SVERIGES GEOLOGISKA UNDERSÖKNING

SERIE C NR 767 AVHANDLINGAR OCH UPPSATSER ÅRSBOK 73 NR 8

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MORPHOGENETIC CLASSIFICATION OF GLACIOFLUVIAL DEPOSITS

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ABSTRACT

On the basis of our present knowledge about glaciofluvial deposits in Sweden the author makes an attempt to construct a systematic and logic classification of these deposits. They are classified according to, 1, their deposition behind, at or in front of the ice margin, 2, upon, within or under the ice, and 3, above, at or below levels of stagnant water. The Table on p. 68 gives a summary of the classification. The article also constitutes a brief summary of Swedish investigations of glaciofluvial deposits, mainly within Sweden.

INTRODUCTION

Classification of glaciofluvial deposits has been surprisingly unsystematic. What appears in most works dealing with those deposits can mostly be described as a glossary, that is, a number of characteristic types with definitions rather than a systematic classification. Even well-known standard books, such as those by Woldstedt (1954) and Flint (1971), deal with glaciofluvial deposits in essentially this way. An exception is Goldthwait's (1975) classification of all glacial deposits. The glaciofluvial deposits make up only a part of this and for special purposes a more complete classification may be necessary than what has been room for within Goldthwait's system. The same applies to the classification used by Sugden and John (1976).

Within the INQUA Commission on genesis and lithology of Quaternary deposits efforts are now being made to systematize all these deposits, beginning with the glacial. Within the project an attempt to classify the glaciofluvial deposits has been made by Jurgaitis (1977). The somewhat contradictory information collected from different countries has, however, made it possible to distinguish between only two main groups, englacial (ice-contact) and proglacial deposits. Within each group a number of individual forms are distinguished. For this reason it can be appropriate to summarize what is known about the glaciofluvial deposits in Sweden from a systematic point of view. What has been done in Sweden in this respect is often published in Swedish only, for instance in descriptions to geologic maps. In general, however, the classifications in the Swedish literature are as unsystematic as in the international. This is the case even in standard works on glacial deposits, such as those by Halden (1923), De Geer (1940) and G. Lundqvist (1940, 1943).

The following article may serve not only as a discussion of problems of classification but also as a brief summary of the most important Swedish literature on glaciofluvial deposits. It has no pretensions to show a complete list but with the aid of references from the quoted literature it is possible to find most of the pertinent works. For instance, some of the old works discussing the genetic problems of eskers, with theories that are now out of date, have been omitted. It must also be observed that, because the purpose is to give an account of what has been done in Sweden, references to the international literature have been restricted to a minimum. Mostly comparisons are made with summaries in handbooks like those by Flint and Woldstedt.

What is described in the following is thus based on conditions in and experiences from Sweden. Examples are chosen mainly from areas from which the author has personal experience. The results, however, can probably be much more widely applied, especially if the system of classification is slightly extented and, perhaps, modified in some details.

DEFINITION OF GLACIOFLUVIAL DEPOSITS

Before we try to classify the glaciofluvial deposits we have to define what should be classified, that is, the sense of this term itself.

In general, a glaciofluvial deposit can be defined as a sediment transported and deposited by streaming water generated by the melting of a glacier or inland ice. Thus the first criterion is that the deposition has taken place along the course of a stream, between its source and mouth in a stagnant water body. The second criterion is that the size and annual rhythm of the depositing stream is controlled by the melting of the ice.

Because tributaries of non-glacial origin can join a stream of glacial origin there is no sharp limit between glaciofluvial and fluvial deposits (cf. also p. 56), but generally the contribution by glacial meltwater is so considerable that there are no great difficulties in defining the origin, at least not as far as regards large deposits. In the case of smaller sediment patches the difficulties may be great, but in these instances the question is usually of minor importance.

At the mouth of a river of glacial origin the delta forms a natural end of the glaciofluvial deposits. The topset and foreset beds of the delta, which are deposited by running water and the material of which is essentially transported as bed-load, are traditionally included among the glaciofluvial deposits. The bottomset bed, transported mainly in suspension and deposited from stagnant water, can not, as an independent deposit, be included among them, but is referred to glaciomarine or glaciolacustrine sediments, not to be discussed in this article.

The separation of glaciofluvial deposits and till offers greater problems. Both types of deposits are often classified under the common term drift, when the sorted glaciofluvial sediments may be described as stratified drift. This is a base of separation that is in some respect unfortunate. Typical till material may sometimes be stratified, while on the other hand there are glaciofluvial deposits with poorly developed stratification or even complete lack of it

The basis of separation ought to be the mode of transportation and deposition. If the transporting agent was ice and the material was deposited directly by ice the deposit should be classified as till, whether there is a stratification or not. When the material was transported and deposited by running water the sediment should be classified as glaciofluvial irrespective of the occurrence of bedding or not.

What is said here also applies to sorting. Generally, of course, till is not or poorly sorted and glaciofluvial sediments are well-sorted — as far as one single strata is concerned. But there are many exceptions, implying, for instance, that the sorting of a water-laid sediment is poor (Fig. 1). Till material may have been generated in different ways. Sometimes it consists of redeposited sorted se-

Fig. 1. Very poorly sorted glaciofluvial material forming a transition to ablation till. From the deposits along the River Mangslidälven, NW of Nyskoga, Värmland. — Photo J. Lundqvist 1955.

diments, in which case the material may still show a certain degree of sorting but has to be classed as till.

Especially in the latter case it is only natural that there is a gradual transition from glaciofluvial — and other water-laid — sediments to till and that the separation offers some problems. In uncertain cases one has to reconstruct the geology of the deposit in order to make an appropriate classification.

The fact that sorted, water-laid sediments nearly always make up a smaller part of the till cover and may gradually become the dominant part causes another difficulty in the separation between till and glaciofluvial deposits. Starting with the above-mentioned definitions of till and glaciofluvial material we may decide that they refer to certain types of *material,* sediments. Any glacial *deposit* may include both types of material (Fig. 2). For these deposits we may in general use the terms moraine, consisting of till, and glaciofluvial deposits, consisting mainly of water-laid, glaciofluvial sediments. The differences between the two types of deposit may be defined as follows.

If the morphology of a certain deposit indicates that the deposition was determined by the ice, its movements or wastage, the deposit should be classed as moraine, irrespective of some content of sorted material or not. The sorted ma-

Fig. 2. Where large glaciofluvial deposits end in an environment of till, transitions are formed in two ways: Banks of till (upper left) occur within beds of glaciofluvial sediments (lower beds), and material of the type shown in Fig. 1 occurs together with those beds (upper right). From the deposits along the River Ljusnan, SE of Kindsjön, Värmland. — Photo J. Lundqvist 1955.

terial can be a redeposited (by ice) sediment or the result of the sorting effect of small meltwater streams within the ice. When the size and activity of these streams increase, so that the morphology of the deposit is determined by the running water, we should talk about a glaciofluvial deposit, even if it contains some till material. It should be observed that also in this case the morphology may — of course — be influenced by the presence of ice, but still there is a difference of principal importance between deposition by or from ice and merely presence of ice.

In some cases similar land-forms may result from the deposition by ice and by running water. A ridge is one example. When there is no morphological evidence in favour of one interpretation or the other there is only one possibility of classification left, and that is according to the dominant material. The deposit could be considered either moraine with inclusions or beds of water-laid sediments, or glaciofluvial with banks etc. of till.

A thorough investigation of a certain deposit will probably mostly give an acceptable base for classification. The problem is, that during regional work it is often impossible to make the necessary investigations in every particular case. In other instances, for example in large gravel pits, we gradually get the necessary information, but a full classification cannot be made until it is too late, that is, when the deposit has been completely removed. For practical purposes, therefore, we have to rely on morphology and scattered observations in gravel pits, sampling pits etc., and be aware of the possibility of misinterpretation between some types of deposit. There are cases when the uncertainty is too great to allow qualified interpretations. At mapping and similar investigations it can sometimes for this reason be necessary to introduce special terms and signs, denoting intermediate types. On the Swedish west coast, e.g., it has become necessary to show some marginal deposits in a special colour indicating content of both till and glaciofluvial sediments (Fredén 1978), and in northern Sweden, Fromm (1965b) found it appropriate to introduce a special colour for till composed of sandy and gravelly, sorted material.

SEDIMENTS AND MORPHOLOGY OF GLACIOFLUVIAL DEPOSITS

All glaciofluvial deposits consist — or may consist — of alternating beds of more or less sorted sediments. The grain size ranges from boulders to fine sand or even silt. We may distinguish between the following main types of sediment. Most typically the glaciofluvial sediments are, as is well-known, very well sorted and consist of well-rounded particles. The sorting is often restricted to one bed — a bulk sample comprising several beds will show a much poorer sorting (Fig. 3). The sorting within each separate bed may be either homogeneous or show a continuous grading. In the first case the beds can be interpreted as representing streams with uniform flow but with intermittently changing courses. The graded beds represent a rhythmic change of stream velocity, sudden flows with continuously decreasing discharge until the next flow sets in.

The sorting can in extreme cases be almost perfect, the bed consisting of one single grain-size (Fig. 4). These diakene sediments — or openwork sediments (Wadell 1936) — are commonly formed by the coarser fractions, from boulders down to fine gravel (a couple of metres to 2 mm). According to Wadell (1936) these extremely well-sorted sediments are ”*gravitational deposits*, i.e. an accumulation of rock fragments which by the force of gravity alone, without any influence of the surrounding medium, have moved to the locality of deposition”. More commonly the degree of sorting is less extreme, the interspaces between the coarser grains being to some extent filled with finer grains and scattered larger clasts occurring. Well-sorted sediments of this type, in grain-size ranging from boulders to silt (a few metres to about 0.02 mm), are most common.

Sometimes the interspaces between larger clasts or grains are gradually filled with finer grains. Well-graded sediments of this type (Fig. 5) are found in gla-

Fig. 3. Ordinary glaciofluvial sediments consisting of beds of well-sorted, coarse or fine, material. River Liukattijoki, W of Svappavaara, Lapland. — Photo J. Lundqvist 1967.

ciofluvial deposits, but the perfect gradation is usually limited to the range from stones to sand (about 200—0.2 mm).

A bimodal sorting is rather common among these sediments. Mostly it means that rounded stones are scattered in a matrix of well-sorted sand. In rare cases we may also find stones or gravel embedded in a clayey or silty matrix. The formation of these bimodal sediments can be interpreted in different ways. Usually there has probably been a synchronous deposition of clasts and matrix from a suspension of fines carrying larger clasts floating due to its greater density. In other cases structures in the matrix, e.g. clay varves, indicate that the matrix has accumulated gradually in a coarse diakene sediment.

Fig. 4. Diakene (openwork) gravel in a glaciofluvial deposit at Norrlanda, island of Gotland. When the interspaces between the stones are filled with a sorted, fine-grained sediment we get a sediment with bimodal sorting. — Photo J. Lundqvist 1969.

With decreasing degree of sorting — and often also of roundness — the sediments grade into more or less till-like sediments (Fig. 1). Among them we certainly find proper tills, deposited by flow, by deposition from icebergs, or by overriding ice. A certain type of poorly sorted sediment is the so-called drainage-gravel. This is a completely unsorted and as a whole structureless mass deposited at sudden drainings of, e.g., ice-dammed lakes. This type of gravel may contain thin beds with better sorting (Fig. 6). It can sometimes be distinguished from ablation till only because of the general topographic situation, a certain morphology and a gradual transition into better sorted sediments.

In this connection there is no room for a detailed sedimentological discussion, but a brief review also of the types of bedding in the glaciofluvial sediments can be appropriate. The following main types can be distinguished.

The simplest form of bedding is a set of horizontal strata. This bedding may be horizontal all through, that is, down to the fine laminae. But there is often a cross-bedding within the horizontal beds. There can be an irregular cross-bedding with layers dipping in different directions, but the individual layers may also form a regular delta bedding dipping one way only. The layers within the horizontal beds may also be slightly undulating, with increasing amplitude getting a

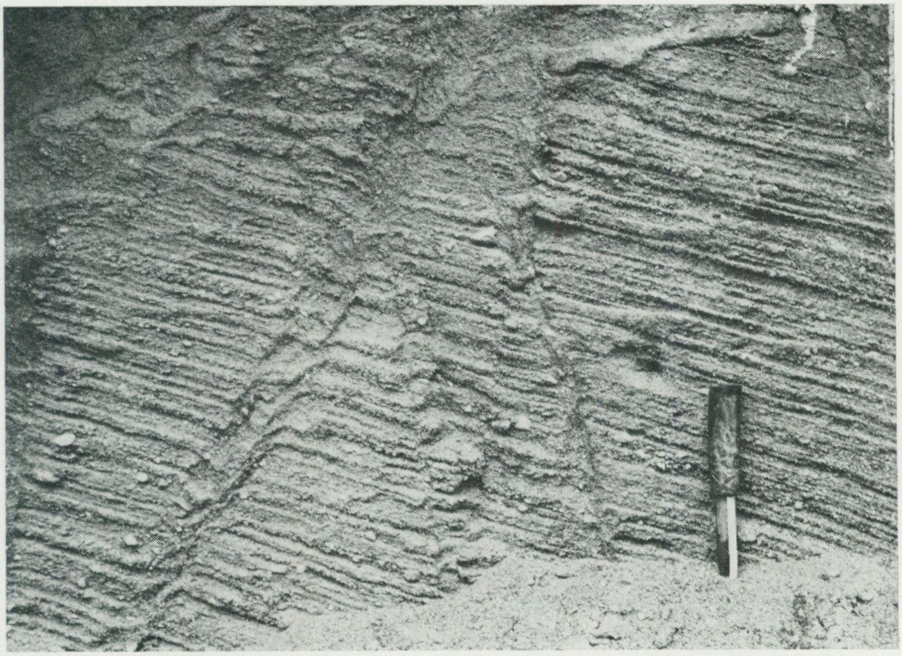

Fig. 5. Well-graded glaciofluvial sediment with a grain-size ranging from stones to silt in an esker at Mellansel, Ångermanland. — Photo J. Lundqvist 1972.

wave-like appearance, which in turn may be replaced by ripples.

Another simple form of bedding is the delta bedding. In glaciofluvial deltas as in any river delta we find the topset, foreset and bottomset beds. In extreme cases the difference in grain-size as well as angle of dip between these beds is very sharply developed; a horizontal topset bed of coarse sediments covers the steeply dipping foreset beds of gravel and sand. The bottomset bed may be formed by silty sediments with a bedding that is horizontal or follows the substratum. In other cases the difference in grain-size is less clearly defined. Then there is also usually a more continuous grading from one set of beds to the other.

In deltas formed at the ice front the bedding sometimes dips backwards. This backset bed (Fig. 7) represents material violently forced out from a subglacial tunnel mouth, and thus being thrown up and deposited on top of previously deposited beds. The backset bed has been described by Hörner (1927) and especially studied by C. E. Johansson (1975).

In some types of glaciofluvial deposits a more or less well-developed vaulted, mantle-like bedding can be found. In the ideal form the bedding consists of a nucleus of coarse sediments covered by "shells" of less coarse-grained beds. This is the bedding typical for eskers corresponding to the descriptions by De Geer in his classical works (e.g. 1940). As a rule, however, irregularities of different

Fig. 6. Deposits formed at sudden drainages of, e.g., ice-dammed lakes are mostly poorly sorted, but may contain beds of well-sorted sediments. Vargfors, Västerbotten. — Photo J. Lundqvist 1959.

kinds make the bedding type less clearly visible. The bedding of this type can be interpreted as a subaquatic delta bedding, partly with backset beds, and formed at the mouth of a subglacial tunnel.

Most characteristic for glaciofluvial sediments are the numerous discordances and faults between different beds. Rarely a glaciofluvial deposit is seen in which no discordance at all can be found. The strata cut each other with various angles and no distinct rules for the types of discordances can be given. In general terms the discordances represent the rapid changes of the course and velocity of the glaciofluvial streams. Phases of erosion have alternated with phases of deposition.

Both the genesis and the resulting morphology are determined by the situation in which deposition took place. Most important in this respect is the situation in relation to ice and to levels of stagnant water (the sea or glacial lakes). It seems most logic to classify the glaciofluvial deposits with regard to their formation environment in relation to the ice.

Fig. 7. Foreset and backset beds in the glaciofluvial delta at Fryksta, Värmland. The stream direction was from left to right. The foreset beds in the upper part cover the slightly undulating, earlier accumulated backset beds. — Photo J. Lundqvist 1967.

From a topographical point of view we can distinguish between three main groups of glaciofluvial deposits: those formed behind the margin of the ice, approximately at the margin, and outside the ice, topographically independent of it. The two latter groups are marginal and extramarginal (or proglacial) deposits, respectively. Within the first group (inframarginal deposits) we may distinguish between deposits formed under the ice (subglacial), within the ice (englacial) and upon the ice (supraglacial or subaerial; Fig. 8). Subaerial deposits that are not supraglacial may be formed behind the ice margin in open channels or crevasses reaching down to the bottom of the ice.

Within these three groups deposits may be formed above, at or below an adjacent surface of stagnant water. In the case of deposits formed behind the ice front the position in this respect has probably minor importance or, at least, is often impossible to interpret only on the basis of the deposits themselves. The supraglacial deposits have to be formed above water surfaces (supraaquatically) but the englacial and subglacial deposits are preferrably treated as two uniform groups regardless of the position in relation to water surfaces. In the case of extramarginal deposits those formed below a stagnant water level (subaquatically) can mostly be termed glaciomarine or glaciolacustrine sediments. They shall not be considered here. The other groups are described below.

