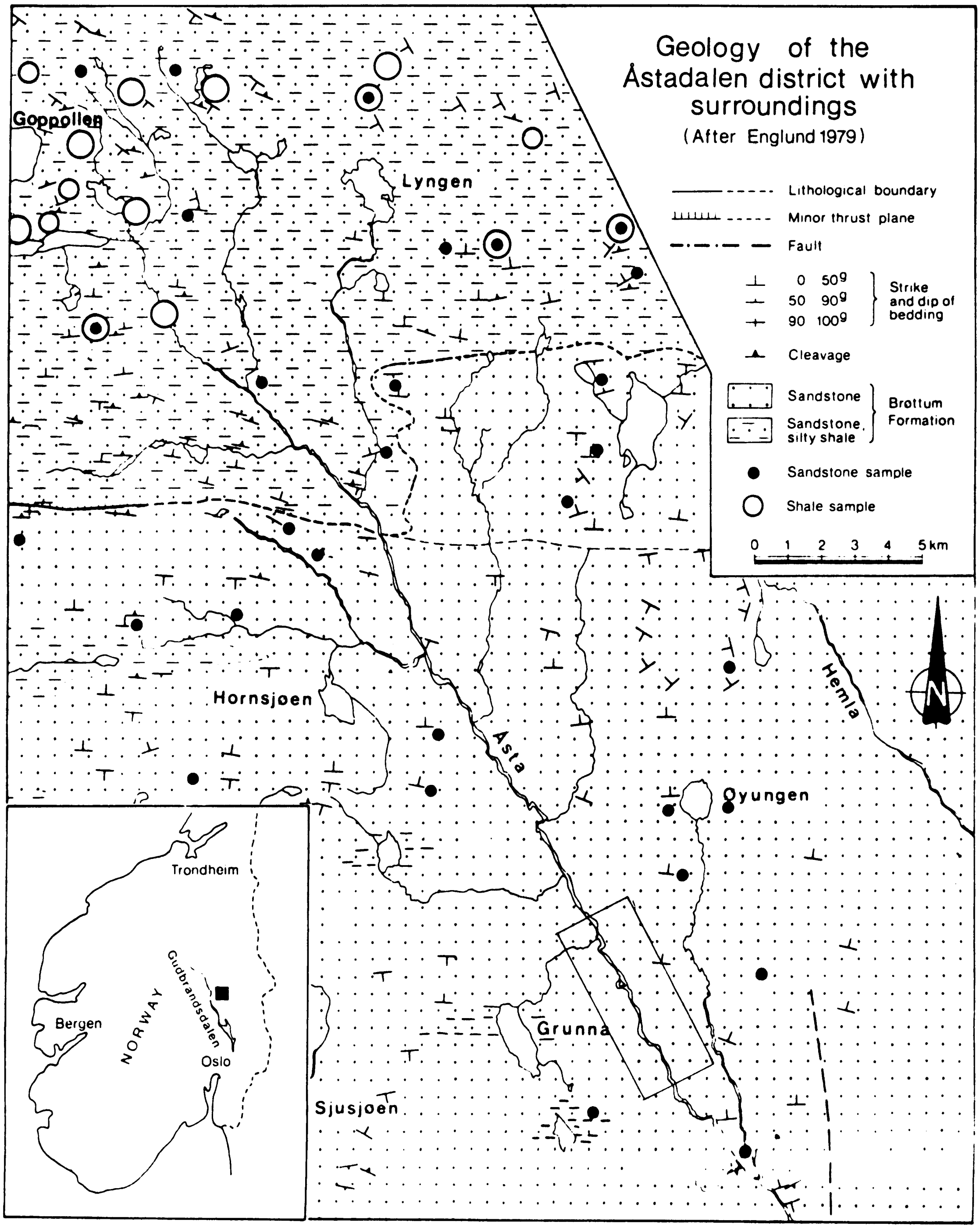


Fig.1 Key map showing the bedrock geology in Åstadalen. The area considered in this study is framed. Inset map shows the location of Åstadalen in Norway.

sandstones alternating with some layers of silty shale, and in the southern part there is a more uniform sandstone. Samples taken from 24 outcrops in the south yielded the average composition shown in Fig. 2 and Table 1. The glacial sediments discussed here are from this southern sandstone area (Figs. 1 & 3).

Subglacial comminution processes

The transition from bedrock to glacial till and subsequently to other glacigenic sediments involves crushing caused by percussion, compression and frost cracking. In addition there may be significant abrasive grinding. These processes are closely connected during glacial transport. Haldorsen (1981 and in prep.) tried to similate separate processes of crushing and abrasion of sandstones from the Åstadalen area by means of several mill experiments. The following are the main conclusions from the experiments:

1. With moderate crushing in a ball mill the grains were crushed until the material was dominated by individual mineral grains. Grain-size analyses of this material (Fig. 4) were compared with the primary size-distribution of minerals in the bedrock (Haldorsen 1981) and a good correspondence was found. It was concluded that the crushing mainly produced cracks between mineral grains and that each mineral retained its size distribution well during this crushing. The mineral composition and the geochemical composition within 1 Φ - interval of

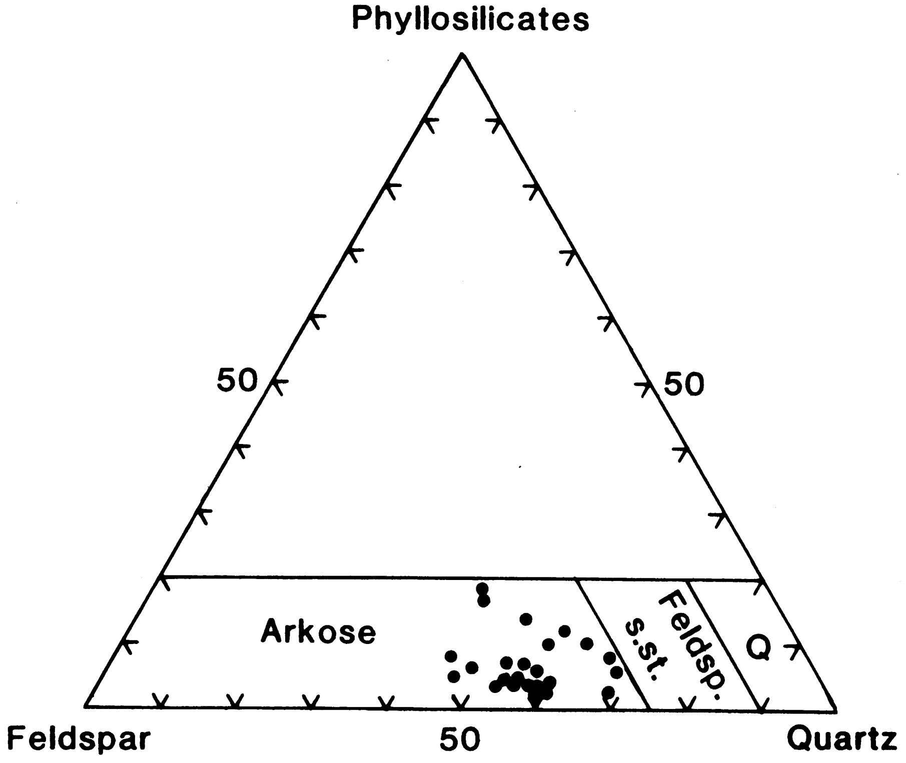


Fig.2 Modal composition of the upper part of the Brøttum Formation. Calculated from 24 bedrock samples from the homogeneous sandstone area in Åstadalen (see Fig.1) (J.-O. Englund, pers.comm. 1980). Q=quartzite.