We may distinguish between glaciofluvial deposits accumulated, 1, along the courses of running water, 2, where the stream reached stagnant water or a break

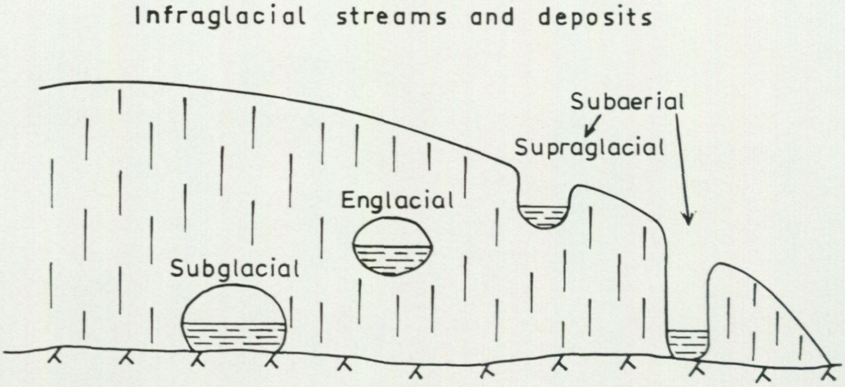

Fig. 8. Sketch illustrating the possible positions of infraglacial meltwater streams.

in the terrain so that the transporting power ceased, and 3, where water hurled down in holes in the ice. In this way three basic morphological types of accumulation were formed: Long ridges (eskers), hummocks (kames) and flat surfaces (deltas and plateaux).

The term esker is preferred to the often used term ose (De Geer 1909), which is a linguistically unfortunate anglification of the Scandinavian word *ås*. The eskers usually follow the direction of ice movement and drainage at right angles to the ice margin as radial eskers. If no other information is given in the following the term refers to radial eskers.

Flint (1928) preferred to distinguish between eskers and crevasse fillings. This is a distinction that seems to be difficult to retain in many areas, so it is more appropriate to denote all narrow, ridge-shaped glaciofluvial deposits as eskers.

The term kame needs a special elucidation. This term has been frequently used and misused in different senses in the geological literature. The term was originally introduced by Geikie (1874) and after him different authors have used it in somewhat different ways. Holmes (1947) has reconstructed the history of the term and concluded that, if we shall follow the original sense of it, a kame should be defined as follows: "A kame is a mound composed chiefly of gravel or sand, whose form has resulted from original deposition modified by any slumping incident to later melting of glacial ice against or upon which the deposit accumulated" (Holmes 1947, p. 248). Thus the word can be applied to almost any hummock of glaciofluvial origin and corresponds in Swedish literature to the term "esker hummock" (*åskulle*). Bergsten (1943, p. 179) has recommended that the use of the term kame should be limited. Characteristic features of different types should in most cases allow the deposits to be referred to other groups within the classification. It should be noticed, however, that there is some difference in the definition of kames in relation to esker nets according to Bergsten (1943) and in this paper.

Karczewski (1974) has discussed the formation of kames and made a thorough classification within this group. As is evident from his description and tables showing the formation of kames there may be reason to subdivide the group kames more than has been done in the classification presented here. The outlines of the formation of kames according to Karczewski is, however, not contradictory to the division presented here.

Contrary to Bergsten, e.g. Weisse (1977) has extended the sense of the term kame and included also hummocks of glaciolacustrine sediments in this group. This can, from a practical point of view, be justified. Weisse based a further classification of kames on their internal structure and sediments.

Reference should also be made to a book about structure and formation of kames, edited by Raukas (1978), which appeared during the printing of this paper.

In many works dealing with glaciofluvial deposits another primary element, the plateau, is often distinguished. The present author prefers to avoid this term, mainly because it has no indisputable definition. It can be either a form of deposition or a remnant of erosion. As primary forms of accumulation the plateaux can be described as deltas, which because of the environment of deposition have received a plateau-like shape, or as flat-topped kames. In the classification presented in this paper the plateaux are to be found within the groups of kames and deltas. If reasons will be considered strong enough in the future, the classification can easily be extended to include one or more plateau classes.

Upon the primary features secondary forms, like stream-channels, banks and dead-ice hollows (kettles) may occur. Banks can in rare cases occur as independent features, a fourth type of primary forms. From the rounded kettles we should preferably distinguish elongate trenches, occurring especially along the sides of accumulations. Sometimes the distinction between kettles and trenches is based on the topographic situation (on or at the side of an esker; see Hjulström 1944, p. 347). However, it seems more convenient to base the definition on the shape, because typical very long trenches can also occur in the middle of an esker, dividing it into two ridges.

All the forms mentioned may be developed freely but are in most cases modified by slumping (due to the melting of ice), ice contacts or erosion. The forms mentioned can serve as basis of classification, but are insufficient for a complete and adequate classification.

EARLIER CLASSIFICATION OF GLACIOFLUVIAL DEPOSITS IN SWEDEN

At the regular mapping of Sweden (by the Geological Survey) the classification of glaciofluvial material is very simple. On many old maps there is no classifi-

TABLE 1. Classification of glaciofluvial deposits according to some Swedish authors. It has to be observed that the purpose of this table is to show the classifications, and not the terms. Therefore, to make comparisons easier, some slight changes

Nelson 1910	*G. Lundqvist 1940, 1943, 1958*	*Bergsten 1943*	*Björsjö 1949*
A. Sub- and infra-marginal	Eskers	Eskers	Frontal, marginal
	Subglacial eskers		Transverse eskers
I. Eskers and esker nets	Subaerial eskers	Subaquatic valley fillings	Terraces
			Plateaux
II. Kames (in part)	Deltas		Marginal eskers
	Marginal deltas	Lateral terraces	Other frontal eskers
	Proximal deltas		
B. Marginal and extramarginal	Marginal eskers	Kames	
	Sandur fields		Radial, marginal (De Geer) eskers
I. Kames (partly)		Marginal eskers and plateaux	
	Kames		Other radial eskers
II. Marginal eskers, marginal esker belts	Esker nets	Marginal deltas	
			Lee- or west-side deposits of glaciofluvial gravel
III. Marginal deltas	Kettle fields		
1. Supra-aquatic (gravel and sand plains, valley fillings)			
2. Subaquatic (marginal deltas *sensu stricto*)			
IV. Lateral terraces			

cation at all. The glaciofluvial deposits are all shown in the same colour. On the oldest maps only eskers were separated with a special colour. Other deposits that were probably glaciofluvial were simply shown as gravel or sand with the same colours as other gravelly and sandy deposits.

On modern maps of Quaternary deposits the glaciofluvial deposits are described as either gravelly or sandy according to the dominant fractions, or as "glaciofluvial deposits in general", where the interior of a deposit is either very complex or incompletely known. This is in accordance with the general principles of the mapping: The basis is the main genetic groups of Quaternary deposits, shown in colours, and within each group the dominant grain sizes are indicated. In addition to the differentiation mentioned, ridges (esker crests or others) are marked. Somewhat more detailed, including also a few more morphologic classes, was the classification of all Quaternary deposits elaborated by G. De Geer (1922), but this system has not been generally used.

In the descriptions to the maps the glaciofluvial deposits are grouped together of terms have been made, and in some cases the terms have been translated from Swedish. Besides, in some classifications other deposits than glaciofluvial were originally included. These have been excluded from the table.

Bergdahl 1953	*Hillefors 1969*	*J. Lundqvist 1969*	*Persson 1974*
A. Eskers I a. (De Geer) eskers, radial eskers b.1. Transverse tributary eskers b.2. Transversely formed marginal eskers II a. Radially formed marginal eskers (b. Beach deposits) B. Non-eskers I. Marginal deltas II a. Flank ridges, esker sides b. Flank plateaux III a. Lateral terraces (b. Beach terraces)	Esker mound rows Radial eskers Proximal eskers — feeding eskers Marginal plateaux Marginal terraces Marginal plains (valley bottom fillings) Lateral eskers Lateral terraces Transverse eskers	A. Subglacial and englacial Supraaquatic eskers Engorged eskers Esker nets Transverse eskers Isolated mounds Kames Dead-ice deposits B. Marginal Subaquatic eskers Marginal deltas Marginal eskers Kame deltas Lateral terraces C. Extramarginal Deltas Supraaquatic deltas Valley fillings	Eskers Esker ridges Transverse-eskers Parallel-eskers Esker-nets Abraded eskers Plateaux, terraces and glaciofluvial hills Plateaux Terraces Kettle-fields Hills

to some types characteristic for each map area. The basis for this grouping is the morphology, which is essentially comparable with the genesis. The classification in this respect is just as unsystematic as mentioned in the introduction. As an exception a tentative classification was elaborated by the present author (J. Lundqvist 1969) for the county of Jämtland. A similar classification has since long been used by the author in lectures on glacial deposits. The classification presented in the following is to a great extent a modification of that system, intended to be more generally applicable.

For special purposes or regions systematic classifications of groups of glaciofluvial phenomena have been constructed by some authors. The most thorough one was developed by Nelson (1910) and, later, with minor modifications applied by Bergsten (1943). Bergsten even proposed a division of southern Sweden into regions based on the distribution of the different types of glaciofluvial deposits. As these authors have emphasized, a number of different factors must be considered at a classification of glaciofluvial deposits. In brief summary these are the situation in relation to the ice and surrounding water, the topographic position, the amount of material supply, and secondary erosion and redeposition. This system of classification was further developed by Persson (1974). It is applicable especially in the southern parts of Sweden.

The classifications mentioned deal with the characteristic deposits within rather limited areas. The deposits are divided into groups or, most commonly, just into types on a mostly unsystematic basis. Often the position in relation to other land-forms, for instance bedrock hills, is considered to an extent that is not justified if we consider the morphology and internal structure of the deposits themselves.

A different classification was established by Bergdahl (1953). The basis of this system was the morphology and the orientation of the internal stones. The result included some of the same types of deposits as the above-mentioned systems, but there are differences as to the definitions. Also some beach deposits were included in the system.

Björsjö (1949) classified the deposits on part of the Swedish west coast. The system was in some respect very detailed, but deposits occurring in other parts of the country were not included. Hillefors (1969) applied the same system and developed part of it still more.

Finally should be mentioned the logic system developed by Mannerfelt (1945). His system was established, however, only for the land-forms occurring within the North Swedish mountain region.

Some of the more important Swedish classifications are shown in Table 1. It must be observed that some terms have been slightly changed from the original version, in order to facilitate a comparison with the nomenclature used in this article.

SUGGESTED MORPHOGENETIC CLASSIFICATION OF GLACIOFLUVIAL DEPOSITS

A good basis for classification is the morphology, but there is some difficulty to obtain a logic system in this way. The morphology, however, to a great extent depends on the genesis. A combination of genetic and morphologic aspects probably offers the best and most logic basis of systematic classification. It seems to be appropriate to consider the original morphology only, irrespective of possible later modifications by running water etc. However, it should be remembered that also the primary forms are to some extent modified by glaciofluvial erosion (cf. Tanner 1932, 1937, and others).

All types of glaciofluvial deposits may be described in terms of the features mentioned above. When we do this, it is appropriate to begin behind the ice margin. This is where the glaciofluvial meltwater streams begin, that is, we follow them from their sources to the sea.

1. DEPOSITS FORMED BEHIND THE ICE MARGIN (INFRAMARGINAL DEPOSITS)

We may notice that often in the following a close neighbourhood of the margin is emphasized. It might seem as if the deposits in question ought to be referred to the marginal deposits of group 2. However, we must remember that probably all glaciofluvial deposits are formed in the marginal zone of the ice and not far behind it. There is, however, a clear difference between those deposits that are described as inframarginal and marginal in the following.

1.1. ENGLACIAL, SUPRAAQUATIC DEPOSITS

1.1.1. *Englacial eskers.* In tunnels in an ice sheet, that is, channels that have also a cover of ice and do not reach the bottom, stream deposits may accumulate. There is no doubt that the process is a reality, but probably it has a limited importance. First, a highly broken relief of the land surface is probably necessary for the transport of sediments in a considerable amount some distance above the ice bottom. Second, as ablation goes on, the covering ice will disappear and the channels are no longer closed, englacial, but subaerial. If sedimentation stops before this happens a string-like sediment bed is formed within the ice and may perhaps, after deglaciation, be left behind as an esker. Bjelm (1976) is of the opinion that englacial eskers are more common than subglacial ones. Both are types of "hydrostatic eskers".

The englacial eskers can hardly be separated from, e.g., the subaerial eskers mentioned below (1.2.1). Some characteristic features may be the following, but can certainly also be absent. There is in principle a complete independence of the surrounding land morphology. The size of these eskers is probably mostly insignificant. Because of deformation at the melting of the underlying ice the morphology is irregular with an uneven and low crest. Due to slumping at the final melting of underlying ice a partition into two or three parallel ridges according to the process described by Price (1966) and under 1.3.1 is possible. The stratigraphy of the sediments corresponds to that of other crevasse fillings, e.g., that of 1.2.1 and 1.3.1 eskers. The substratum should be till and also a thin, more or less coherent coating of till may occur.

1.2. SUPRAGLACIAL, SUBAERIAL, SUPRAAQUATIC DEPOSITS

These deposits are formed either upon the surface of the ice, or in open channels in the ice, not reaching down to its bottom. The following two types of deposit can be defined.

1.2.1. *Subaerial eskers.* If, in a broken country like the mountain region of Sweden, a channel in the ice surface was formed, the sediments were deposited as a string-like river bed in this channel. After disappearance of the ice they could be left behind as a ridge, an esker of the subaerial type emphasized by, among others, Holst (1876) and Tanner (1937). G. Lundqvist (1943, p. 51), however, considered it impossible that the deposits would retain the shape of an esker after disappearance of the ice. If they exist, it is probably difficult or often impossible to separate this esker type from some of the others mentioned in the following, but a few criteria exist. The topographic occurrence is principally independent of the surrounding land morphology. The eskers of this type are generally small. Their ideal bedding is the one more thoroughly described under 1.3.1, that is, in cross-section horizontal and in length-section a delta-bedding within each separate bed. Probably, the bedding is more often very irregular. Till cover is lacking and so is a cover of fine-grained sediments. The originally even length-profile has been modified to a more hummocky shape at the melting of the underlying ice. During this process also a formation of small parallel ridges or a partition into two parallel eskers may have been caused by slumping when the underlying ice melted. This process has been described by Price (1966). The substratum of this esker type is till.

1.2.2. *Supraglacial kame deltas.* In a similar situation as under 1.2.1 kame fields, often with delta-like contours, occur on the slopes (Fig. 9). The regular contour indicates that the sediment (gravel, sand) was collected essentially as a delta or fan freely, without obstacles preventing the accumulation. The hummocky morphology (kames, cf. below) indicates a modification of the original deposit due to a change of the substratum, that is, melting of underlying ice. These deposits always occur where there may have been considerable differences in level between the ice surface and ice-free areas. Meltwater from a higher ice surface — or non-glacial water — has passed over an ice-free area and transported material to be deposited on a lower ice surface as a delta. This probably happened quite close to the ice margin, before the stream could form a channel in the ice. At the wasting of the underlying ice the hummocky morphology developed. More extensive kame fields of similar genesis are probably more exclusively restricted to the ice margin zone and are consequently described under 2.1.1.

1.3. SUBAERIAL, SUPRAAQUATIC DEPOSITS

1.3.1. *Eskers.* Eskers of the above-mentioned type could probably only be formed

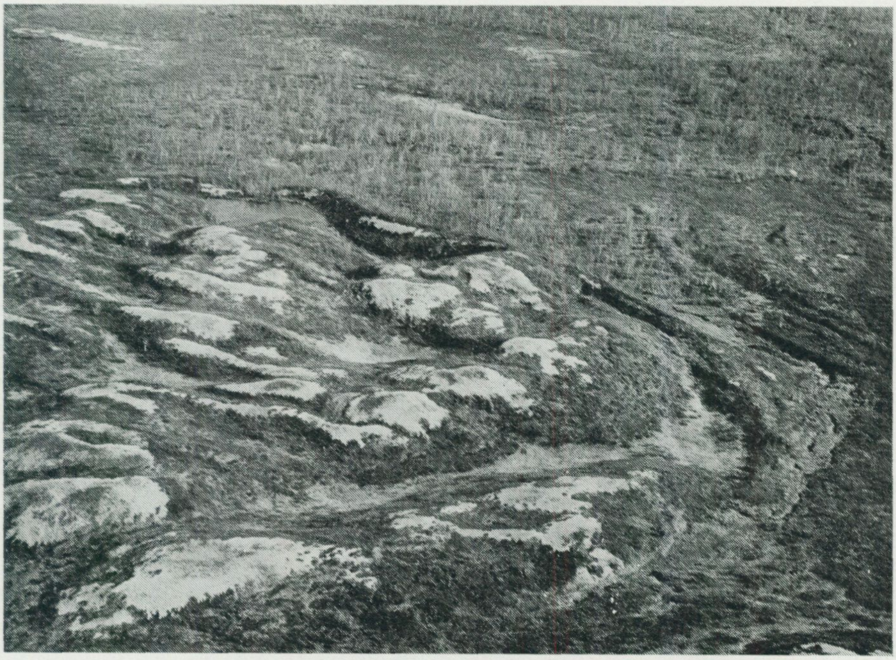

Fig. 9. Kame delta (1.2.2) SW of Nakerjaure, N of Kiruna, Lapland. The delta is bordered by a low ridge, which should be compared with the ridge of the nearby deposit shown in Fig. 15 and the eskers in Fig. 13. — Photo J. Lundqvist 1975.

in a country with very strong relief or, near the margin, also in flat country. In other positions there was most probably not material enough in the upper parts of the ice to allow formation of glaciofluvial deposits even if there was meltwater. On the other hand, in the marginal zone where the ice was disintegrating, the supraglacial meltwater streams probably rather soon found their way down to the bottom of the ice. The material deposited in the stream beds were no longer supraglacial, even if it is true that remnants of the ice or frozen basal till could be left behind under the streams. The material of gravel and sand was deposited in gorges between ice walls and the detailed morphology was determined by the disintegration of the surrounding ice. This is the type of esker that was especially emphasized by Holst (1876) and Tanner (1937). After a series of detailed studies of eskers Tanner (1928, 1932, 1934, and others) even concluded that all the studied "*esker formations have arisen by sub-aerial accumulation in valleys in the dead land ice margins, but that in no place has the sub-glacial esker theory proved itself applicable to esker formation in supra-aqueous areas*" (Tanner 1937, p. 26). The latter conclusion is doubtful (cf. below), but nevertheless Tanner's studies clearly demonstrate the importance of this esker type.