one crushed sample are shown in Figs. 5 & 6. These are, in accordance with the conclusion from previous papers (Haldorsen 1981 and in prep) believed to reflect the primary composition of the bedrock sample.

2. In another mill experiment some angular gravel grains from the same bedrock sample, were tightly packed to prevent crushing occurring; the comminution process now was an abrasive grinding. The experiment was finished when the gravel grains had reached a subangular to subrounded stage. The abrasion created cracks across minerals and produced a rock flour consisting of coarse to medium silt (Fig. 4). From a detailed till study from Åstadalen Haldorsen (1981) showed that an increase in just the coarse to medium silt of the till corresponded to increased abrasion. Thus the artificial abrasion experiment seems to be illustrative for the process of glacial abrasion.

Both the crushed and the abraded material show the same trend; there is a relative decrease in the content of quartz with decreasing grain-size from coarse silt to clay (Fig. 5). This is reflected in an increase of the Al_2O_3 relative to SiO_2 and in K_2O (Fig. 6). The main difference is that the abrasion gave an enrichment of mica and feldspar in the silt (Fig. 5) because these minerals were more easily comminuted than the quartz. The quartz grains partly retained their original size and were thereby enriched in the sand (Fig. 5). This is reflected in the geochemistry of the sand by the 'excess' of SiO_2 and 'deficiency' of Al_2O_3, Na_2O and K_2O (Fig. 6).

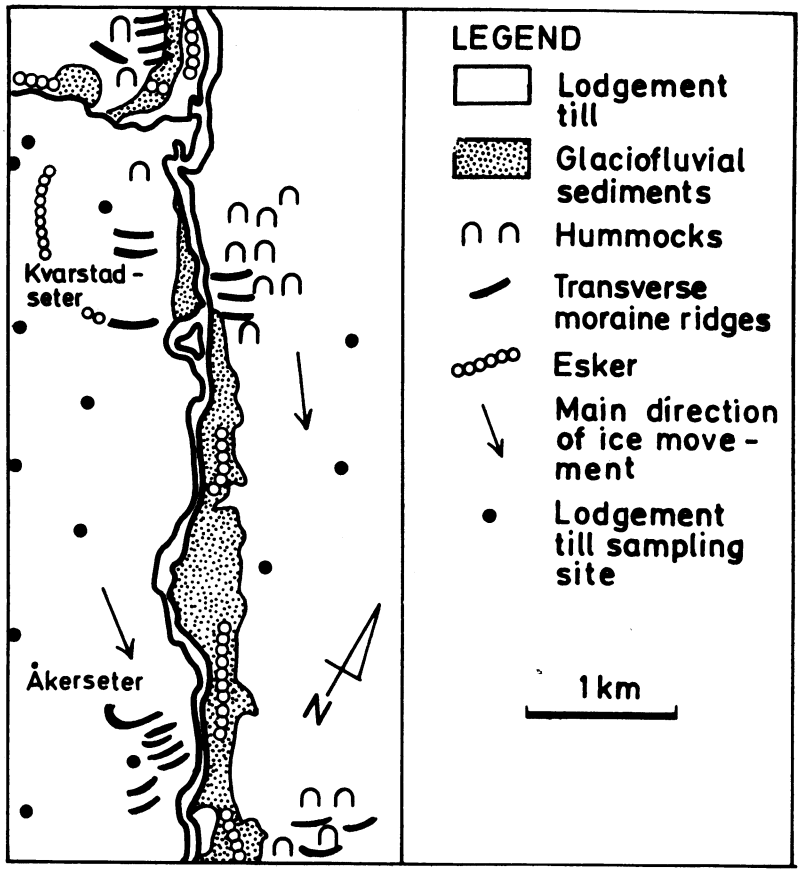


Fig.3 Quaternary geology of the investigated area.