The eskers are generally restricted to the lower parts of the terrain. This applies particularly to the large eskers. The smaller they are the less pronounced is this topographic condition. Their size varies within a wide range. The large inland eskers above the highest coastline and above levels of glacial lakes belong to this type but also most probably numerous smaller ridges, although these can not regularly be separated from other types (1.2.1, 1.5.1). The courses of long esker systems follow in detail the lowest parts of the terrain, but in outline they may also cross higher ground, e.g., run from one valley to another. Even so, they mainly follow the lower passes and the depressions in the terrain, not ordinarily the top parts. Some criteria, although not conclusive, are the following.

The crests of the ridges are often very even in length-section. Even if the surrounding terrain is undulating or more or less hummocky the absolute height is constant and independent of the surrounding. The crest may be a sharp hog-back, but flat, road-like crests are very common (Fig. 10). Parallel ridges are quite common (Fig. 11). Sometimes the esker is divided into two equally large ridges, sometimes there is a smaller ridge on one or both of its sides. Well-developed examples may be mentioned from Arjeplog (Svenonius 1882) and Jukkasjärvi in Lapland. The process of formation is not clearly understood, but possibly it is connected with the covering of ice remnants during the sedimentation. If ice is buried under the esker, slumping may give rise to the parallel ridges (cf. 1.2.1). The fact that three parallel ridges seems to be a common phenomenon (see many examples by Tanner 1915) indicates that the process may be more complex. Other processes may be involved, e.g. the division of the stream into several branches. An evidence of this explanation is the occurrence of several (at least six) parallel ridges in some areas (Tanner 1915, p. 391, Pers-

Fig. 10. Esker (1.3.1) cut by a gravel pit at Lake Juvatssjön, Medelpad. The flat crest, representing the surface of a stream bed surrounded by ice walls, is clearly visible. — Photo J. Lundqvist 1975.

son 1974). The occurrence of parallel ridges often gives the whole system the appearance of an esker with trenches on its sides.

Typical for the eskers in question is also that especially the larger ones are connected with short transverse ridges, kame-like forms (Fig. 11) and other dead-ice forms. It is clearly seen that the glaciofluvial accumulation took place in the disintegrating outer zone of the ice sheet.

There are many examples of these eskers being divided into shorter parts displaced *en échelon* to each other (e.g. Tanner 1915, several examples). This phenomenon is perhaps best interpreted as the effect of the blocking of the drainage channels by accumulations. From time to time the stream was forced aside.

In some connections it has been emphasized that eskers of this group could have been formed at sudden draining of an ice-dammed lake. The water from the lake broke through the damming ice, forming an ice canyon in which the esker was deposited. This explanation has been suggested by Gavelin (1910) and Halden (1942). However, at least in some instances the interpretation was speculative and objections have been raised (see, e.g., Kulling 1944). If the theory is a reality, this way of formation would influence the material in the esker rather than the morphology. The sediment can be supposed to be poorly sorted.

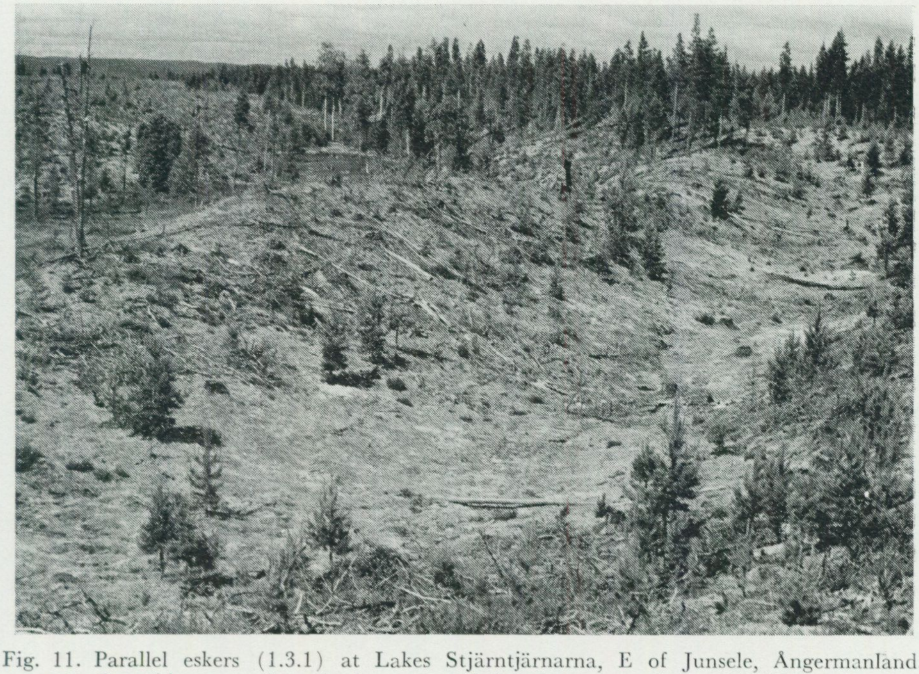

Fig. 11. Parallel eskers (1.3.1) at Lakes Stjärntjärnarna, E of Junsele, Ångermanland. One ridge runs through the center of the picture, one is seen behind a trench to the left, and the side of a third one is just visible to the right. — Photo J. Lundqvist 1974.

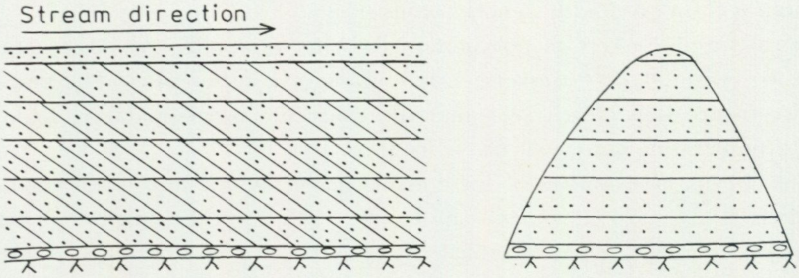

Fig. 12. Sketch illustrating length- and cross-section of the typical bedding in a subaerial, infraglacial esker (1.3.1).

The sediments of these eskers vary within wide limits. In the larger ones they are often well-sorted, but beds of till, flowed or slumped from the surrounding ice, are common. Discordances and faultings due to slumping or changes of the stream velocity and course are almost a rule, but an important basic type is the following. The sediments form banks, in cross-section seen as a horizontal bedding. In length-section the same bedding is seen, but within each separate bed there is a delta-bedding dipping downstream (Fig. 12). The general stratigraphy is important. The substratum of the glaciofluvial sediment is often the bedrock. Till is often lacking, especially under large eskers. Smaller ones may partly rest on till. The glaciofluvial material reaches the top of the esker. Fine-grained sediments are generally lacking, but sometimes a thin cover of silt or clay may exist on the crest, a sort of plateau clay (Westergård 1906).

1.3.2. *Kame fields.* Because kames (p. 14) very often occur in groups or clusters we can often use the term according to Nelson (1910, p. 30). However, we had better distinguish between kames and kame fields Therefore we here discuss kame fields as a term even if, in particular cases, single kames of the same origin may occur.

Under 1.3.1, eskers, was mentioned that those eskers are often connected with kame fields. This is natural, regarding the origin of the eskers: in the disintegrating marginal zone of the ice. If the accumulating stream follows a well-defined channel in the ice an esker is formed. In more broken ice, sometimes at a later stage than the corresponding esker formation, the stream is diverged into crevasses in the wasting ice and, finally, between separate blocks of ice. If sedimentation occurs, the result will be a more irregular landscape of glaciofluvial sediments, a glaciofluvial correspondence to dead-ice moraine. As a matter of fact, transitions between kame fields and dead-ice moraine occur, but generally it seems as if the difference is clear enough, at least as far as concerns kame fields formed as outlined above. As is discussed further below, kame fields can be formed also in other environments.

Sometimes the outer shape of a kame field can be delta-like. A reasonable interpretation is that the sediments were deposited as a delta in a temporarily stagnant water, while remaining disintegrating ice prevented the free formation of a delta. J. Lundqvist (1969, p. 75) used the term kame delta for such deposits. It should be observed that this sense of the term is different from the one used by Goldthwait (1975). Kame deltas in the sense of the present author sometimes occur as swellings of eskers. A kame field of this type can be connected with both a "feeding esker" and an "outlet esker". The kames then occupy a flat depression in the course of the esker. Related phenomena are probably the eskers described by Hausen (1913) as "comet eskers" from Estonia (cf. also Raukas et al. 1971, p. 116) and kame fields with a proximal "feeding esker" described by, among others, Halden (1936).

The sediments of the kame fields under discussion here are very similar to those of the corresponding eskers (1.3.1). Till that has slumped or flowed down from adjacent ice seems to play a little more important role, but this statement is rather uncertain. As stated above the difference between glaciofluvial and moraine deposits is often clear.

1.4. SUBGLACIAL, SUPRAAQUATIC DEPOSITS

In many cases it is very difficult to determine if a particular deposit was formed in an open channel or in a tunnel at the base of the ice. In some instances, however, the general circumstances clearly indicate that accumulation must have taken place under covering ice.

1.4.1. *Engorged eskers.* This term was introduced by Mannerfelt (1945) to denote eskers running downslope, at right angles to the contours. They were formed where meltwater in a broken country hurled down between the ice and a slope, the upper part of which was already free of ice. These eskers vary in size from a height of about 10 m down to a few cm. Their course may be slightly winding, but because it is determined by the slope it is independent of the ice and its direction of movement and recession. Where no accumulation took place the engorged eskers may be replaced by features of erosion, subglacial chutes. Because of the general conditions of formation these eskers are restricted to broken country above the level of the sea and glacial lakes. Mostly they are known from the mountain region above the timber line. To some extent this is due to the fact that those small land-forms are difficult to observe in forested country, but nevertheless many examples have been described also from such areas (e.g., J. Lundqvist 1958, 1969).

The interior of the engorged eskers is characterized by irregular conditions: sediments ranging from very coarse to rather fine particle sizes, discordances, faults, other disturbances, tilted beds, till inclusions etc. A thin till cover is quite common. Mannerfelt (1945) showed some typical sections. The sediments are sometimes surprisingly fine-grained considering the environment of accumulation. This, however, can also be observed in recent glaciers, where water engorged in sink-holes may deposit even fine sand or silt, which are the finest sediments found in engorged eskers.

1.4.2. *Subcircular eskers.* Small eskers that form part of or sometimes an almost complete circle, some tens or maybe a hundred metres in diameter, occur in many slopes in the broken parts of the country (Fig. 13). The height of these eskers is generally small, only a few metres. Their material has not been studied in detail but as far as is known it consists of typical glaciofluvial gravel and sand.

Below the mountain range subcircular eskers have not been described. There is one possible exception at Fjällandet, Jämtland (J. Lundqvist 1969, p. 303). Its pattern is the same although this esker is much larger (more than 10 m in height and a diameter of 800 m) and was interpreted as formed in open crevasses. The topographic situation is comparable with the common one, although in a flatter country. The sediment in this esker is well-sorted stony gravel with

Fig. 13. Subcircular eskers (1.4.2) E of Lutsetjåkka, NW of Kiruna, Lapland. The circles can be more or less complete. — Photo J. Lundqvist 1975.

a bedding similar to that of the eskers of group 1.3.1.

The process of formation is not clearly understood. The occurrence in slopes with a comparatively low gradient indicates that these eskers were formed below the marginal part of the ice where its thickness decreased against the slope. Sometimes several eskers occur in the same slope at approximately the same level. This fact indicates that at one particular stage during the downwasting of the ice conditions were favourable for their formation. Anyway, it is hard to explain the formation in other ways than as filling of subglacial channels or crevasses. This assumption is supported by an observation from Iceland of a similar esker melting out from the ice (Fig. 14). It remains to explain, however, how the circular crevasse pattern is formed.

A combination of subglacial and supraglacial processes is not out of question. There are examples of subcircular eskers surrounding insignificant kame-like accumulations, e.g. near Nakerjaure, northwest of Kiruna, Lapland (Fig. 15). In this way at least apparent transitions to the supraglacial kame deltas of group 1.2.2 arise.

1.5. SUBGLACIAL, SUPRAAQUATIC — SUBAQUATIC DEPOSITS

In the above-mentioned two examples the general conditions indicate that formation took place supraaquatically. There are many closely related types of gla-

Fig. 14. Recently formed subcircular esker (1.4.2) at the Tungnaárjökull, Vatnajökull, Iceland. This esker seems to have been formed subglacially and melts out of the ice. — Photo J. Lundqvist 1962.

Fig. 15. Subcircular esker (1.4.2) surrounding a few kames SW of Nakerjaure, Lapland, near the kame delta shown in Fig. 9. Thus a transition between the classes 1.2.2 (or 1.5.4) and 1.4.2 is formed. — Photo J. Lundqvist 1975.

ciofluvial deposits in the case of which it is clear that similar forms can arise below as well as above water-level. The decrease of the transporting power of the accumulating stream could be caused both by running into stagnant water and by local conditions in the stream course.

1.5.1. *Eskers.* Eskers similar to those of group 1.3.1 can probably be formed also in closed tunnels under a cover of ice. This opinion was suggested by Strandmark (1885, 1889). As was emphasized as early as by Hummel (1874) the two types can hardly be separated from each other, but the occurrence of eskers with a bedding typical for the subaerial crevasse fillings can be observed also far below the highest coast-line. These eskers must have been formed at a considerable depth of water. Because it is difficult to imagine open crevasses reaching that depth it is concluded that these eskers were formed subglacially.

Indirect evidence of a subglacial origin also occurs in the case of numerous eskers in central Jämtland. We know that they were formed below the level of ice-dammed lakes, but the general conditions demonstrate that there was no open water, just stagnant ice (J. Lundqvist 1969, 1973). If the crevasses, in which these eskers were formed, had been open upwards it is surprising that no fine-grained sediments occur on and around the eskers. The only natural explanation, also regarding the topographic situation, is that the crevasses were closed tunnels near the bottom of the ice. The very even crest of some eskers, in spite of an undulating surrounding, speaks against an englacial formation according to group 1.1.1. The opinion of an englacial formation earlier suggested by the author (J. Lundqvist 1969) is thus revised.

As an evidence in favour of a subglacial interpretation we may consider the occurrence of dry stream channels across the crest of an esker. Probably the esker was formed subglacially, while at a later stage supraglacial streams came in contact with it. The evidence may be doubtful. Tanner (1915, p. 337) knew about at least one example, and still he stated (Tanner 1937, p. 26) that he had never found any evidence in favour of the subglacial theory. A similar observation has been made in Denmark by S. A. Andersen (see Flint 1971, p. 218).

Some characteristic features of these eskers are the following. The size varies within wide limits, but generally the eskers are lower than about 10 m. The crest is even or slightly undulating. Even in narrow passes a sharp ridge form is retained (cf. Bergdahl 1953). According to Bergdahl (1953, p. 150) it is also a characteristic feature that these eskers are surrounded by flat gravel fields. The eskers form discontinuous courses. In the case of the above-mentioned examples from Jämtland the occurrence is on the downsloping sides of highlands. On the opposite, upsloping, sides eskers are lacking or replaced by till ridges in the same direction. The crests may be slightly undulating. Gillberg (1956, p. 210) and Persson (1974) even described eskers of this group that are divided into series of hummocks, "kame eskers".

Eskers with double crests belonging to this group can be formed in parallel tunnels of the type described by Halliday & Anderson (1970). The depressions between the crests can be described as trenches, which in this way get one possible explanation.

The formation of trenches in general, however, offers a special problem that has not yet got a satisfactory solution. As the most typical example of trenches we can consider the long series of narrow trenches along both sides of large eskers both above and below the corresponding water-level. Below the highest coast-line the Badelunda esker along the river Dalälven is a good case in point. The trenches here occur at least down to 120 metres below the highest coast-line. Above this line there are several good examples in Ångermanland, e.g. between Junsele and Myckelgensjö.

The trenches have mostly been considered a type of kettles, that is, dead-ice hollows. However, it is difficult to apply this explanation far below the sea-level and many authors therefore have preferred to interpret the trenches as erosion features (A. G. Högbom 1913, Hjulström 1944). Recent investigations have given this theory some support. Larson (1974) found that the trenches could be formed also in fine-grained sediments. The central ridge between them was

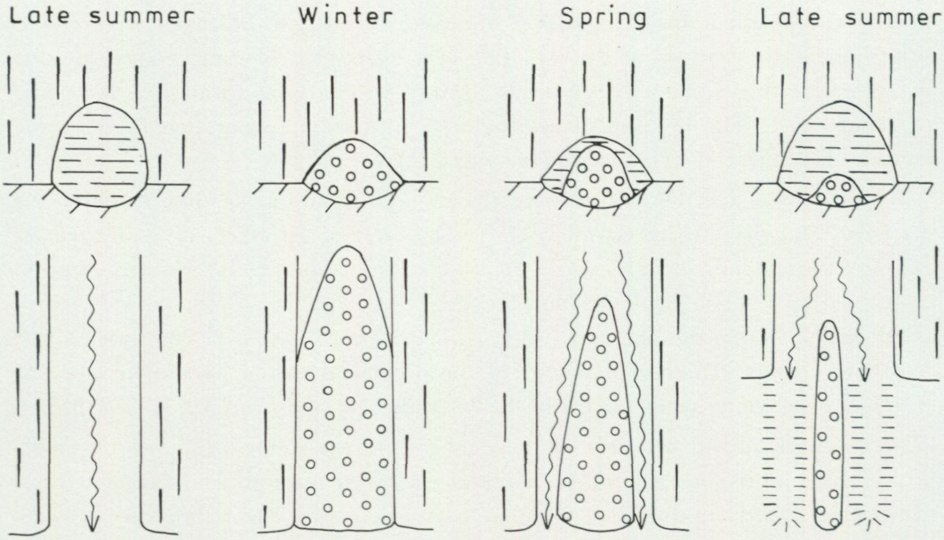

Fig. 16. Sketch showing a possible way of formation of trenches along an esker in vertical (above) and horizontal section. When a tunnel in the ice near its front is flooded (late summer) it is kept open and erosion of its bottom is exerted. When the current ceases sediments fill the tunnel. When water begins to flow again in the spring the strongest erosion is exerted along the tunnel filling. In the following late summer a remnant of the filling (an esker) is left behind, surrounded by trenches.

not an esker, but just an erosion remnant in these sediments. Smedman (1974) found that the bottoms of a series of trenches were situated on corresponding levels, together showing the pattern of a slightly winding river course. Wenner (1974) suggested an explanation implying that a supraglacial river deposited sediments upon the ice. These deposits could protect the ice around the stream course even in a subaquatic position when the ice melted down. Considering the fact that the trenches occur far below the sea-level of that time the explanation seems less plausible. Another possible explanation may be the following (cf. Fig. 16).

Some distance behind the ice margin the subglacial stream exerts mainly erosion activity. A subglacial channel, tunnel valley, is formed in the substratum. Deposition takes place closer to the margin. Because of the annual rhythm in the stream activity, the tunnel in the ice is variable (cf. Glen 1954, Shreve 1972). During flood, that is towards the end of the summer, it is large in cross-section. In winter, when the stream is insignificant or lacking, the ice pressure will close the tunnel at least to some extent. Therefore, when a certain part of a tunnel valley reaches the accumulative phase its size is not necessarily the same as during the phase of erosion. If it is smaller, the remaining erosive forms may be traced on one or both sides of the accumulation, the esker. This effect can be increased in the final phase of formation. When a tunnel near the margin has been filled with sediments during a period of large discharge the ice will close around it when the discharge ceases, in winter time. When spring comes and the stream more or less suddenly becomes very active again, the water will find its way along the tunnel filling — which may be either coarse-grained or fine-grained. Before a new tunnel has been formed around the filling, by melting of the ice, some erosion of the tunnel bottom has taken place along the sides of the filling. If the ice front recedes before the eroded channels have been filled with new sediments, these channels will be left outside the ice margin and only partly filled with distal, fine-grained sediments. In extreme cases the result may be an esker in a tunnel valley (cf. Pietkiewicz 1928, 1977).

The sediments within the eskers of 1.5.1 may show a horizontal bedding as in the case of group 1.3.1. More typical, however, is an irregular bedding with numerous discordances, faults, tilted layers etc., and a rich amount of poorly sorted sediments and even till beds. Thin layers of silt may be included in the stratigraphy. Ringberg (1971) found a slightly convex bedding most common.

The substratum can be till. Sometimes even the lower part of the esker itself consists of compact basal till (Fig. 17; see also, e.g., J. Lundqvist 1969, p. 70).

Fig. 17. Section through an esker of type 1.5.1. The glaciofluvial material (dark, coarse-grained) rests upon a dense till (light, seen to the right between cones of slumped material) forming the lower part of the esker. W of Risliden, Västerbotten. — Photo J. Lundqvist 1972.

In such instances the differences between the glaciofluvial beds, including some till, and the underlying till is very distinct. This makes it probable that the till is not just part of a crevasse filling. A plausible assumption is that it is part of the general cover of basal till. If so, the fact that the till below the esker reaches a higher level than the general till cover can either indicate that there were still movements in the surrounding ice when the esker was formed or be traces of the subglacial erosion described above. In any case it can be considered an evidence for the subglacial origin of the esker.

1.5.2. *Transverse eskers.* Especially in connection with other eskers of groups 1.3.1, 1.5.1 and 2.3.1 one can find smaller eskers at approximately right angles to the main stream direction. For these ridges Nelson (1910, p. 34) used the term transverse esker (strictly, Nelson always used the word ose instead of esker), to be clearly distinguished from the term marginal esker (see 2.4.1). The transverse esker in the sense of Nelson refers to ridges in esker nets (see below) running transversely to the main stream direction, but here we use it for more independent features.

The transverse eskers were formed in crevasses in the ice. Their direction shows that these crevasses must have been closed — if they reached the surface of the ice, the outer part of the ice must have been separated from the main ice and disappeared. They occur as a common part of the esker-and-kame landscapes of groups 1.3.1 and 1.3.2, but more independent examples have been described by Möller (Möller and Stålhös 1969) and Persson (1974). In the case described by Möller, north of Södertälje in the Stockholm region, a number of small ridges of this type occur as branches from a large subaquatic esker (Fig. 18). Similar phenomena above the highest coast-line occur around a large esker at Rörström, Ångermanland (Fig. 19).

The material of the transverse eskers corresponds, as far as we know, to that of the adjacent radial eskers. Investigations by Johnsson (1956) indicate that the transverse eskers were formed by water running away from the main esker in transverse crevasses in the stagnant marginal zone of the ice.

1.5.3 *Esker nets.* A landscape of anastomosing eskers, radial as well as transverse and at oblique angles to the main stream direction, all of varying height, forms a network and can be called an esker net (Nelson 1910, p. 28, although he wrote "ose nets"). These nets can be formed in connection with the supraaquatic eskers of group 1.3.1, but generally the dead-ice conditions have caused more coherent kame-and-kettle landscapes — kame fields. The difference can be defined as follows. The kame fields consist entirely of glaciofluvial sediments (with till inclusions). Even the bottom of the depressions, kettles, are glaciofluvial material. In the esker nets only the ridges consist of glaciofluvial sediments. In the

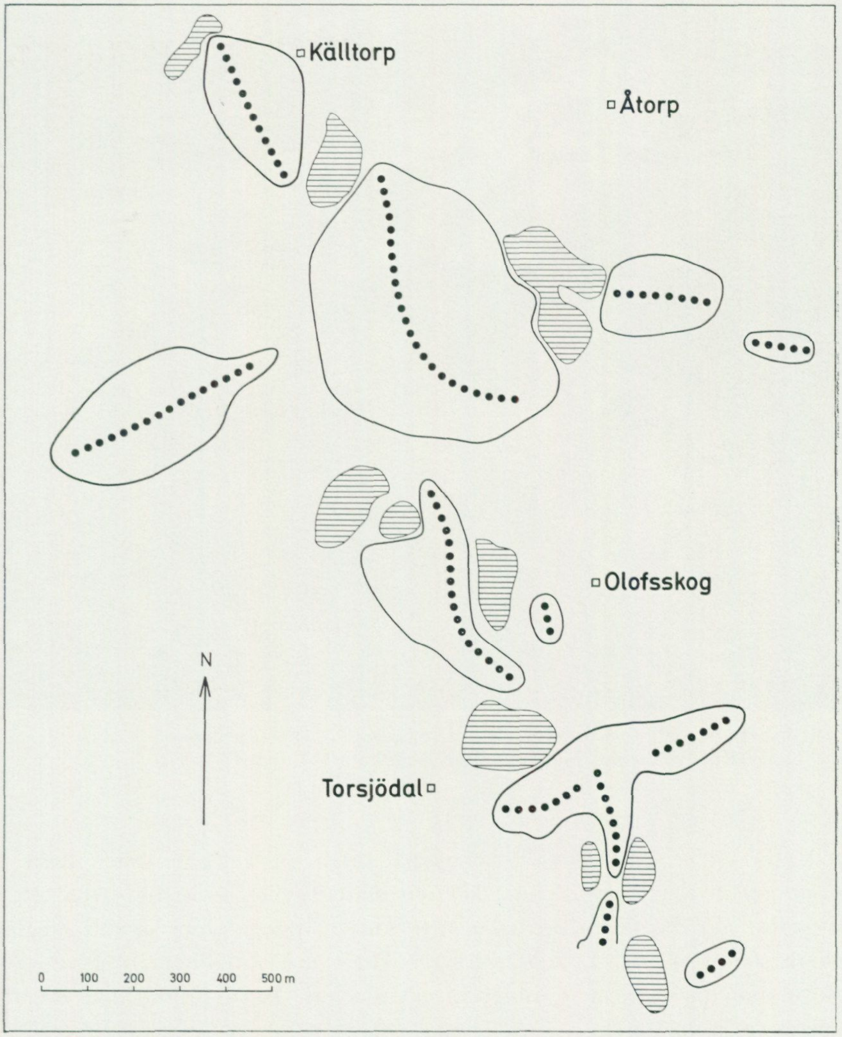

Fig. 18. Transverse eskers (1.5.2) surrounding a subaquatic esker of type 1.5.1 or 2.3.1 W of Södertälje, Södermanland. Dotted lines = crests, lined areas = kettle holes. — From Möller and Stålhös 1969, Fig. 17.

bottom of the depressions the general till cover is exposed.

The most typical esker nets belong to the broken country in the mountain region but are also common in, e.g., the much flatter South Swedish Highland (Persson 1974, Bjelm 1976). Series of engorged eskers (1.4.1) may join at a valley bottom to form a network of ridges. The area of Lakes Dörrsjöarna, Oviksfjällen, Jämtland (Fig. 20; Mannerfelt 1945, J. Lundqvist 1969), can be chosen as type area. The close connection with the undoubtedly subglacial en-

Fig. 19. Esker, probably of type 1.5.1, surrounded by short transverse eskers (1.5.2) in Lake Rörströmssjön, Ångermanland. — Photo J. Lundqvist 1970.

gorged eskers directly shows the subglacial origin of the net. When there is a continuation in the shape of an esker out of the valley with the esker net, this esker must also be formed subglacially. This is also a proof of the subglacial origin of some eskers (cf. above, 1.5.1). There are also direct observations of the formation of esker nets under recent glaciers. Price (1966) has described one example from Alaska.

The known esker nets occur above or slightly below the highest coast-line (cf. Nelson 1910, p. 29). The fact that some types of kame fields may be formed also far below this level (see below) makes it possible, however, that esker nets may be formed also subaquatically. This is the reason why they are grouped here under 1.5 and not 1.4.

The material in the ridges in the esker nets does not differ from that of other subglacial eskers. In the Dörrsjöarna complex it is a comparatively well-sorted fine gravel.

1.5.4 *Subglacial kames.* If the network of an esker net is closed, so that the entire field is composed of glaciofluvial sediments, we should no longer use the

Fig. 20. Esker net (1.5.3) and engorged eskers (1.4.1) at Lakes Dörrsjöarna, Oviksfjällen, Jämtland. The engorged eskers join to form one or a few central eskers (also seen below the water surface). Cf. Mannerfelt 1945. — Photo J. Lundqvist 1963.

term esker net. The resulting hummocky glaciofluvial deposit coincides with what has been described above as a kame field (group 1.3.2), but it is evident that these forms may arise also in subglacial position. In the individual cases it is often impossible to determine whether the accumulation took place subglacially or in open crevasses.

There is at least one example evidently supporting the assumption that similar kame fields can be formed also subaquatically. The flat glaciofluvial deposit of Sörmon in Värmland has earlier been interpreted as a subaquatic delta (Sandegren, in Magnusson and Sandegren 1933, J. Lundqvist 1958, p. 145). Blomquist (1969), however, has shown that this deposit was originally formed as a kame field, but has later been levelled by abrasion. Because the accumulation took place about 100 m below sea-level, it is impossible that the kames were formed in open crevasses. A subglacial origin seems to be the only reasonable interpretation.

Similar examples, although perhaps not quite so indisputable, have been described from Jämtland (J. Lundqvist 1969) in a very characteristic position. This is where large subaquatic eskers (of group 2.3.1) are divided in two branches, or where two eskers join to form a single one. As type areas can be taken the occurrences at Tossön and Staa west of Östersund where eskers join, and at Finneråsnäset (east of Stugun) where a tributary esker is diverged. In all instances deposition took place well below the Ice Lake of Central Jämtland and the sea, respectively.

In the cases mentioned the individual hummocks may reach a height between 10 and 20 m. The sediments range from boulders to silt, with a good sorting within each separate bed. Till beds occur. Vertically turned layers and other structures of slumping are common. Often beds from adjacent hummocks cut each other discordantly. This indicates that the different kames were formed independently of each other.

Hummocks similar to those of the kame fields may occur as individual units. According to the definition (p. 14) these hummocks should also be called kames, but in Swedish the term *åskulle* (esker mound) is recommended. The hills in question occur both below and above the highest coast-line. They may reach a height of several tens of metres. A famous example in a supraaquatic region is the hill Potatiskullen (Potatoe Hill) at Ammarnäs, Lapland. Similar deposits were described from Inviken, Jämtland, by J. Lundqvist (1969, p. 212). A noteworthy example, consisting entirely of large, rounded boulders without fine matrix is the Antamåla Rör, southern Småland (Fig. 21; Knutsson 1965). In subaquatic regions similar kames have been described from Värmland (J. Lundqvist 1958, p. 79). They were interpreted as short eskers of the subaquatic type (2.3.1), but a subglacial deposition, analogous to that of the supraaquatic hills, is perhaps more plausible. In favour of this explanation speaks the absence of long, discontinuous eskers, of which the kames could be isolated parts. At this point, however, there is a great uncertainty.

A more clear example, constituting an intermediate type between the kame fields and the isolated kames, was described from Toneby, Värmland, by J. Lundqvist (1958, p. 167). At the junction of a tributary valley with scattered glaciofluvial deposits and a main valley with similar deposits there are two kame fields with relative height differences of several tens of metres (Fig. 22). The whole fields rise as giant complex hills, about 60 m high and with an area of about one square km each, above the surrounding clay and silt fields. The situation below the sea-level of that time makes it probable that accumulation took place subglacially, although we cannot completely exclude the possibility of formation in open crevasses.

1.5.5 *Lee-side ridges.* From the southwestern and eastern parts of Sweden it is

Fig. 21. Antamåla Rör SW of Emmaboda, Småland, is a kame (1.5.4) composed solely of big, rounded boulders. — Photo J. Lundqvist 1977.

known that the till on the lee-sides of bedrock knobs is often very rich in layers and lenses of sorted material (Hessland 1943, Björsjö 1949, Möller 1960). Especially from the descriptions by Björsjö (1949) it is evident that the amount of sorted, glaciofluvial, material may be considerable. In many places in the county of Västernorrland the present author has observed how this "lee-side lens till" may pass directly into ridges of pure glaciofluvial sediments. Many examples could be mentioned from the regions of Sollefteå and Kramfors. These deposits occur mainly below the highest coast-line but have been observed also above it.

The ridges in question are straight or slightly winding and rather small features: less than 10 m high and a few hundred metres in length, at the most. The crest often slopes distally from the proximal rock. The material changes from till-rich, very coarse in the proximal end towards fine gravel and sand in the distal end. These features are characteristic and separate the deposits from all types of eskers discussed here. Therefore it seems to be appropriate not to use the term esker for these little ridges. Especially the occurrence of two "poles", distinct proximal and distal ends, discriminate the ridges from the eskers. This fact should be kept in mind also when we discuss the term esker.

It seems probable that these glaciofluvial accumulations have been formed in the same way as the layers in the till: Subglacial meltwater had a tendency to run towards places where the internal pressure of the ice was lowest. This was on the lee-sides of hills and knobs of the bedrock.

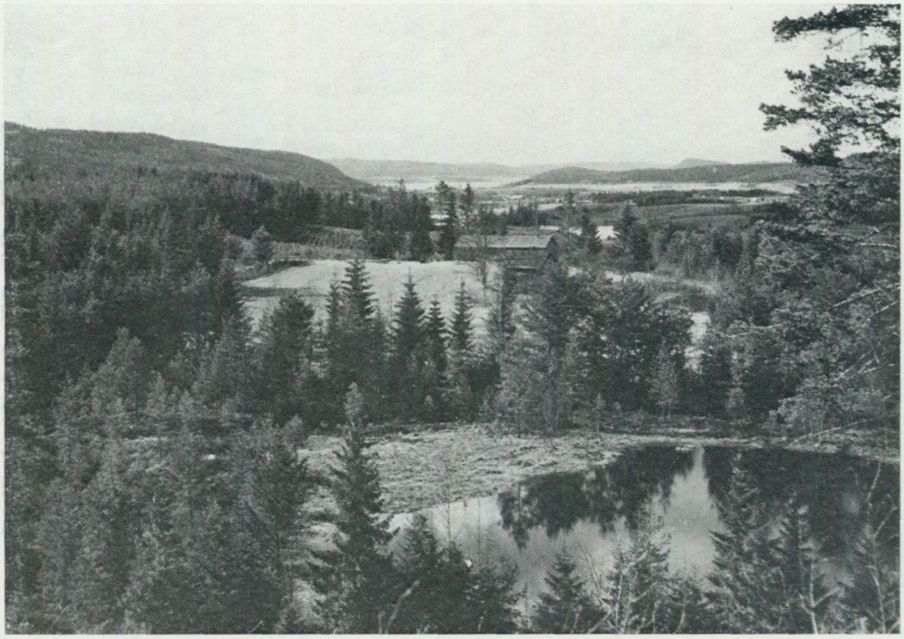

Fig. 22. At Toneby, Värmland, two kame fields (1.5.4) rise as hummocky plateaux over the valley bottom. Between the individual kames small tarns are ponded. — Photo J. Lundqvist 1955.

1.5.6 *Valley-side deposits.* From the highest coast-line and downwards there occur more or less terrace-shaped accumulations of glaciofluvial sediments. Often they can be misinterpreted as beach gravel and sand, but sometimes typical glaciotectonics or a cover of glacial clay is evidence for their glaciofluvial origin. If similar terraces occur above the highest coast-line — or levels of glacial lakes — they are called lateral terraces (see 2.1.2). On the level of a former water surface we may also use this term, and Nelson (1910, p. 47) even used it for all deposits which are here, with a more general term, called valley-side deposits. Because the origin of the deposits above and below a water surface is somewhat different, it may be appropriate to separate the deposits under different terms.

The valley-side deposits form narrow terraces or more irregular patches of glaciofluvial gravel and sand attached to steep valley sides. They are typical for broken landscapes with long and narrow tectonic valleys common in the southwestern parts of Sweden. Examples have been described from the west coast (Gillberg 1956) and Värmland (J. Lundqvist 1958). The terrace form may well be the result of later abrasion. The deposits must have been formed in crevasses between ice in the valley and the valley side. Ice pressure has forced the sediments into pockets in the bedrock and caused glaciotectonic structures (Fig. 23). The deposits could not possibly be accumulated in this position without the presence of ice. It is not clear, however, if the crevasses were closed or reached the surface, but general considerations of the depth below sea-level etc. make it probable that in most cases they were closed.