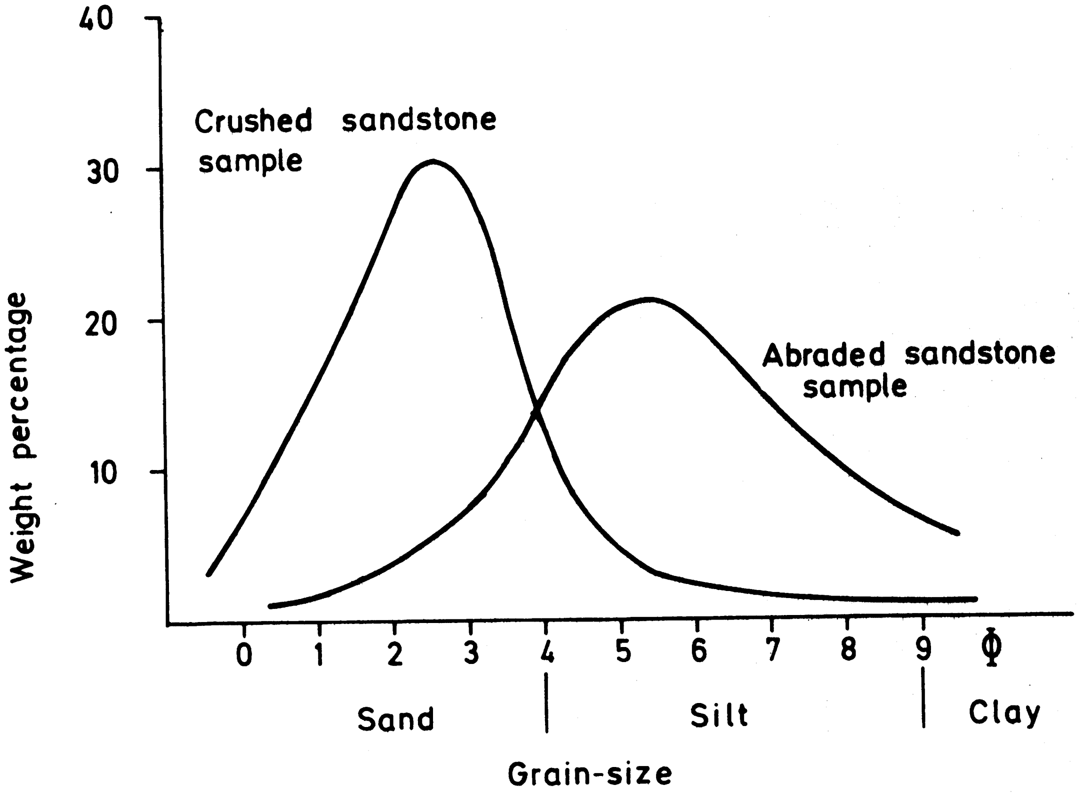


Fig.4 Grain-size distribution of one artifically crushed and abraded sample of the Brøttum sandstone. The sample was first crushed in a ball mill and was afterwards fractionated by sieving and settling in a sedimentation sylinder. The abraded material was formed by attrition of gravel grains of size 16-32 mm. Further explanation about the experiments are given in the text and by Haldorsen (1981).

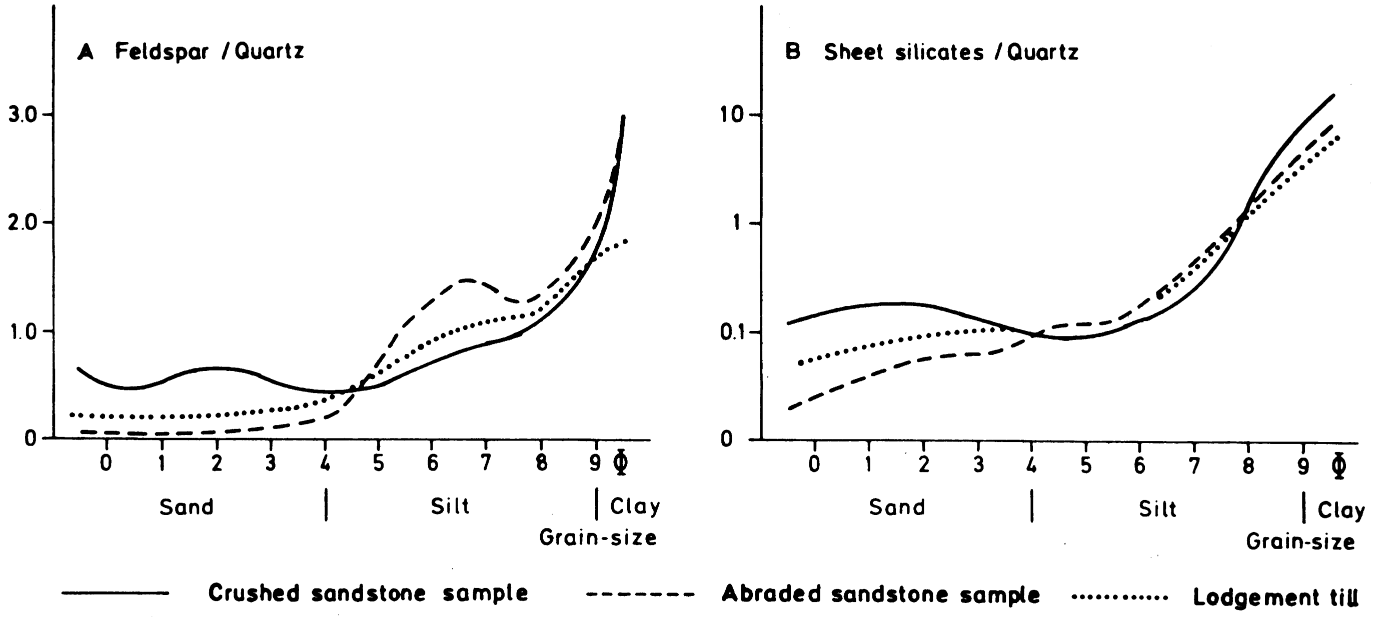


Fig.5 Mineralogical composition of different particle size intervals of the crushed and abraded sandstone sample (for further explanation, see Fig.4) and one lodgement till sample.

Glacigenic sediments

The Åstadalen area represents a typical inland area where the glacial deposits mainly were formed after the Weichselian maximum. An active glacial phase was followed by a phase with rather stagnant ice (Haldorsen in prep).

The formation of different glacial sediments is schemically shown in Fig.7.

Lodgement till

In the Weichselian the sandstone bedrock was glacially eroded and comminuted. During the active glacial phase the debris was deposited as lodgement till (Fig. 7, point A). That means till deposited from an active glacier, by lodging of clasts one by one, and a plastering on of finer grained material (see Boulton 1976).
In Åstadalen lodgement till lies directly on the bedrock, and no underlying Quaternary sediments were observed. The lodgement till is thus regarded as the oldest glacial sediment in the area.

A detailed geochemical study of the silt + clay fractions of lodgement till is reported by Haldorsen (in prep.), where data for 125 till samples from the southern sandstone area west of Åsta (Fig. 1) were presented. The samples were collected from C-horizons. South of the influence from the shale horizons in the north the till is homogeneous both in vertical sections