The valley-side deposits may occur as independent accumulations, but may also be parts of more continuous eskers, that occasionally have been formed against valley sides. A good case in point can be seen at Hagfors, Värmland, where a large esker of group 2.3.1 reaches the side of a hill and forms a broad terrace. Morphologically and seen as an isolated phenomenon this terrace belongs to the group valley-side deposits, but in a wider context it is just a part of an esker.

Related examples of different types are found where long continuous esker systems cross large valleys at an oblique angle. Through the ice pressure the glaciofluvial stream was forced against the down-glacier side of the valley and could in many cases be diverged out of the valley. Glaciofluvial valley-side sediments were accumulated as sometimes terraced, sometimes more irregular deposits. The material is essentially gravel and sand, but because of a certain stagnancy of the stream in the positions in question also more fine-grained beds are

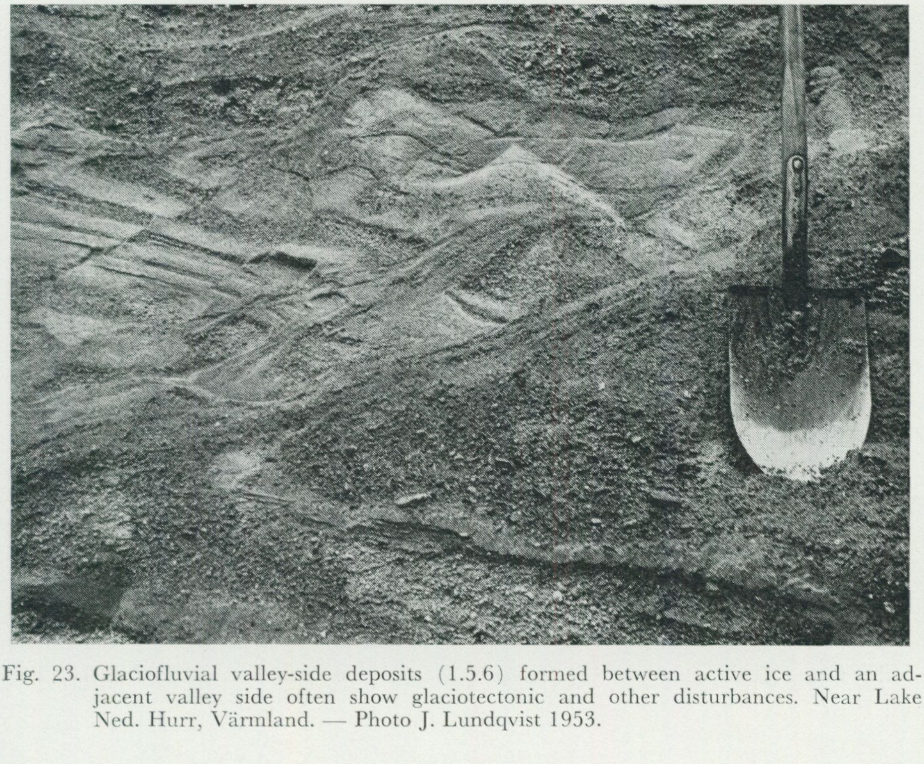

Fig. 23. Glaciofluvial valley-side deposits (1.5.6) formed between active ice and an adjacent valley side often show glaciotectonic and other disturbances. Near Lake Ned. Hurr, Värmland. — Photo J. Lundqvist 1953.

Fig. 24. Where eskers have been forced up against a valley side, disturbed deposits containing till as well as glaciofluvial sediments have accumulated. Moliden near Bollstabruk, Ångermanland. — Photo J. Lundqvist 1970.

quite common. So are irregular beds of till. If these deposits were formed below the sea-level later reworking by wave action may deform the accumulations and give rise to stratigraphic sequences that are difficult to interprete. Terraces may be developed, and the deposit itself will probably get a terrace shape, even if it was originally more irregular.

A few examples of the deposits in question may be given from the county of Västernorrland. At Erikslund east of Ånge the Ljungan esker, running WNW—ESE, has been forced against the southern slope of its valley by a N—S movement of the ice. The result is a broad terrace, Slättheden, of gravel with irregular bedding and inclusions of till. At Bollstabruk north of Kramfors a smaller esker has in the same way been forced against the southern side of a valley. An extensive valley-side deposit with sediments ranging from coarse, boulder-rich gravel to silt with till inclusions, glaciotectonics etc. has been the result (Fig. 24).

2. DEPOSITS FORMED AT THE ICE MARGIN (MARGINAL DEPOSITS)

A number of the deposits mentioned under 1 and especially 3 can be formed at or very close to the ice margin. The true marginal deposits (group 2), however, are those that necessarily demand an ice margin for their formation. All of these deposits are subaerial or subaquatic. Subglacial deposits are treated under 1, even if they are sometimes formed very close behind the margin. The sediments of the group 2 deposits are often referred to as ice-contact stratified drift (see, e.g., Flint 1971).

Fig. 25. Kames (2.1.1 or 1.2.2) under formation at Breiðamerkurjökull, Iceland. Glaciofluvial outwash has been deposited upon the thin marginal zone of the glacier. When the ice melts, large and small kettles are formed and the flat gravel surface obtains a kame morphology. — Photo J. Lundqvist 1977.

2.1. SUPRAAQUATIC DEPOSITS

These deposits can be formed down to a water level, but such a level is not necessary for the formation.

2.1.1 *Marginal kames.* As has been emphasized by Ahlmann (1938) one of the most important situations where dead-ice is formed is the marginal zone of a glacier or ice-sheet. By stagnation of the movement in the margin a narrow belt of dead-ice is separated from the active ice. This process can take place upwards from just below the level of the sea or glacial lakes. Upon, within and under this stagnant ice glaciofluvial sediments can accumulate (Fig. 25). Thus conditions are favourable for the formation of — besides dead-ice moraine — elongated kame fields, the course of which and also of the individual kames (cf. Raukas et al. 1971, p. 138) indicates the former marginal zone of the ice. We can preferrably separate elongated narrow kame fields of this type from kame fields in general, but their sediments and morphology in detail are essentially the same as those of other kame fields.

Extensive marginal kame fields seem to be rare. They probably demand a

Fig. 26. Kame field (2.1.1) forming an extended marginal deposit at Ljungstorp, Östergötland. — Photo J. Lundqvist 1975.

long still-stand by the ice front to allow accumulation of a sufficient amount of sediments. In Sweden they are known from the Middle Swedish End Moraine zone. As type area can be mentioned the Valle Härad field in Västergötland, southwestern Sweden. However, as has been shown by Munthe (1905), Ahlmann (1912) and E. Johansson (1934) this field is much more complicated, including also end moraines, deltas and other forms. A more regular marginal kame field, although it contains a large amount of till, is found at Ljungstorp, west of Mjölby, Östergötland (Fig. 26). Some examples in the large river valleys in northern Sweden may also be comparable with marginal kames, e.g. those at Krångede in Jämtland (J. Lundqvist 1969, p. 312).

2.1.2 *Lateral terraces*. Between the ice and ice-free slopes in broken terrain meltwater streams can erode drainage channels or accumulate sediments. Where the ice forms lobes in valleys, or around local glaciers, we may speak of lateral deposits formed along the sides of the lobes and frontal deposits at the end of the lobes. There is, of course, a gradual transition. However, it can be appropriate to include among the lateral terraces also deposits formed behind the ice margin around nunataks and other ice-free areas. Such deposits are principally of the same type as lateral terraces *s.str*. As type example of very large deposits of this kind can be mentioned those at Hökensås, Västergötland, described and inter-

Fig. 27. Lateral terraces (2.1.2) are often composed of alternating beds of till and better sorted sediments — ice contact stratified drift. From terraces surrounding the basin of Lake Kirkkoväärtijärvi NE of Kiruna, Lapland. — Photo J. Lundqvist 1967.

preted by Norrman (1971). Smaller deposits have been described from southern Jämtland (J. Lundqvist 1969). Also deposits formed in basins with isolated ice bodies may be included in this group. Examples are transitions to deposits of glacial lakes (ice-lake types 5 and 6 of J. Lundqvist 1972) found in many places in Jämtland. A case in point worth mentioning are also the deposits in the basin of Lake Kirkkoväärtijärvi northeast of Kiruna (Fig. 27).

The lateral deposits are left behind as terraces when the ice disappears. Sometimes these terraces have an undulating surface. For this reason they have, especially in American literature, after Salisbury (1893), been called kame terraces. This term is generally accepted, which is unfortunate. The undulating morphology may be due to true kames, but generally it is the effect of numerous kettle holes caused by the remnants of the ice margin being imbedded in the sediments. Thus the land-forms are negative rather than positive, as are kames. Therefore, in this article as mostly in Swedish literature, the term lateral terrace is preferred, although the author is aware that the term kame terrace is established by usage and impossible to exterminate. There are, of course, also cases where there are good reasons to retain the term kame terrace. Especially this applies to the

Fig. 28. Laterally formed terraces and deltas are often traversed by dry stream channels showing how meltwater has flown from the delta over the adjacent ice and vice versa. Other surfaces are pitted by numerous kettle holes. The Gröndalen delta SE of Vålådalen, Jämtland; cf. Fig. 36. — Photo J. Lundqvist 1956.

lowest terraces, formed almost on the sea-level.

Morphologically the lateral terraces are variable. Especially the highest terraces in the mountain region are narrow and beach-like. As a matter of fact transitions to beaches formed in narrow lakes, e.g. nunatak lakes, occur. On lower levels, but still far above the sea-level, the terraces are often broader. Isolated kames or groups of kames may occur, but far more common are kettle holes. The terraces may be completely pitted as a moon landscape. Dry stream channels are also common. Sometimes their courses show how meltwater streams alternated between the terrace and the adjacent ice. Fig. 28 shows some variations of the terrace surfaces.

On lower levels there are, as mentioned above, a tendency of the terraces to get a more pronounced kame or kame-and-kettle morphology. The kame fields surrounding the eskers of group 1.3.1 may gradually develop into terrace-shaped kame fields, separated from the esker itself by elongated depressions. The lateral terraces that could most pronouncedly deserve the name kame terrace are found in distinct valleys approximately on the highest coast-line. The well-known Brattforsheden delta complex in Värmland (Fig. 38; Hörner 1927) is a case in point. On the proximal side of the main delta the deposits extend along the valley sides as hummocky terraces surrounding a water-filled depression. Evidently, in such a position the ice lobe remaining after the general deglaciation of the area got its margins broken up by the heaving effect of the water. In this surrounding of disintegrating dead-ice the deposits were accumulated laterally to more compact ice.

The sediments in the broad lateral terraces are dominantly ordinary gravel and sand, often well-sorted. In the higher situated, more typical terraces they show all the variations characterizing ice-contact deposits (Fig. 27). The sorted material ranges from boulders to sand and silt, and till is a common constituent. Discordances, faults, slump structures etc. are very common. A typical section has been shown by von Brömssen (1966).

Because lateral terrace is a topographic description that does not refer to any mode of sedimentation it is natural that within these terraces we find sediments formed in different ways. There are delta beds, supraaquatic fluvial banks, deposits of stagnant water and material transported by flowing or sliding.

2.2. DEPOSITS FORMED AT A WATER LEVEL

The morphology of these deposits is determined by the presence of a level of stagnant water close to the ice margin. This water was usually the sea, sometimes ice-dammed lakes.

2.2.1 *Marginal deltas.* Deltas usually belong to the main group 3. Some of them were formed close to the ice margin and could be called marginal deltas in a wider sense. Here the term is used in a more limited sense. The deltas called marginal deltas here were formed at the ice margin where it was situated in water. It should be observed that the term marginal delta is used also in a more restricted way than by Nelson (1910). He included for instance supraaquatic deltas etc. in this group. However, because the general conditions of formation are — or can be — very different this revision has been made. The true marginal deltas were formed where there was a stagnancy in the recession of the ice front. In that way enough sediments could accumulate to form very large deltas or delta complexes. Such halts in the recession could be caused by general climatic conditions, like those of the Younger Dryas Time that caused the stagnancy along the Ra–Salpausselkä line. More common are topographic reasons. At valley mouths e.g., or where floating shelf ice reached the bottom in shallower water there were local stagnancies. Well-known examples from the

Younger Dryas line (Middle Swedish End Moraines) are the delta of Dal's Ed (De Geer 1909), the Djurkälla plateau at Motala, the Mjölby terrace and others. Part of the Brattforsheden complex (Hörner 1927), the Kil and Mellbymon deltas and others in southern Värmland are examples of the topographically controlled type.

Marginal deltas in the restricted sense got their sediment supply directly from the ice. Therefore no stream channels can be traced upstream from the proximal side of the deltas. The delta ends with a steep and distinct ice-contact slope, and thus it can form a plateau limited by both proximal and distal slopes. The sides may also form steep slopes, in which case the delta gets a plateau-like shape, but may also adhere to valley slopes. Sometimes a "feeding-esker" may protrude from the proximal slope. The surface of the delta is usually situated approximately on the level of the water in which it was deposited. Then it is often crossed by stream channels (e.g. De Geer 1909). Some lowering due to abrasion may also have occurred and in other instances the delta surface may never have reached the water surface. In the latter case, if the depth was considerable, the delta is here referred to group 2.3.2. Here are discussed deltas that in principle, even if not exactly, were built up to the water surface and the morphology of which was determined by this surface.

Because of the close vicinity of the ice, blocks of it could be buried in the sediments. As a result the delta surface is sometimes pitted by kettles.

As examples of marginal deltas, the shape of which has been modified by ice contacts, the Väse Allmänningshed (Hörner 1927) and Lidetorpsmon south of Degerfors — both in Värmland — can be mentioned. On both deltas there are very deep kettle holes caused by the embedding of large separated parts of the ice margin. In both cases also the feeding-eskers can be seen. A number of marginal deltas on the west coast have been described by Gillberg (1956).

The general stratigraphy of the marginal deltas is to some extent that of any river delta, that is, bottomset, foreset and topset beds. The bottomset bed consits of sand, silt or clay, often varved, while the upper beds mainly contain gravel and/or sand. A difference from ordinary river deltas is the backset bed that can be seen in the proximal part (Fig. 7; cf. Nelson 1910, p. 50, C. E. Johansson 1975, p. 90). The sediments were transported along the bottom of the ice and at the mouth they were thrown up on top of earlier deposited sediments.

A special type of marginal delta is formed between the ice margin and a pass in front of it. In this position there was first an ice-dammed lake in which sediments were deposited. These were glaciolacustrine, fine-grained deposits the bottomset bed of a growing delta. Gradually the delta filled the lake completely. If the ice front then receded faster than the delta grew, the latter was left behind as a terrace against the outlet pass. The terrace may contain some kettles. It is limited by an ice-contact scarp, below which fine-grained glaciolacustrine sedi-

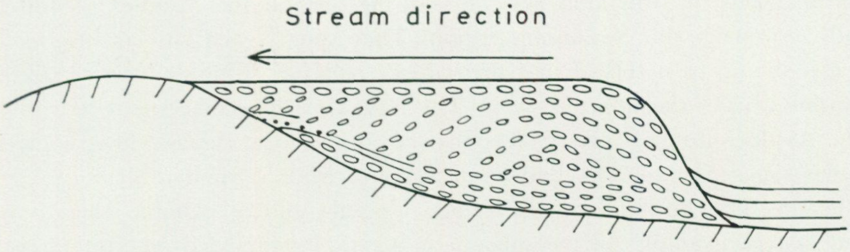

Fig. 29. When a glaciofluvial delta (2.2.1) accumulates between the ice and a nearby pass, thus filling up a small glacial lake, its morphology will be reversed, compared to that of a delta formed in open water.

ments extend. Thus the delta has in some way the inverted shape of an ordinary delta of group 3.2.1 (Fig. 29). Examples can be mentioned from Malmagen at the western part of the Ljusnan Ice Lakes in Härjedalen, Ulvåtjärn in western Jämtland (J. Lundqvist 1969, pp. 266, 319), and Pulsujärvi northeast of Kiruna, Lapland.

2.3. SUBAQUATIC DEPOSITS

2.3.1 *Subaquatic eskers (De Geer eskers)*. According to De Geer's (1897) theory eskers were formed at the mouth of subglacial rivers below the sea-level (or levels of glacial lakes). The transported material was deposited at the very mouth as a miniature delta when the transporting power suddenly ceased. During the retreat of the mouth with the ice front numerous similar deposits accumulated successively to form a ridge, a radial esker. As has been stated above, this is by far not the only way in which an esker can be formed, but the stratigraphy of many eskers gives an indication that this way of formation is a reality. According to the opinion of some researchers the term esker should be used only for ridges formed in this way. Whether we find this desirable or not we must, however, realize that it is impossible to perform such a separation consequently. It needs a knowledge of the interior of every glaciofluvial ridge that we do not possess. Often we cannot obtain it until the ridge has been removed by, e.g., gravel mining. Besides, most eskers are probably complex formations (cf. p. 60 and Fig. 35).

Some characteristics of the subaquatic eskers are the following. These eskers are often very big ones. Their height over the surroundings can reach 50 to 100 m. A height of 85 m is reported from an esker at Miellätno between Lake Virihaure and the Sarek mountains in Lapland (Hamberg 1900, Melander 1975) although there is some doubt concerning the nature of this accumulation (see Tanner 1934, p. 88). A height of 60 m is, however, reported from the area of a small ice-dammed lake in Härjedalen (J. Lundqvist 1969, p. 379). The most typical eskers of this kind are the very big ones in the Middle Swedish lowlands, especially the Stockholm region. They often reach similar heights, and then it should be observed that their upper part has certainly been removed by abrasion during the uplift of land. The length of these eskers can be considerable. As discontinuous eskers or courses of glaciofluvial deposits they sometimes extend some 100 km. The Badelunda esker of Middle Sweden is about 250 km in length. This one and the Enköping, Uppsala and Stockholm eskers may be used as type examples of the subaquatic eskers. For detailed descriptions of the interior of parts of the Stockholm esker reference is made to von Post (1942) and K. G. Eriksson (1960).