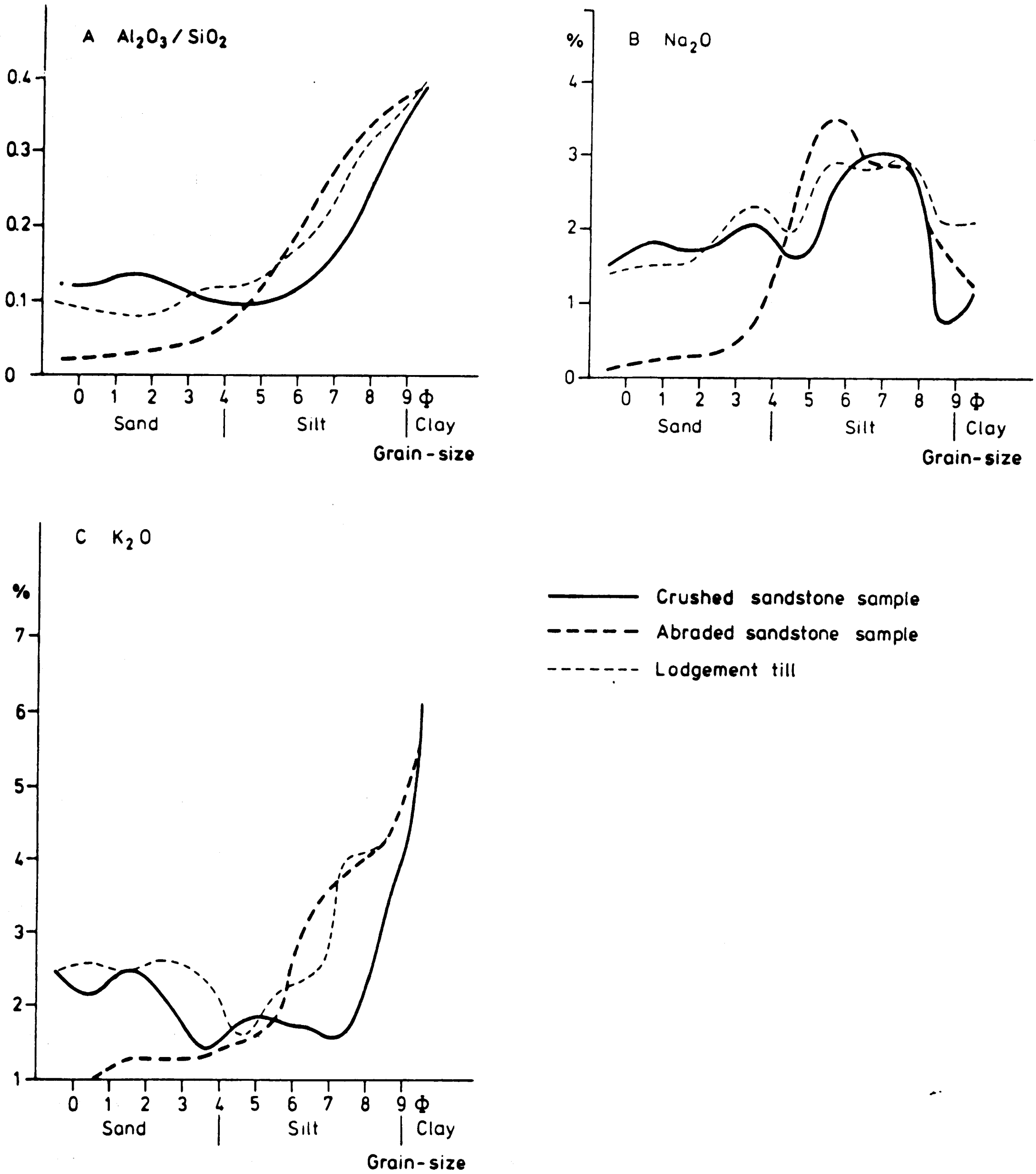


Fig.6 Distribution of some geochemical components in different size grades of crushed and abraded sandstone sample (further explanation, see Fig. 4) and one lodgement till sample.

Table 1 Chemical composition of bedrock and the fraction finer than 2 mm of glacigenic sediments from Åstadalen

	Bedrock N=24		Lodgement till N=12		Melt-out till 1 N=8		Glaciofluvial N=25		Melt-out till 2 N=10	
	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
SiO_2	81.5	4.9	80.9	2.7	*82.2	2.9	** 84.9	2.9	** 83.9	3.1
Al_2O_3	8.4	2.0	8.6	1.2	8.4	1.6	** 7.0	1.1	* 7.8	1.7
Fe_2O_3	2.1	1.1	2.3	1.8	2.1	1.4	* 1.5	1.6	1.9	1.9
MgO	0.6	0.4	0.8	0.3	0.9	0.4	* 0.6	0.5	* 0.6	0.4
Na_2O	1.8	0.4	2.0	0.2	** 1.7	0.2	** 1.4	0.4	** 1.5	0.4
K_2O	3.2	0.5	2.9	0.2	** 2.5	0.3	** 2.3	0.3	** 2.4	0.3
CaO	0.5	0.4	0.6	0.2	0.6	0.2	0.5	0.2	0.6	0.2
	98.2		98.1		98.5		98.2		98.7	

** Significant difference from lodgement till at a 5 % level of significance

* Significant difference from lodgement till at a 10 % level of significance.

and regionally. From this till 13 samples within the present studied area (Fig.3) were further analysed. The bulk geochemistry of the material finer than 2 mm is given in Table 1. This also represents the parent bedrock composition, as more than 90 % of the sandstone minerals are found in the sand and silt (Fig. 4). The geochemistry of the lodgement till accords well with the geochemistry of the bedrock. There are no indications of primary quartz enrichment in this till type.

The lodgement till is rather rich in silt (Fig. 8, curve A) because much of its material was derived by abrasion (Haldorsen 1981). As the formation of the lodgement till involved both crushing and abrasion (Fig. 7) its mineralogy and geochemistry resembles those of the artifically crushed and artificially abraded materials (Figs. 5 & 6).

Subglacial melt-out till, type 1

A subglacial melt-out till is formed by a passive melt--out process of stagnant debris-rich basal ice (Fig. 7, point B). It is recognized by its low degree of compaction and in many cases by the lenses of sorted sediments which indicate the presence of running melt-water (see Dreimanis 1976). Such a subglacial melt-out till is found in the transverse moraine ridges in Åstadalen (Fig. 3). These were formed by the stacking of debris-rich basal ice (Haldorsen & Shaw in prep.) (Fig. 9). The ridges are in some cases found to rest on a compact lodgement till. At least parts of the melt-out till thus were deposited after the lodgement till.

In the lateral end of the ridges, i.e. away from the centre of the valley the coarse material of the melt-out till is similar to the coarse material of the lodgement till, which is reflected both by the roundness of gravels (Fig.10A & B) and the mineralogy of the sand (Fig. 11). These characteristics indicate that the melt-out till was formed from the same type of debris as the lodgement till.

The silt content is lower in this melt-out till than in the lodgement till (Fig. 8) mainly due to the removal of fines by water during the melt-out process (Fig. 7).

The removed fine-grained material was clearly richer in feldspar and sheet silicates than the reamining sand (see Fig. 5). The latter therefore became enriched in quartz relative to the original lodgement till and has a higher content of SiO_2 and a lower content of Al_2O_3, Fe_2O_3, MgO, Na_2O and K_2O. (Table 1). In Fig.12 this quartz enrichment is shown schematically and listed as a quartz enrichment of type 1.

Glaciofluvial sediments

Subglacially formed glaciofluvial sediments are found in hummocks, eskers and terraces in Åstadalen (Fig.3). They were deposited from the time when the glacier became

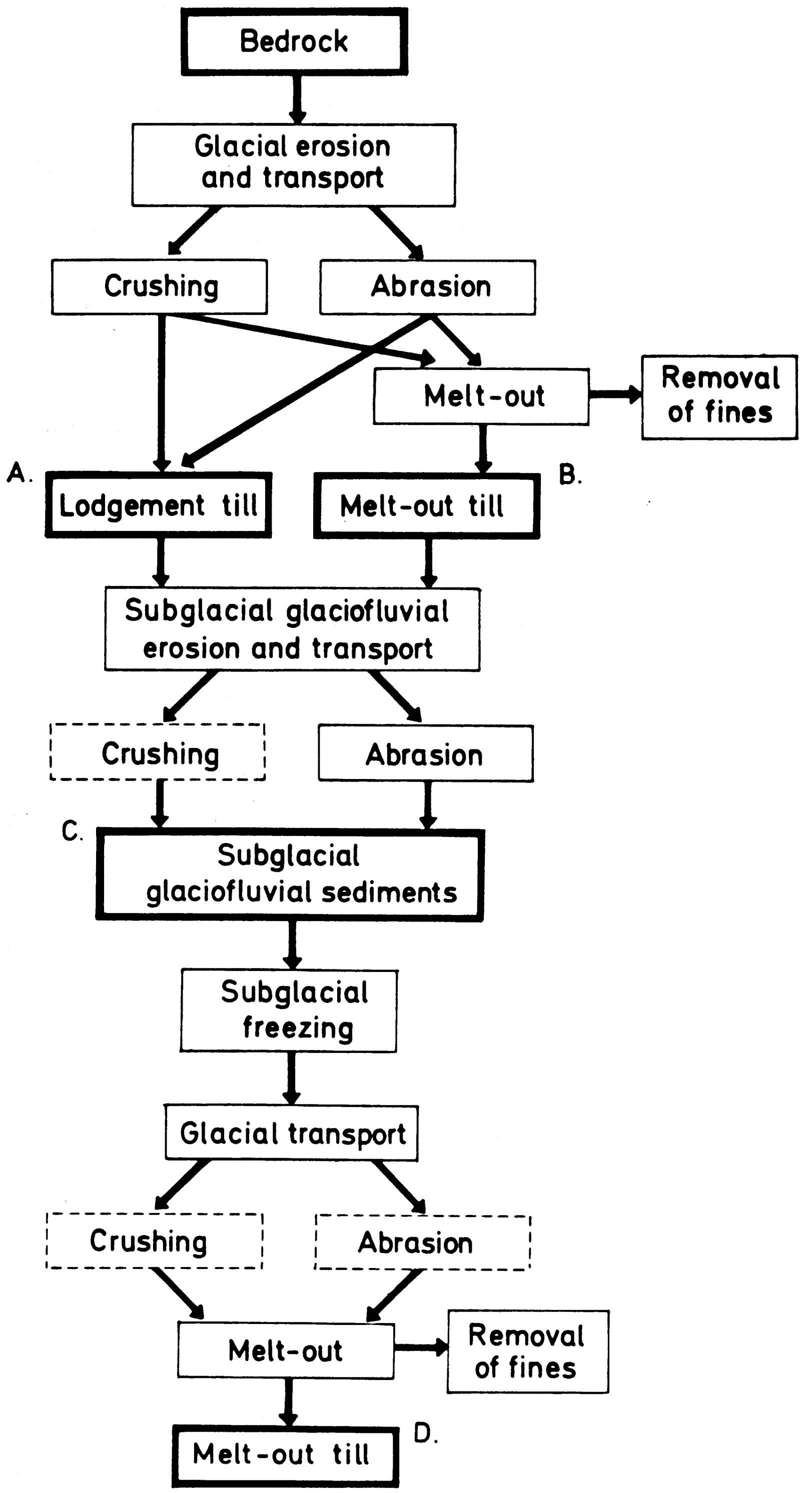


Fig.7 Postulated formation of different glacigenic sediments in Åstadalen.

sufficiently thin for the melt-water to penetrate down to the base. This deposition continued until the deglaciation was completed. Glaciofluvial erosion of tills is several places witnessed by the many meltwater channels which penetrate the surface of the lodgement till. The glaciofluvial sediments are sometimes found to rest on the till. The surface of the underlying till sheet has then features reflecting the influence of meltwater activity. Based on these observations it is concluded that the dominant part of the glaciofluvial sediments are formed either by erosion of tills (Fig.7, points A-C) or from basal ice debris.

Bulk samples were taken of most of the glaciofluvial sediments in the area, from road cuttings and gravel pits in hummocks, eskers and terraces.

The glaciofluvial material can be divided into two groups.

1. Small eskers and kames. The source is probably local. The gravel of these deposits is significantly more rounded than the gravel in the lodgement till and the melt-out till, type 1. (Fig 10 A-C). This shows that considerable abrasion occurred even during a short glaciofluvial transport.

2. Main eskers and terraces along the center of the valley (Fig.3). The gravel material has a relatively high degree of roundness (Fig. 10D)

The glaciofluvial material has a sand which is significantly richer quartz than the two tills described above

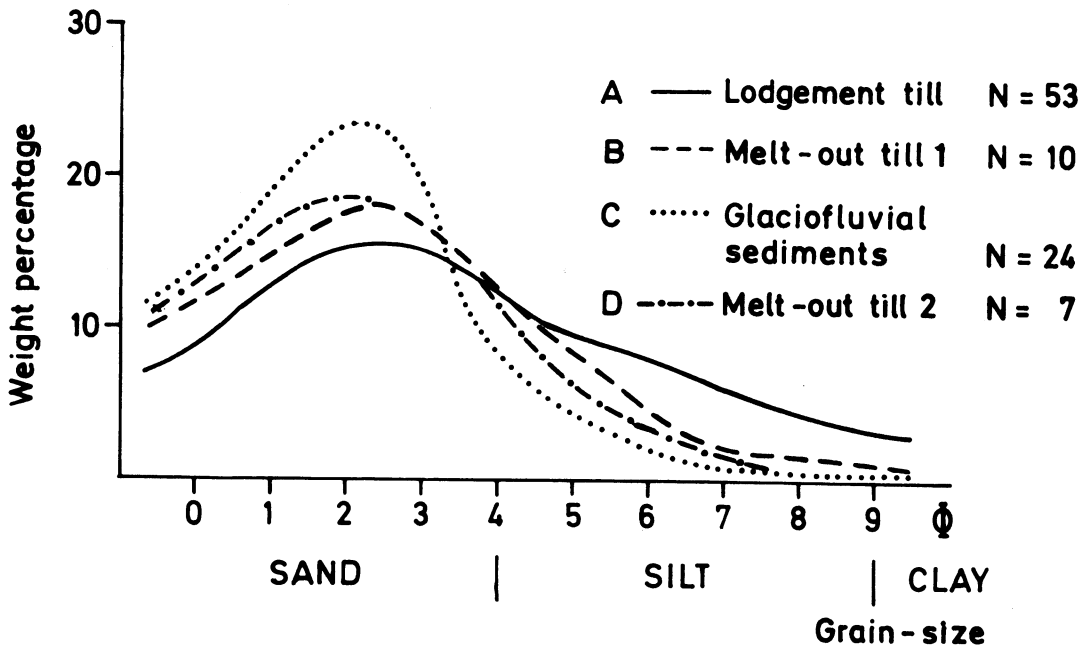


Fig.8 Grain-size distribution of glacigenic sediments in the investigated part of Åstadalen.