The subaquatic eskers follow the lower parts of the country in the general direction of the ice recession, though not in detail. A characteristic feature is often seen where they follow narrow depressions in a flat country. There the eskers are not confined to the bottom of the depressions. Often they seem to be located also at the sides of the valleys (Möller, in Möller and Stålhös 1964). Due to breaking up of the ice in such positions ice blocks may have been embedded in the eskers also well below the sea-level, giving rise to kettles below the highest coast-line (see Hjulström 1944, Björklund 1973).

The crest of these eskers is very uneven, although later abrasion may often have given it a straighter profile. The eskers are divided into coherent hummocks, each one representing one year's accumulation according to the original theory (De Geer 1897, 1940, Bergdahl 1925). This assumption must probably in many cases be modified, but nevertheless the hummocks, esker centres, represent short-term depositions. Möller (1962) has described a distinct rhythm in the occurrence of esker centres. In the area studied by him the centres correspond to the annual retreat of the ice front as determined with clay-varve chronology. The size of the centres changes between large and small hummocks with a regular 11-year periodicity. Möller correlated this periodicity with the sunspot cycle. Also the 70-year cycle could be traced. Another characteristic feature is that there are breaks in the eskers at the small centres, where the parts of the eskers are displaced *en échelon* (Hjulström 1944, Möller 1962).

The common stratigraphy of the subaquatic eskers is the following (Fig. 30). The substratum is mainly the bedrock. The large glaciofluvial streams in question have removed the main part of the basal till. The centre of each annual deposit consists of coarse material (boulders, stones). Upwards — and distally — follow more gravelly and sandy layers concentrically like shells upon each other (e.g. von Post 1942). The upper layers are the most fine-grained. Gradually they pass into the more silty to sandy bottom layers of the glacial clay. These are followed by the main part of the glacial, often varved clay. Finally there may be a cover of non-glacial clay.

This simple stratigraphy is usually complicated by discordances and irregular

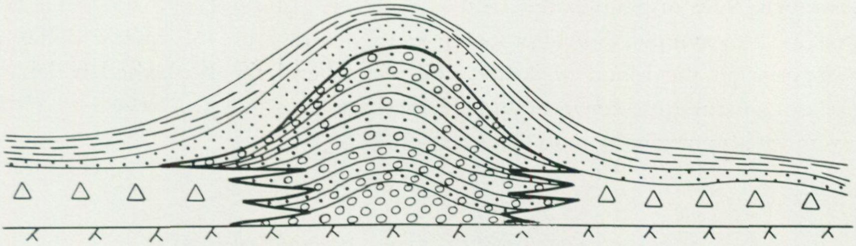

Fig. 30. Sketch of a section through an esker of the subaquatic type (2.3.1). The underlying till (triangles) has been removed by erosion. The esker is covered with clay (broken lines). Circles and dots = gravel and sand.

changes of the sediments due to shiftings of the stream etc. An important irregularity is caused by the redeposition of the upper part of the esker. Gravel and sand from the crest have been redeposited as beach sediments on top of the clays. In fact much of the gravel and sand seen in a section may be beach deposits underlain by clay. The importance of later abrasion for the esker morphology has been studied and emphasized by Bergdahl (1953).

A different stratigraphy is known from the esker at Gustafs, Dalarna. This esker was described by Nelson (1910). Later, borings have shown that the eastern part of the esker, consisting of stony gravel and sand, rests upon silt. The stratigraphy can probably best be explained by the formation of the esker at a glaciofluvial river mouth in an estuary in the ice front. The esker grew like a delta in the estuary, covering bottomset beds of silt.

2.3.2 *Subaquatic deltas.* If there is, for climatic or topographic reasons, a stagnancy in the retreat of the ice front there will be a larger annual accumulation in an esker of the above-mentioned type. The deposit may reach the water surface and form a marginal delta. If this does not happen there will be just a swelling of the esker, that may, however, reach a considerable size. We may call such a widening a subaquatic delta. The necessity to separate these deltas from others can be discussed, but because the delta bedding of the subaquatic type is less distinct and a topset bed is absent it seems appropriate to give it a term of its own.

It must be remembered that abrasion during the land uplift may have changed the shape of a subaquatic delta considerably. This has been emphasized by several authors. The Kallaxheden delta at Luleå, Norrbotten, e.g., which is mentioned below as one example of a subaquatic delta, was interpreted by Enequist (1946) as strongly abraded. An ordinary delta reaching the surface may have been broken down to a lower level. Beach and other shallow-water sediments resulting from the abrasion may surround the deposit and hide its original form. A more irregular deposit can in this way get an even and delta-like appearance. The original kame field of Sörmon (group 1.5.4) has been mentioned as an example. Some probable examples of true subaquatic deltas are the deposits on the island of Arnön, Värmland, and the Kallaxheden delta. It is not out of question, however, that future investigations will reveal that these deposits are also originally more irregular ones.

2.4. SUPRAAQUATIC — SUBAQUATIC DEPOSITS

There is one type of deposit that seems to be formed independently of the situation in relation to water surfaces. Essentially the same morphology is developed above, at and below the level of the sea or glacial lakes.

2.4.1 *Marginal eskers.* A ridge of glaciofluvial sediments that runs transverse to the movement of the ice and was built up against the ice front is called a marginal esker or, better, just marginal ridge. It should be distinguished from a transverse esker (see 1.5.2; Nelson 1910, p. 34). The marginal esker is the glaciofluvial correspondence to an end moraine, into which it may often pass gradually (cf. Fredén 1978). For the latter reason the term marginal ridge may be preferable.

Marginal eskers have been described from the Scandinavian mountain range, high above the highest coast-line, mainly from the region below this line, and accidentally even from the very coast-line. They often form sharp ridges, several tens of metres in height, but also small ridges similar to De Geer moraines occur. They may be particularly large where there was a halt in the ice recession. Many examples occur on the west coast, among them the well-known Fjärås Bräcka, south of Gothenburg (Nelson 1910, Caldenius 1942, Wenner 1952), which is part of the so-called Gothenburg Moraine, extending along the west coast. For the accumulation of the Fjärås Bräcka there seem to be climatic as well as topographic causes. The marginal esker Sutterhöjden in Värmland (Hörner 1927), situated not far below the highest coast-line, mainly has topographic causes. In the province of Värmland there is also a marginal esker at the glaciofluvial Götå delta (J. Lundqvist 1957), being formed at the sea-level of that time. As a well-developed marginal esker in the mountain range the esker at Lakes Bunnersjöarna, Jämtland (J. Lundqvist 1969, Fig. 37), may be mentioned.

The accumulation of the ridge may take place in different ways. Sediments may be transported laterally along ice lobes to collect around its front. The transport may also take place on a broader front upon the ice or, possibly, subglacially. There may be several minor glaciofluvial streams, or alternating stream courses, contributing to the accumulation. In supraaquatic situations obstacles of remaining ice blocks just in front of the ice may diverge a stream to follow the front. After the disappearance of the ice the river bed remains as a low ridge.

This process has been observed at Vatnajökull, Iceland.

A more complex process of formation is also possible. Tanner (1933) considered part of the Salpausselkä formed of till hummocks, around which supraglacial streams deposited small deltas. Then the final ridge was to a great extent formed through wave action. Similarly, Wenner (1952) interpreted the Fjärås Bräcka as being basically formed as a few end moraines. On top of them several glaciofluvial streams deposited short deltas and eskers, which joined to form a ridge transverse to the stream direction.

As is evident from the way of formation there are transitions between marginal deltas and marginal eskers. Glückert (1977), from a sedimentological point of view, described three types of marginal deltas, one of which corresponds to the marginal esker, as described above. Also Glückert's second type could be considered a type of marginal esker. As this term is used here, we should use it if the deposit forms a ridge with a narrow, vaulted surface, and delta if the surface is flat. The principal difference is that a delta is formed during a longer time by, often, one single stream. An esker may be formed in a much shorter time and several streams or water on a broad front contribute.

The sediments of a marginal esker show the same changes as other glaciofluvial sediments. A delta bedding transverse to the ridge is often seen. Sometimes several centres of coarser material can be identified, as a consequence of the formation by several — or alternating — streams. An example is the Rösered plateau near Gothenburg (Hillefors 1969). The orientation of the stones is often along the ridge, contrary to the transverse orientation in radial eskers. Particularly on the proximal side there are often disturbances of glaciotectonic nature. Fine-grained sediments may have been forced into the esker deposits. Inclusions and beds of till are also common on the proximal side. Among others, Tanner (1930) has described this stratigraphy from the Salpausselkä.

3. DEPOSITS FORMED OUTSIDE THE ICE MARGIN (EXTRAMARGINAL OR PROGLACIAL DEPOSITS)

Sediments carried away from a glacier by meltwater streams are generally called outwash (see, e.g., Flint 1971, p. 185). They form deposits, the morphology of which is independent of the ice even if, occasionally, also these deposits may be accumulated against and influenced by the ice.

3.1. SUPRAAQUATIC DEPOSITS

A common term for the supraaquatic extramarginal deposits is valley train (e.g. Flint 1971, p. 188). This term has, although well established, some disadvantages. First, the gradual transition in a valley train from proximal, coarse material to distal, more fine-grained is mostly complicated by repetition of the same sequence many times as the ice recession proceeded. Second, some very large deposits of this type are not restricted to valleys, but extend over broad, flat areas. A more adequate terminology seems to be the following, although in special cases we may use valley train as a parallel term. Most of the deposits in question can be regarded as types of supraaquatic deltas. It is appropriate to separate a few distinct types.

3.1.1 *Glaciofluvial fans.* The simpliest type of the supraaquatic delta is a fan-shaped, rather small accumulation formed during a short time. Meltwater from the ice has crossed a low ridge at the ice margin. At the foot of the ridge a little fan, similar to ordinary alluvial fans or cones, was accumulated. Numerous examples occur in the broken, northern part of Sweden. Examples are described from, i.a., the Hotagsfjällen mountains in Jämtland by J. Lundqvist (1969, p. 219).

The sediments of the fans change rapidly from very coarse at the proximal end, the apex, to more gravelly and sandy along the distal side. They may in some cases be very coarse throughout the deposit.

3.1.2 *Sandur plains.* A supraaquatic outwash plain, the surface of which is formed by numerous alternating and changing stream channels, a braided river system, may with an Icelandic term be called a sandur. A sandur plain originates from one, or usually more meltwater outlets from the ice. It is best developed when it can spread sidewards unlimitedly, but virtually the same deposit can be formed also in a narrower valley. In the broad, unlimited plains the stream pattern is very regular, at least in so far as the feeding streams are all of the same size. Especially in narrow valleys there is a tendency of the water to collect in broad channels along the valley sides. Such channels then separate the glaciofluvial sediments from the surrounding till. The plain itself becomes for similar reasons often highest in its central part — it has a convex transverse profile.

The characteristic features of a sandur are the spool-bars. Such a bar is formed by deposition of coarse sediments in the middle of a stream channel, that is, just in front of the most rapid stream. When the transporting power of the stream is slightly reduced, either by decreasing velocity or by incorporating of too much bed-load, a bar of bottom-transported material is formed. This bar splits the stream into two parts, which may form new bars or join other streams etc., altogether forming a braided river system. For details of these processes reference is made to Krigström (1962).

A sandur plain may begin to form immediately at or even upon the ice front. If thick sediments accumulate we can then obtain a sandur ending proximally with an ice-contact slope (outwash head, according to Flint 1971, p. 210). J. Lundqvist (1973) has described several examples from Härjedalen. It is common that the proximal side slopes into a lake that marks a large dead-ice hollow formed at the isolation of the snout of an ice lobe. The sandur plain may extend on both sides of the lake as a kind of lateral terraces. Examples can be mentioned from Rätan and Lake Härjeåsjön in Härjedalen.

The sandur sediments vary within wide limits, but the coarse, stony and gravelly beds dominate (Fig. 31). Due to the rapid changes between streams of high velocity and stagnant water very coarse beds may rapidly alternate with thinner, sandy to silty beds. Sometimes there seems to be a bimodal composition of the sediments, with stones and coarse gravel surrounded by a more silty or sandy matrix.

Sandur plains are common in Sweden especially where there are broad valleys and where there has been rich supply of sediments. The Ljusnan and tributary valleys in Härjedalen offer several good examples (Frödin 1954, Krigström 1960, J. Lundqvist 1969). Other, still bigger plains, which are less known, occur between the Kalix and Kaitum valleys southwest of Kiruna, Lapland. Also in the valleys in the mountain range smaller but well-developed sandurs occur (see, e.g., Mannerfelt 1945, p. 79, Hoppe *et al.* 1959).

3.1.3 *Glaciofluvial river terraces.* Along many rivers and streamlets of today there are often terraces and banks, the size of which indicates that the depositing stream must have been much bigger than the present one. General considerations

Fig. 31. The sandur (3.1.2) sediments are coarse-grained and horizontally bedded. The sorting in some beds may be poor and big boulders occur. Near Lake Äldern, Jämtland. — Photo J. Lundqvist 1972.

make it clear that it must have been a glaciofluvial stream. The surface of the terraces may often be crossed by dry stream channels and banks. The material is ordinary glaciofluvial gravel and sand. If sedimentation had gone on, a sandur plain would have been formed, but evidently sedimentation ceased before this could happen. The deposits that we now see cannot be classified as sandur plains, nor as any other of the types discussed here, so we need a special term for them. Type examples can be found along many streams in Sweden. From the literature may be mentioned those along the river Storån in Jämtland (J. Lundqvist 1969, p. 226).

3.1.4 *Indifferent valley trains.* The sandur plains particularly belong to broad valleys or valleys at some angle to the direction of ice retreat. In narrow valleys in which the ice front receded along their course true sandurs are replaced by more indifferent valley fillings of glaciofluvial sediments. We may call them just valley fillings or, better, indifferent valley trains. The epithet is necessary, because these deposits do not exactly agree with the definition of a valley train (see, e.g., Flint 1971, p. 188).

The morphology of the deposits in question has most probably originally been that of sandur plains alternating with deltas and other sediments deposited in temporary lakes. Because of the ice recession along the valley there has been a considerable water discharge as a direct continuation of the glaciofluvial activity. The result is that possible primary sandur and delta forms have been changed to more indifferent valley-floor forms. These are characterized by slightly undulating plains with terraces and other erosion features. In scattered places eskers protrude through the sediments, in other places eskers buried by the sediments give rise to a somewhat hummocky morphology. The process of valley filling has been further discussed by Bergsten (1943) and Daniel (1975). According to the preconditions mentioned on p. 18 it may appear incorrect also to consider secondary forms. In this case, however, the secondary forms are an integrated constituent of the morphology and therefore it is not possible to reconstruct primary forms in order to get a better basis for classification.

The sediments of the indifferent valley trains are in the upper beds mainly gravel and sand, although they may sometimes be covered with thin fluvial sediments, deposited during high-water stages when the plain was flooded. On a geological map the valley sediments are often just marked as glaciofluvial gravel. Towards the depth the gravelly and sandy sediments may continue. Sometimes, however, the deeper beds are surprisingly fine-grained. From the upper Klarälven valley in Värmland J. Lundqvist (1957) has described thick sandy to even silty beds below the superficial gravel (Fig. 32). In the valley of the river Västerdalälven in Dalarna similar beds of silt make up a large volume of the deep valley sediments. Possibly these fine-grained beds were originally deposited as the bottomset bed of deltas, built out in temporary lakes behind obstacles of

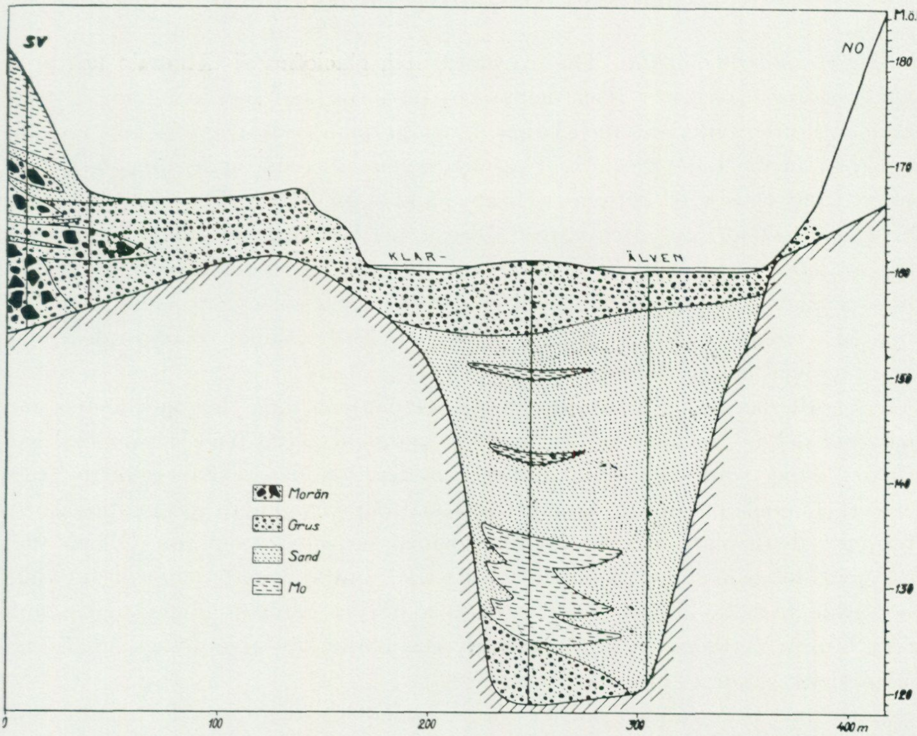

Fig. 32. Section through an indifferent valley train (3.1.4) at Klarabro in the Klarälven valley, Värmland. Morän = till, grus = gravel, sand = sand, mo = fine sand to silt. — From J. Lundqvist 1958, Fig. 4.

glacial deposits, lakes that have later been completely filled and buried under supraaquatic sediments. In many valleys in the north the stratigraphy of the valley trains is probably simpler, consisting of gravel, mainly.