(Fig. 11). As the glaciofluvial material in this case mainly originates from till or basal drift, incorporation of weathered material seems unlikely. Thus, the enrichment of quartz in the sand must mainly result from glaciofluvial abrasion. This is in accordance with the artificial abrasion experiment (Fig. 5). The enrichment of quartz in the sand, caused by selective comminution of feldspar and sheet silicates is listed in Fig. 12 as a 'quartz enrichment of type 2'.

No extensive silt deposits are found in Åstadalen today, and the glaciofluvial sediments are poor in silt (Fig. 8). Most of the silt produced by the glaciofluvial abrasion, and silt eroded from till must have been removed from the area by meltwater (Fig. 7). Consequently the glaciofluvial fraction finer than 2 mm is richer in quartz, and SiO_2, than both the lodgement till matrix and the melt-out till, type 1 (Table 1).This is an enrichment of quartz of type 1 (Fig. 12). The conclusion is that the glaciofluvial sediments have enrichment of quartz of both type 1 and type 2.

Subglacial melt-out till, type 2

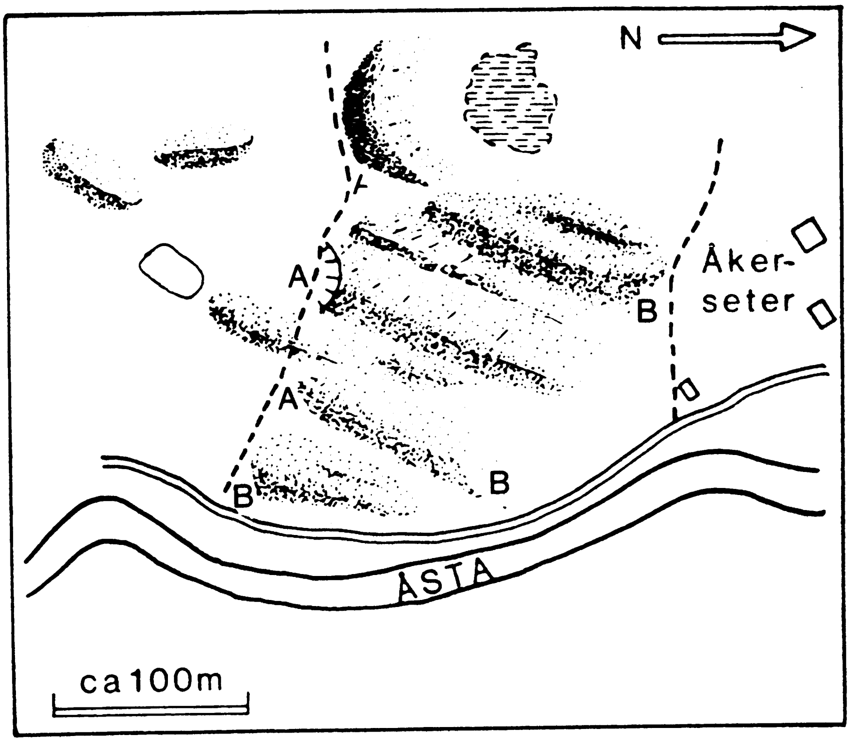
In the centre of the valley the till of the transverse moraine ridges (Fig. 3) occasionally contains a considerable amount of rounded gravel material (Fig. 10E). This indicates incorporation of a water transported sediments. Such till is located in areas where glaciofluvial sediments are abundant and in some places is found to rest directly on glaciofluvial sediments. Such till has been interpreted as a subglacial melt-out till with a depositional history like that of the type 1 subglacial melt-out till.

The incorporation of glaciofluvial material may have occurred in places where subglacial melt-water streams changed cource and glaciofluvial material locally froze on to the base of the glacier. The till contains rather angular gravel material too (Fig. 10E) indicating that the incorporated material was mixed with ordinary basal debris during the glacial transport.

Samples were taken from the three sections where such till is exposed. The content of silt is on average lower than in the type 1 melt-out till (Fig. 8), probably as a result of the incorporation of glaciofluvial sand. The sand grades of this till are significantly richer in quartz than the same grades of the original tills (Fig. 11). From the discussion above it is concluded that this is the result of incorporated glaciofluvial sediments.

The SiO_2 content of the bulk matrix is higher in type 2 melt-out till than in type 1 (Table 1), due to the enrichment of quartz in the sand and to the lower content of fine-grained material (Figs. 8, 11 & 12). Type 2 melt-out till thus has both a quartz enrichment of type 1 and a quartz enrichment of type 2.

A



B

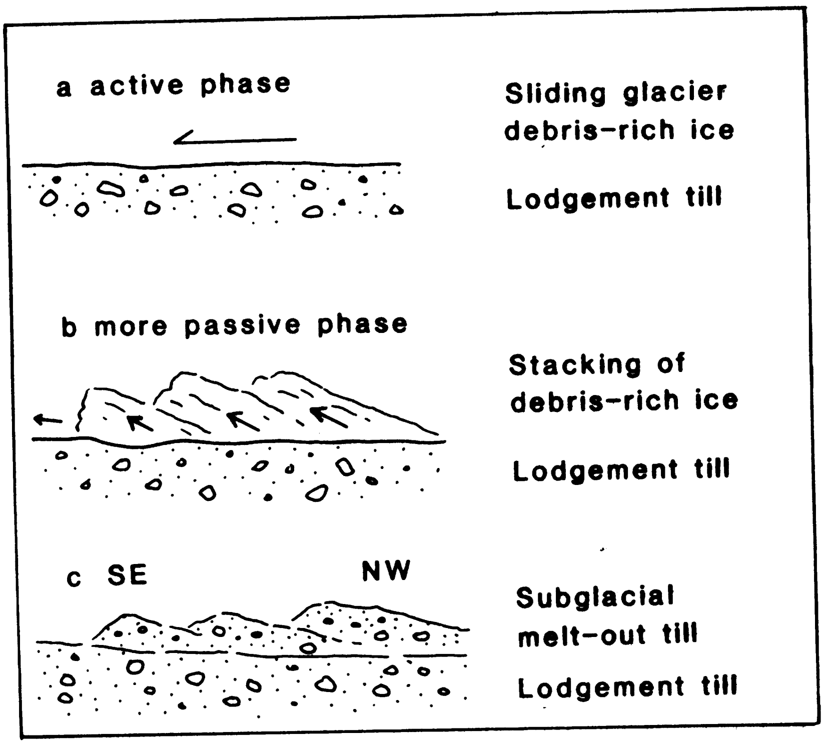


Fig. 9 A. Transverse moraine ridges at Åkerseter (see Fig. 3). A: subglacial melt-out till, type 1, B: subglacial melt-out till, type 2.

B. Postulated formation of the ridges, a: active glacial phase with deposition of lodgement till, b: more passive glacial phase with folding/stacking of basal ice, c: final morainic morphology and till sequence.

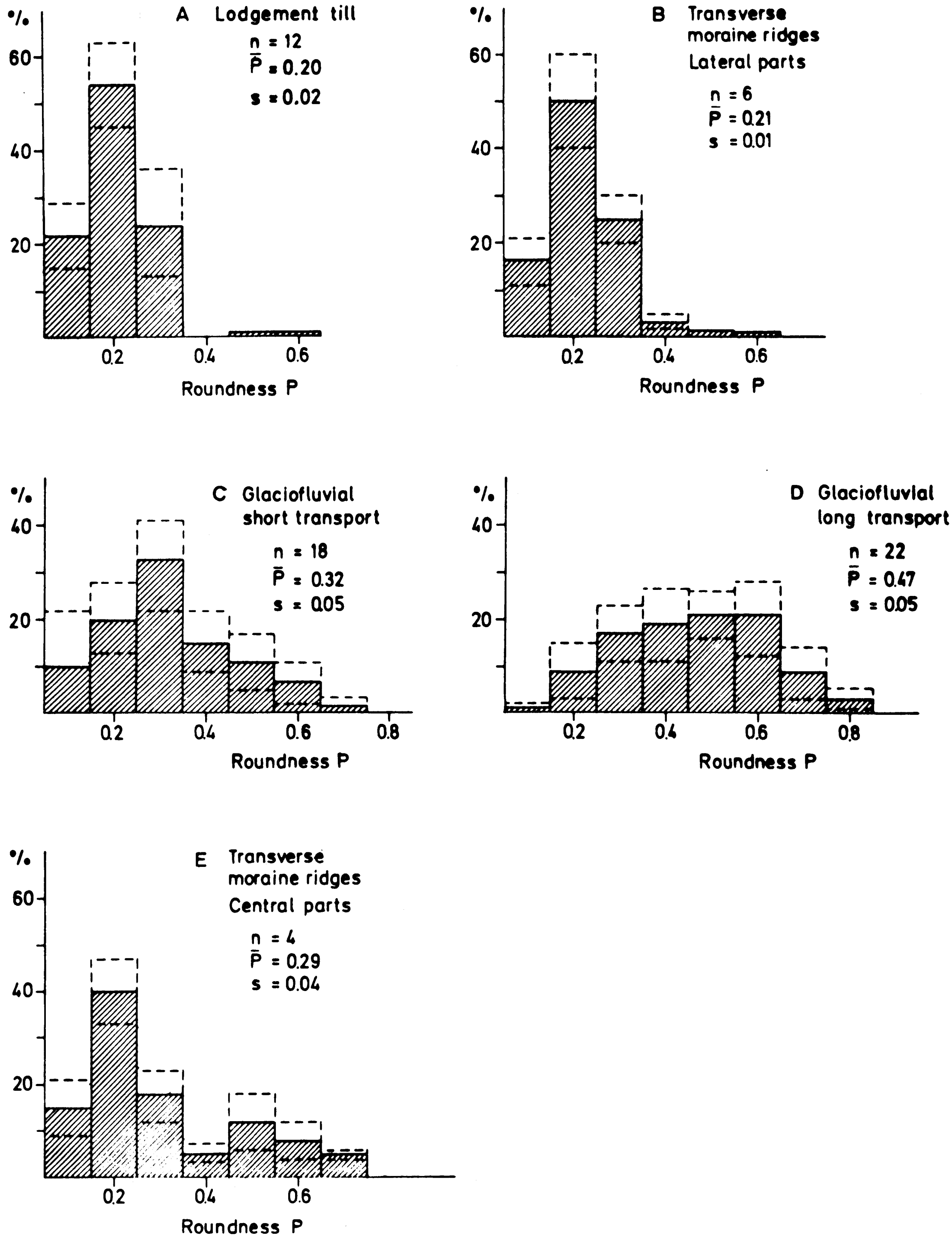


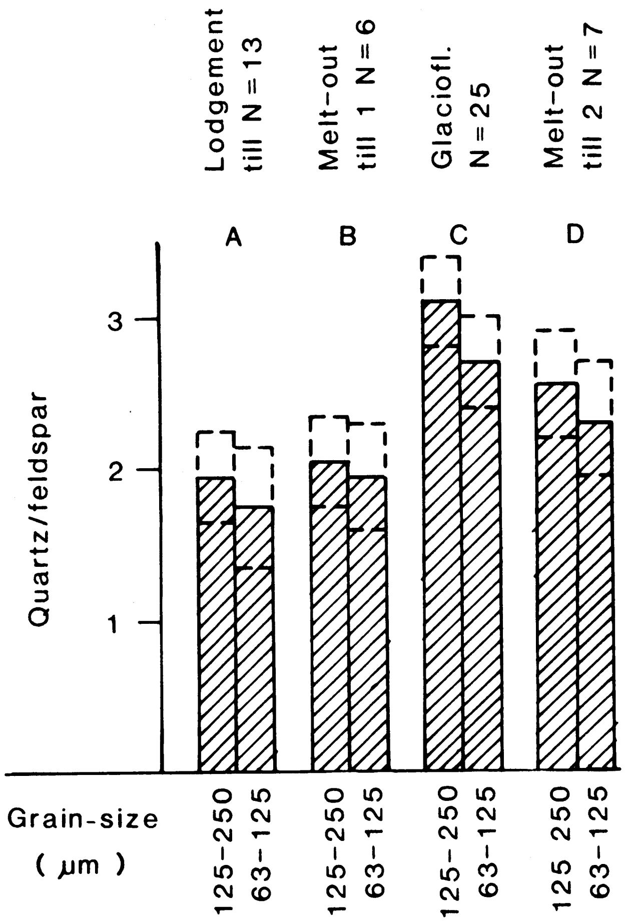
Fig.10 Degree of roundness of gravel 16-32 mm for different sediments in Åstadalen. Roundness index after Krumbein (1941).