3.1.5 *Residual deposits.* Outside the ice margin the glaciofluvial streams could also exert a considerable erosive activity. In some positions accumulations dominate, but in others there are mainly big erosion channels. Today these may be water-filled but often they are seen as dry valleys. On their bottoms there is often till or bare-washed bedrock. Sometimes we also find very coarse, boulder-rich material there, which is to a minor extent transported. Transport may be indicated by some roundness of the boulders. Mainly, however, this material should be considered the residual of till (or glaciofluvial deposits), from which the finer fractions have been washed away. It may appear unnecessary to have a special term for this material, but because in some areas it can form deposits that must not be neglected, and because it does not belong to any other group of the classification presented, the term residual deposit is suggested.

3.2 DEPOSITS FORMED AT A WATER LEVEL

3.2.1 *Extramarginal deltas.* The extramarginal, glaciofluvial deltas do not principally differ from other river deltas, but their size and the coarseness of their sediments often reflect a much larger discharge than corresponding to a present-day river in the same position. Thus the deltas are more or less regularly fan-shaped and consist of bottomset, foreset and topset beds. The bottomset beds are glacial silt to clay, often varved. The upper beds may be sandy or gravelly. The granulometric composition seems to a large extent to be a question of material available. Often the proximal end of the delta passes into either morphology of erosion or a kame field. The gravel of the kames corresponds to the most proximal part of the topset bed.

As briefly mentioned above, the difference between these "regular" deltas and marginal deltas (group 2.2.1) is that the marginal deltas have a proximal ice-contact slope, while the deltas under consideration here extend directly from erosion channels or supraaquatic glaciofluvial deposits. There is a continual rise from the delta plane towards more proximal deposits. From this follows that marginal deltas are most common in the flat, southern parts of Sweden, while the ordinary deltas occur in valleys with a steeper gradient in the higher and more broken northern parts. Particularly this applies to large deltas. Small "regular" deltas occur all over the country.

The deltas were formed outside the ice where its meltwater discharged into, most often, the sea, sometimes into ice-lakes. They began to form as soon as the ice front receded from the water level. Consequently the deltas occur where the water level was immediately after the deglaciation. In most parts of Sweden this is the highest level reached by the sea, the highest coast-line. Thus these deltas are mostly what is in Swedish called HK- (or MG-) deltas (after *högsta kustlinjen,* highest coast-line, and *marina gränsen,* marine limit). Glaciofluvial deltas are common as HK-deltas along the highest coast-line all over Sweden, but especially in the northern part from Värmland in the southwest to Norrbotten in the north. A number of examples have been described in the literature. Here may be mentioned the Bredåkra delta in Blekinge (Andersson 1927, Ringberg 1971) and the Götå delta in Värmland (Fig. 33; J. Lundqvist 1957). A number of deltas that are often more complex formations have been described from northern Sweden by Sandler (1917). Sometimes only a part of them is a delta in the sense in which the term is used here. This is elucidated in a following chapter.

Because the conspicuous deltas occur along the highest coast-line they may be used for an approximate determination of this level. For more exact determinations they are unsuitable. The reason is that they are often composed of several planes with only small differences in level (Fig. 34). One of these corresponds to the highest coast-line in an exact sense. Above this level other planes may

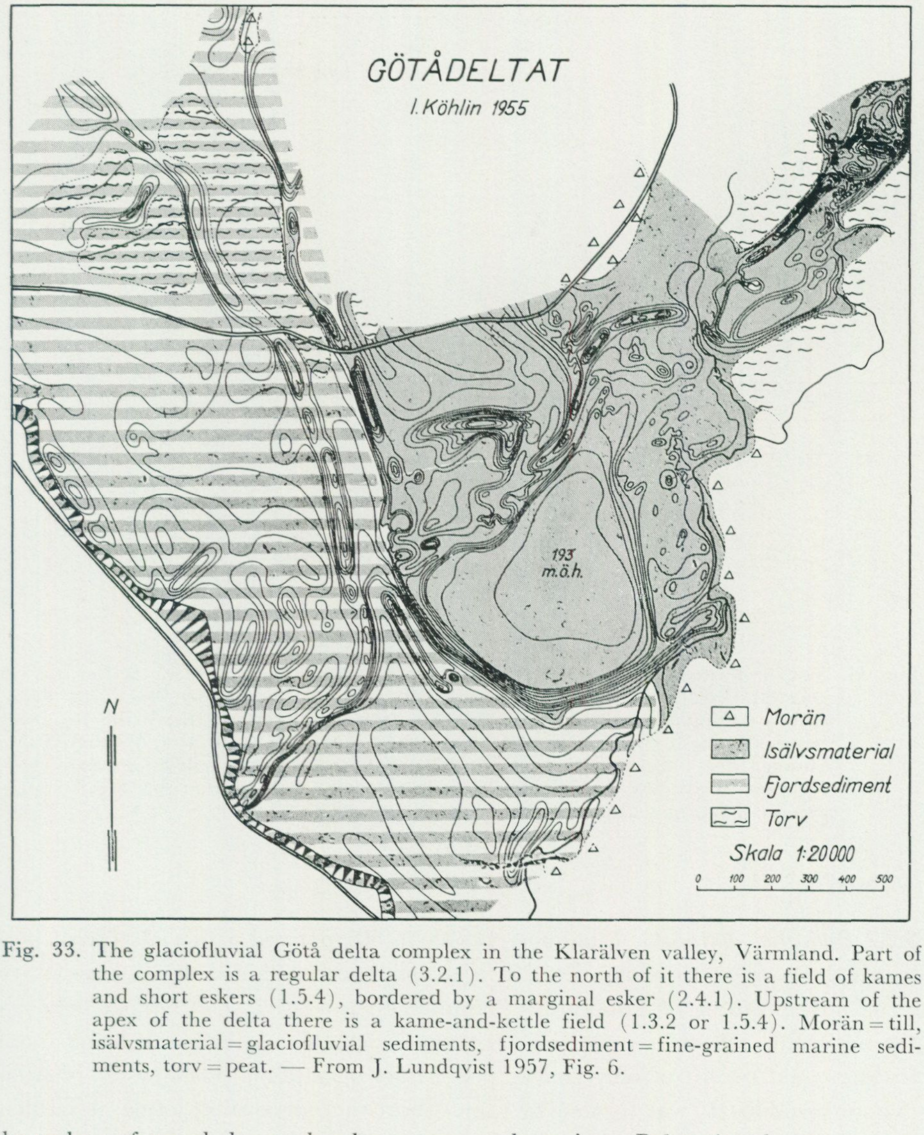

Fig. 33. The glaciofluvial Götå delta complex in the Klarälven valley, Värmland. Part of the complex is a regular delta (3.2.1). To the north of it there is a field of kames and short eskers (1.5.4), bordered by a marginal esker (2.4.1). Upstream of the apex of the delta there is a kame-and-kettle field (1.3.2 or 1.5.4). Morän = till, isälvsmaterial = glaciofluvial sediments, fjordsediment = fine-grained marine sediments, torv = peat. — From J. Lundqvist 1957, Fig. 6.

have been formed due to local, temporary dammings. Below it, planes may occur due to the fact that the uplift of land proceeded during the delta formation. Planes just below the original sea-level were formed at somewhat later stages, partly by continued supply of fresh material, partly by redeposition of material eroded from the first delta deposits. Therefore only remnants of the first delta plane, which corresponds to the highest coast-line, might remain. A scrutiny of all the planes may answer the question about the highest coast-line, but in reality the problem is in most cases very complicated. A study of the relation between delta surfaces and water levels has been made by Bergsten (1943).

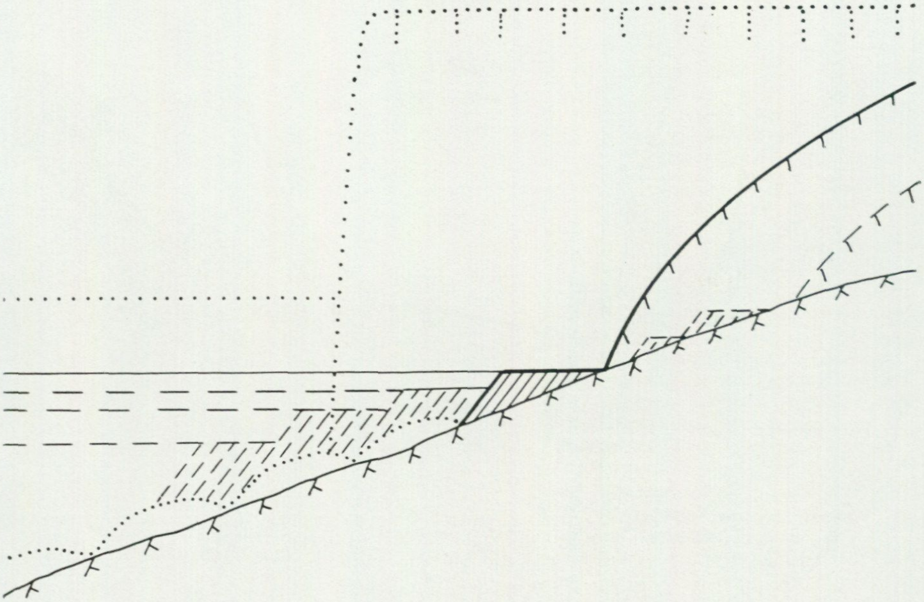

Fig. 34. Sketch illustrating the complexity of a glaciofluvial delta (3.2.1) at the highest coast-line. At stage 1 (dotted) the ice front is situated in the sea — no delta, only a subaquatic esker, is formed. At stage 2 (unbroken lines) the ice front passes the sea-level — a delta on the highest coast-line is formed. At stage 3 etc. (broken lines) the ice recedes from the sea shore — the first delta is partly eroded, new deltas are formed at successively lower levels of the sea. Small supraaquatic deltas may also be formed.

3.2.2 *Proximal deltas.* G. Lundqvist (1940, p. 50) defined a special type of delta which he called proximal delta. It is somewhat uncertain if this is a necessary term, but according to Lundqvist's definition there is a clear difference between the proximal and ordinary deltas. A proximal delta should be smaller and more irregular and consist of only coarse, poorly sorted material. The surface is often rich in boulders. It was formed by rapid, short-time deposition, often at sudden drainings of dammed waters, contrary to the ordinary deltas, which were formed during longer times and at comparatively more quiet conditions. It is, however, a true delta formed at a water surface, and not a supraaquatic deposit. As type examples may be mentioned those described by G. Lundqvist (1940, p. 50) from the Smedjebacken region in southern Dalarna.

Fromm (1965a) described other examples from Messaure, Lapland. There a series of deltas below the mouths of deep canyons together form a terrace on the highest coast-line. Within the terrace it is possible to distinguish individual deltas.

3.3. SUBAQUATIC DEPOSITS

The subaquatic extramarginal glacial sediments are nearly always to be described as glaciomarine or glaciolacustrine, fine-grained deep-bottom sediments and not as glaciofluvial. There is possibly one exception.

3.3.1 *Gravel ridges.* Rytterberg (1943) has described a peculiar type of gravel ridge from the Avesta region in Dalarna. Such a ridge is only a few metres high, some 100 metres in length, with a crest that slopes downstream. The ridges often occur on the lee-sides of bedrock knobs in plains of more fine-grained sediments. The altitude is some 20—70 m below the sea-level of that time. The material is stones, gravel and sand forming distinct beds.

It is not quite clear how these ridges were formed. G. Lundqvist (in G. Lundqvist and S. Hjelmqvist 1946, p. 83) interpreted them as post-glacial beach deposits. According to Rytterberg (1943), however, they should have been formed as stream ridges or banks during periods of extremely large water discharge from the ice, possibly caused by sudden drainings. The term fluvial is thus not quite adequate, because the accumulating streams were rather bottom streams in shallow sea water. Because the origin of the stream was glacial, because of difficulties to find a more adequate classification, and finally because of the doubts as to the way of formation it may be appropriate to include these ridges among the deposits to be discussed in this article.

COMPLEX DEPOSITS

In the description above, the glaciofluvial deposits have been sorted into rather simple elements. In the field, however, many deposits are much more complex. Either may one single element have been formed by several processes and belong to different groups in the classification, or may a deposit consist of several parts, belonging to different groups. A few examples will elucidate this problem, and others could easily be found.

GENETIC COMPLEXITY

Already from what has been said in the descriptions of the groups it is clear that eskers and kames can be formed in different ways. They appear in several places within the classification system. Evidently the conditions may change from one

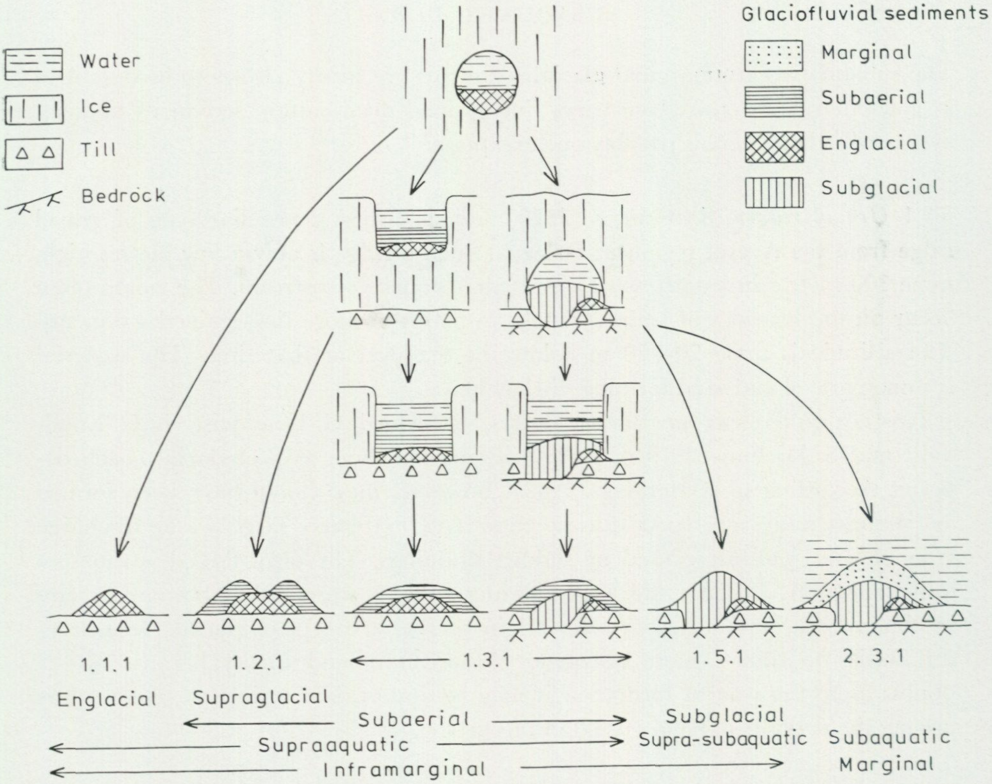

Fig. 35. Sketch showing in cross-section the development of meltwater streams in a glacier and the deposition of sediments in somewhat different environments. The result will be eskers containing sediments accumulated in different positions.

class to another without this being visible in the morphology and stratigraphy of the deposits.

An esker may be originally established as an englacial river bed. During ablation the covering ice may disappear. Then we have got a subaerial river bed, but still supraglacial. Melting of the underlying ice will give us a subaerial river bed that is no longer supraglacial, although infraglacial. Theoretically sedimentation may continue during all these conditions. The result is an esker of complex genesis (see Fig. 35, the left esker 1.3.1).

In other cases there may be subglacial, subaquatic accumulation in a tunnel at the ice bottom. On top of these subglacial deposits there can be further accumulation when the mouth of a stream moves upstream and passes by. Then we get a subaquatic esker (De Geer type) with a core corresponding to a subglacial and/or englacial esker. This is illustrated by Fig. 35, esker 2.3.1. The same explanation, that is, the beds of the esker form more than one generation, has been proposed by K. G. Eriksson (1960) for a part of the Stockholm esker.

Subglacial accumulation of kames may continue during the break-up of the ice at the deglaciation. Then there is also continued kame formation. We get a kame field that is subglacial—subaerial in combination.

Because the term lateral terrace has a somewhat different basis of definition, the topographic situation, than most of the other terms it is inevitable that transitions to other deposits and genetic complexity may occur. As is evident from the description above, a lateral terrace may show the morphology of a kame field, a supraaquatic delta etc. This fact will probably not cause any serious difficulties. It is more embarassing when other types of deposits in the classification system were formed in lateral positions. For instance, a delta may be formed by rivers flowing against the ice margin, either from other ice lobes or glaciers or of non-glacial origin. Examples have been described from the Torneträsk area in Lapland (Holdar 1957) and Jämtland (J. Lundqvist 1969, 1973) where meltwater from ice in and south of a mountain region accumulated deposits against the margin of ice north of and at the foot of the mountains.

These examples also indicate that the problem of terminology is not so difficult to solve. Generally the deposits in question may be recognized as deltas, sometimes supraaquatic ones, even if they were formed in a lateral position. In one instance, at Hårdeggen near Handöl, Jämtland (see also von Brömssen 1966), a small delta forms part of a lateral terrace. There is still a clear difference between the individual delta and the rest of the terrace, and the definition of the different parts does not cause any problem.

In some instances the terminology may be a question of viewpoint. From one point of view a deposit may be called a delta, from another a lateral terrace, for instance. The Gröndalen delta in Jämtland (Kj. Eriksson 1914, J. Lundqvist 1969) may be taken as an example (Figs. 28 and 36). The example is theoretical only, because actually we do not know the exact interior structure of the deposit. The so-called delta was formed in a small ice-lake between the ice margin and a mountain massif by meltwater running mainly laterally. We can imagine that the first sediment to be deposited was a subaquatic esker at the ice margin. Upon it there were, later, accumulated fine-grained glaciolacustrine sediments, being the bottomset bed of a growing delta formed by lateral and supraglacial streams. These fine sediments were gradually covered by foreset and topset beds of gravel and some sand. The delta filled the lake entirely. Finally, on top of it all, a sandur plain was formed. In the sandur sediments numerous ice blocks were embedded, giving rise to kettles. The result, as we see it today, is a 60 m high, broad terrace, the surface of which is a typical pitted sandur plain. This terrace may be called a lateral terrace considering its position in relation to the ice, an ice-lake deposit considering the original formation in open ice-dammed water, a delta considering the bulk of the deposits, and a -- pitted — sandur plain considering the superficial morphology.