Discussion and conclusion

An enrichment of quartz was formed in tills from Åstadalen purely by subglacial processes and without influence from intervening or preceeding ice-free periods. The abrasion process alone was responible for the enrichment of quartz in the sand while the combination of mechanical comminution and removal of fines by meltwater gave en enrichment of quartz in the bulk sediment. The processes described here have certainly occurred in several other areas too.

The abrasion experiments (Figs. 5 & 6) reflect the general principle that a quartz grain, because of its greater mechanical resistance, ends up in coarser fractions than for instance the feldspars (see also Moss et al. 1981). If the bedrock is variable, with coarse-grained types alternating with more fine-grained ones, the processes of abrasion or comminution in general and the removal of fines by water may result in an enrichment of quartz in both the sand and parts of the silt. This effect would be even stronger with repeated cycles of till formation and fluvial activity.

The model is, however, only valid in an 'open system' allowing the removal of fine-grained material. In a 'closed system' where the removed component was put back into the budget, there would have been a balance between the bulk sediment composition and the bedrock. Such a 'closed system' is in the present study represented by the relation between the bedrock and the lodgement till.



t-test values

125-250 µm	A	B	C
B	0.3		
C	7.2**	4.4**	
D	3.2**	2.5**	2.4**

63-125 µm	A	B	C
B	0.5		
C	4.5**	3.4**	
D	1.4*	1.5*	1.5*

Fig.11 Quartz/feldspar ratio for the fine sand grades of sediments from Åstadalen. One standard deviation is stipled. Right part of the figure gives statistical significance of the difference between the sediments.
**significant difference at a 5 % level of significance.
* significant difference at a 10 % level of significance.

However, in many cases it is difficult or impossible to ensure that every original component is considered in a till study and whether the system has been 'open' or 'closed'.

Based on detailed geochemical and mineralogical studies, Rosenqvist (1961, 1975a, 1975b) assumed an incorporation of preglacially (Tertiary) weathered material in till from Numedal, and related the great quartz enrichment found in the till to this incorporation. The same conclusion was given by Korbøl & Jørgensen (1973) and has been discussed by Roaldset (1978). An enrichment of quartz in tills has been reported from several other places in Scandinavia too (Collini (in Lindén 1975), Linden 1975, Perttunen 1977). The quartz enrichment described from Åstadalen is much smaller than that calculated by Rosenqvist (1975a, 1975b) for the Numedal tills, and the model discussed in the present paper can therefore not serve as an alternative explanation of the quartz enrichment in Numedal. However, a general conclusion from the present work is that if a certain quartz enrichment is observed in a till from a limited area, it is extremely difficult to decide whether it is caused by an incorporation of preglacial weathering products or for instance by sedimentary processes like those described here. This is even more complicated if the till contains material formed during more than one glaciation as Gillberg (1977) suggested for some of the Scandinavian tills.

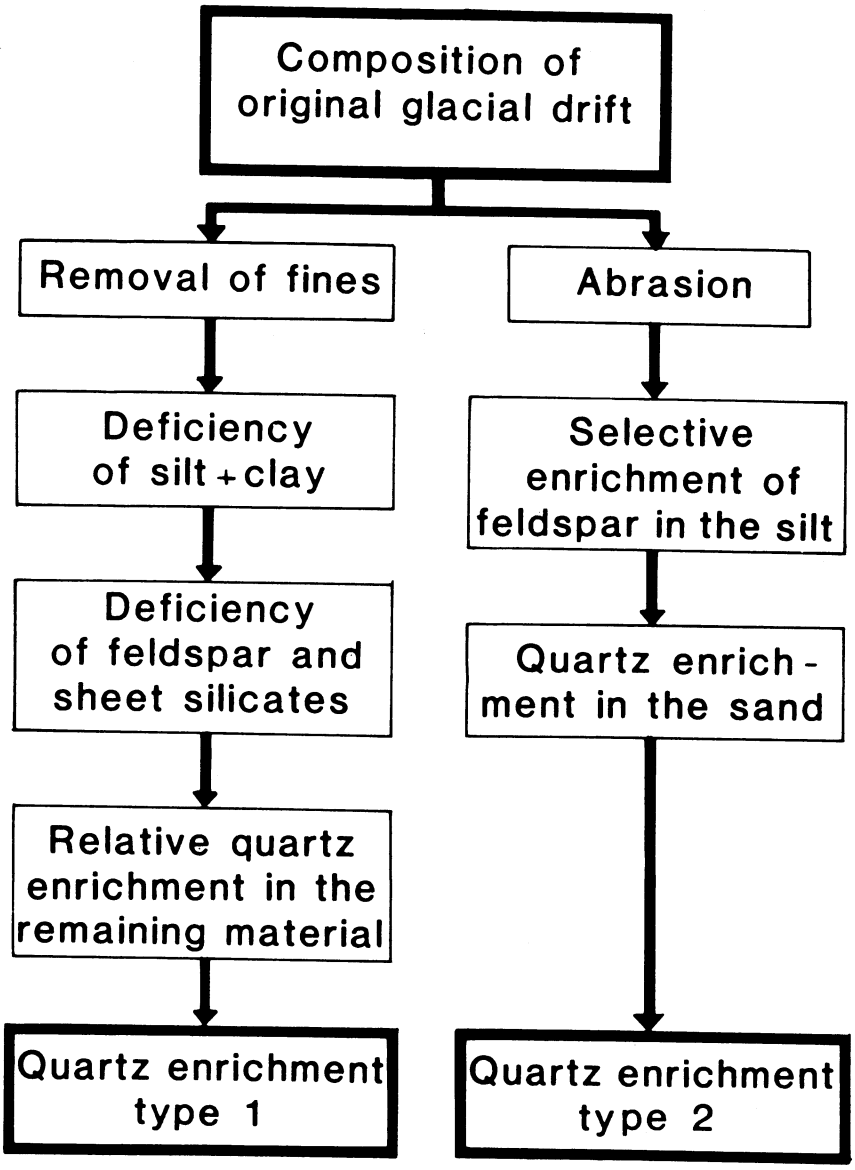


Fig.12 Two alternative ways of quartz enrichments in sediments from Åstadalen.

In my opinion the processes described in this paper is generally the most probable explanation of the quartz excess in many Scandinavian tills.

Acknowledgements. Knut Bjørlykke and Elen Roaldset have given constructive critisism of the manuscript. Adrian Read kindly corrected the English text and suggested some alternations of the content. Grete Bloch performed the laboratory analyses, Åslaug Borgan drafted the figures and Marie-Louise Falch has type-written the manuscript. To all these persons I tender my sincere thanks. Financial support was provided by the Norwegian Council for Science and the Humanities (NAVF)

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