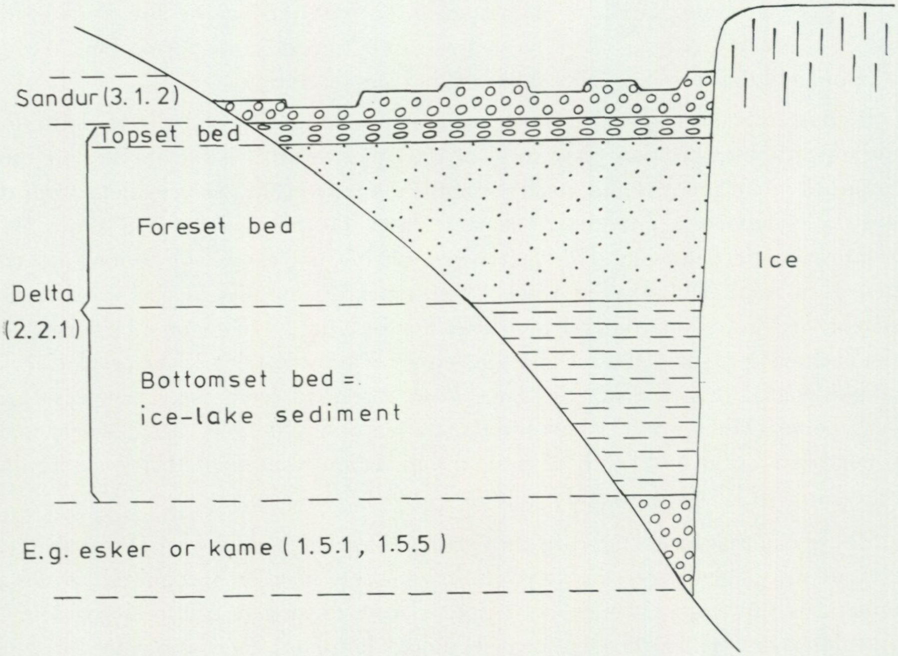

Fig. 36. Sketch showing a possible complexity of a deposit formed between ice and adjacent valley side by the filling of a small glacial lake, e.g. such a deposit as is shown in Fig. 28.

MORPHOLOGIC COMPLEXITY — COMPOUND DEPOSITS

Many of the deposits within the classification system may occur together. Often it is easy to separate them and treat them as individual units even if the geographic connection is very close. In other cases, however, they form integrated parts of complex deposits, within which it is more difficult or useless to separate the units. Some conspicuous types are the following.

Esker-and-kame fields may consist of a central esker, often divided into two or more parallel ridges and surrounded by trenches, kettles and kames (Fig. 37). The trenches and kettles are most common in the esker, dividing it into branches, and along its sides. Often there are chains of them, occupied by tarns or bogs or sometimes dry. Among and outside these chains there are kame fields. The kames are often elongate, which makes the difference between the kame fields and kettle or trench fields difficult to recognize. The kames may protrude branches, sometimes as transverse eskers, between the trenches towards the central esker. The kame morphology is sometimes still more complicated by the presence of dunes, forming similar hummocks. If the complex occurs in a valley

Fig. 37. Esker surrounded by a kame-and-kettle landscape (1.2.1 + 1.2.2 or 1.5.1 + 1.5.4) at Långvattnet, Ångermanland. Cf. Lindström 1973. — Photo J. Lundqvist 1970.

the kame fields may form terrace-like borders along the valley sides. If there are no valley sides to limit the complex there are often more even plains outside the kame fields. The kames become lower and flatter, the kettles disappear and there may be smooth delta-like surfaces, sometimes sloping out from the centre.

These complexes are supraaquatically formed, or most often close to the corresponding sea-level. Many examples could be mentioned from the interior of northern Sweden. In the Junsele region, Ångermanland, there are very well-developed, conspicuous cases in point, e.g. at Långvattnet, north of Backe and Vallen, at Lake Ysjön, and between Hälla and Tjäl. The three first-mentioned have been thoroughly studied by Lindström (1973). In Lapland there are more and even larger examples, although less known. Here shall be mentioned only those at Lakes Rasikkajärvet west of Soppero, and between Radnejaur and Jerfojaur northwest of Arvidsjaur.

Valley fillings with parallel eskers were also described by Persson (1974) from the South Swedish Highland. The number of parallel eskers may sometimes be 5 or even 6. The eskers were formed by parallel streams in disintegrating ice. As isolated units they belong to the groups mentioned in this article but together with the interjacent deposits they constitute a complex formation.

An interesting *combination of eskers and terraces* was described by Rydström (1971) and Persson (1974). The eskers in question were interpreted as formed subglacially or in open crevasses behind the ice front. At a somewhat later stage broader inlets developed along the eskers. These became filled with glaciofluvial sediments forming terraces along the eskers, and sometimes also isolated plateaux. The sediments accumulated up to or somewhat above the corresponding water level. Strictly, the terraces are a kind of lateral terraces, although formed at low level between ice and another glaciofluvial deposit. The result is an esker, bordered by lateral terraces. The Växjö and Alvesta eskers in Småland show examples.

Delta complexes are formed at the contemporary sea-level and consist of several individual deltas grading into and in close connection with other deposits. The deltas may have the character of marginal or ordinary deltas. Sometimes it is possible to divide the complex into separate units, but often this is impossible or useless. Then it is appropriate to use the term delta complex for the whole formation. Several detailed studies have been devoted to such complexes. A few of them will be mentioned in the following.

The delta complexes are often formed around ice lobes in valleys cutting the highest coast-line. Along the lobes lateral streams contributed to the sedimentation. At the ice front these marginal streams cooperated with subglacial and supraglacial streams to form frontal deposits. Subglacial deposits make up part of the complexes. When parts of the ice lobes were separated from the active ice, or when the activity of the entire lobes stagnated, conditions could change and new deposits were superimposed on the ones accumulated first.

A well-known illustration of these conditions forms the marginal delta complex of Brattforsheden, Värmland (Fig. 38), described by Hörner (1927). Most of the deposits are distributed around the basin of Lake Alstern. The basin is an enormous dead-ice hollow, formed by the remaining part of a narrow ice lobe which became isolated and stagnant. On both sides of the basin kame fields forming lateral terraces extend. Some parts of the terraces were formed as marginal deltas from the ice lobe, while most of the terrace sediments seem to be deposited by marginal streams approximately at the contemporary level of the sea. In front of (on the distal side of) the lake basin larger marginal deltas extend, with surfaces approximately on the level of the highest coast-line. Small dead-ice hollows occur in them, on straight line with the lake basin. The more distal, the more filled out by sediments are these hollows. Particularly at the biggest, central delta there is a clear extension of the proximal delta end as a feeding esker. A continuation of this esker is seen as long and narrow islands and shallows in the lake, constituting a discontinuous esker probably of subglacial origin. On the proximal side of the lake basin more fine-grained glaciofluvial sediments extend, covered with well-developed transverse dune arcs. These sediments are the distal deposits from more distant, younger ice margins. Be-

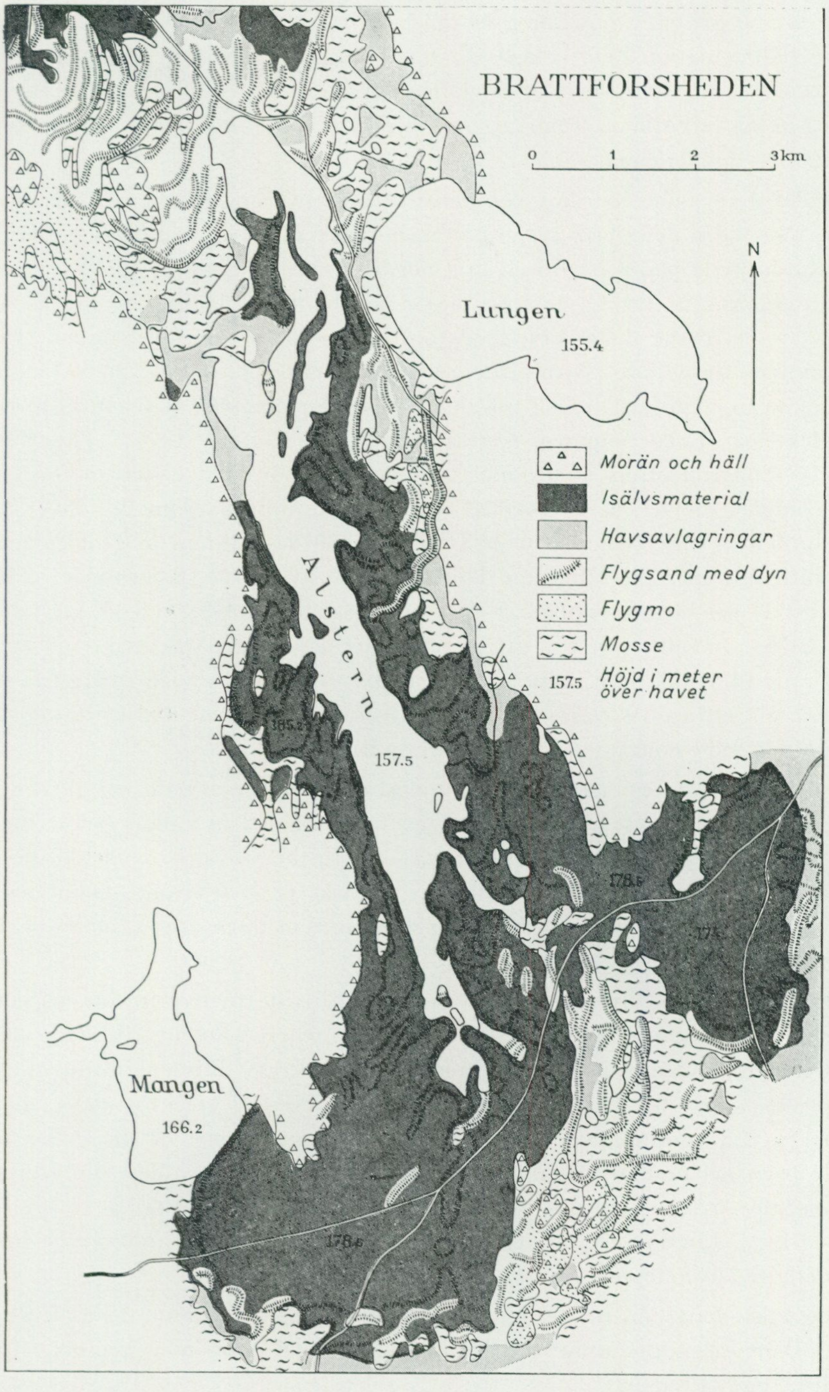

Fig. 38. The Brattforsheden delta complex, Värmland. Lake Alstern is a giant dead-ice hollow in which there is a subglacially formed esker (1.5.1). In front (south) of the lake regular delta terraces (2.2.1) extend. Along the lake there are small deltas (2.2.1) and laterally formed kame fields (2.2.1—2.2.2). — Redrawn after Hörner 1927, Pl. 1.

cause of the ice body remaining in the lake basin they could not fill the basin before sedimentation here ceased. In this example, here very briefly described, it is possible after the detailed investigation by Hörner (1927) to identify separate units, but still it seems appropriate to consider the whole formation as a unit, a marginal delta complex.

Similar but somewhat less complicated combinations of deltas, kames and eskers have been described in the literature. Here may be mentioned the Hållsjö and Riddarhytte plains northwest and north of Örebro (Nelson 1910) and parts of the deposits in the Grythyttan region north of the Hållsjö plain (Sundius 1922). Some of the deltas described from northern Sweden by Sandler (1917) are complex formations. Within them delta surfaces were formed at the sea-level as well as in slightly dammed positions. A similar complex is the Svalsjö delta complex near Lake Sommen, Östergötland (Agrell 1973, 1974). The Räväla delta in Dalarna offers an example of complex morphology due to formation of incomplete deltas, partly formed at sudden drainings (Tunelli 1940). Brief descriptions of other complexes may be found in descriptions to geologic maps.

A different example offers the Djurkälla plateau at the eastern side of Lake Vättern. It has been described in detail by Bergsten (1943) and H. G. Johansson (1976). In outline it consists of two marginal delta parts, deposited as terraces around a hill. The terraces have joined to form a kind of marginal delta plateau. Its surface is characterized by a very broken kame-and-kettle morphology. Also a more continuous esker occurs on its surface.

The examples mentioned are all complexes in connection with marginal deltas built up to the highest coast-line but generally situated in valleys below the region where this line cuts the valley floor. Where the two lines coincide the glaciofluvial deposits are formed as ordinary deltas (cf. p. 56) and conditions are often less complicated. However, also in this position there are examples of delta complexes.

The valley of the river Klarälven, Värmland, is instructive in this respect. A series of deltas occurs on the highest coast-line where hanging tributary valleys open into the Klarälven valley. These deltas illustrate different forms of delta complexes where the highest coast-line cuts a valley floor. Proximally, all the deltas have a continuation in supraaquatic deposits. Some of the deltas have partly been accumulated against an ice lobe in the main valley, but still they are recognized as deltas, not as lateral terraces. All these deltas have been described by J. Lundqvist (1957), to which reference is made, and can be briefly characterized as follows.

The Likå delta can be morphologically described as a kame delta. In a few places short eskers rise above the delta sediments and a low marginal esker forms the distal end of the delta.

The Femtå delta is to some extent an ordinary delta of rather coarse sediments.

Numerous dry channels from the surrounding till over the proximal part of the delta make its contours somewhat diffuse. The distal delta part is more complex. It forms a lateral terrace along the side of the main (Klarälven) valley. The northern (right) terrace branch is flat, while the longer, southern (left) terrace is more hummocky. This part deserves the name kame terrace, but forms at the same time the most distal delta part, grading into more fine-grained marine sediments.

The Halgå delta has a distal part of similar lateral terraces, although their surface is less hummocky. The surface slopes more steeply where the glaciofluvial sediments grade into marine ones. The proximal delta part, beginning at bare-washed rocks with a canyon, forms a kame field with steep and sharp, some 5—10 m high hummocks. This kame field can be considered a dead-ice deposit of very coarse gravel, sometimes only rounded boulders. It is surrounded by dead-ice moraine. The morphology is similar, but there is a clear difference between the till and the glaciofluvial material.

The Götå delta (Fig. 33) is not laterally deposited. Its contours are those of a delta, but whithin this field there is a smaller, perfectly delta-shaped terrace reaching approximately to the highest coast-line. This terrace is a delta, forming part of the delta complex. The distal part of the field is bordered by a high sharp marginal esker. Behind this esker there is a lower gravel plane with a few curved esker ridges. The proximal part of the complex is a kame-and-kettle field surrounding a somewhat diffuse central esker.

Supraglacial complexes of deltas etc. are often formed in connection with drainage landscapes. These complexes are characterized by often numerous drainage channels with residual deposits. Around the channels we find glaciofluvial river terraces, small sandur plains and other delta deposits. These deposits are mostly incomplete due to erosion. The sediments are often interstratified by till beds, probably flow till. It is evident that the whole complex was formed in a surrounding of disintegrating ice, where erosion, accumulation and till flow took place contemporaneously. As a type area of such complexes the area along the lower courses of the river Linaälven immediately east of Gällivare, Lapland, can be mentioned.

CONCLUDING REMARKS

Table 2 will probably be sufficient as a summary of this article. A few general comments on it may be appropriate.

The examples given above have shown that complex deposits and transitions between different types are common. More examples could be given but those given above may be sufficient to demonstrate the theoretical complexity of glaciofluvial deposits. We may ask then if there is any reason to have a classification like the one presented here. However, this still seems to be justified. First, we need a system from a theoretical point of view, to help us to explain the features we find in the field. Second, where the formation of the deposits under discussion can be directly followed at recent glaciers, the processes seem to be less complex, from a genetic point of view, than suggested above. The deposits seem to be accumulated comparatively quickly and simply. Morphological elements form quickly outside the ice, or melt out of it in a completed stage.

For practical purposes and for simple description a classification based on granulometric composition or on morphology may be enough. If we want to understand the processes contributing to the formation of glaciofluvial deposits we must have a more complete classification system. The one proposed is based on the conditions found within Sweden. It will probably be applicable also in other glaciated regions, at least after some amplification. In any case it could serve as a brief summary of what is known, up to now, of glaciofluvial deposits in Sweden.

TABLE 2. Suggested morphogenetic classification of glaciofluvial deposits.

1. Inframarginal deposits	*2. Marginal deposits*	*3. Extramarginal deposits*
1.1. Englacial supraaquatic 1.1.1. Englacial eskers	2.1. Supraaquatic 2.1.1. Marginal kames 2.1.2. Lateral terraces	3.1. Supraaquatic 3.1.1. Glaciofluvial fans 3.1.2. Sandur plains 3.1.3. Glaciofluvial river terraces 3.1.4. Indifferent valley trains 3.1.5. Residual deposits
1.2. Supraglacial subaerial supraaquatic 1.2.1. Subaerial eskers 1.2.2. Supraglacial kame deltas	2.2. Water-level 2.2.1. Marginal deltas	3.2. Water-level 3.2.1. Extramarginal deltas 3.2.2. Proximal deltas
1.3. Subaerial supraaquatic 1.3.1. Eskers 1.3.2. Kame fields	2.3. Subaquatic 2.3.1. Subaquatic (De Geer) eskers 2.3.2. Subaquatic deltas	3.3. Subaquatic 3.3.1. Gravel ridges
1.4. Subglacial supraaquatic 1.4.1. Engorged eskers 1.4.2. Subcircular eskers	2.4. Supraaquatic-subaquatic 2.4.1. Marginal eskers	
1.5. Subglacial supraaquatic-subaquatic 1.5.1. Eskers 1.5.2. Transverse eskers 1.5.3. Esker nets 1.5.4. Subglacial kames 1.5.5. Lee-side ridges 1.5.6. Valley-side deposits		

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SGU = Sveriges geologiska undersökning

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