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Till Genesis and Hydrogeological Properties

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Hydrogeological properties of tills are highly dependent upon factors as grain-size distribution, compaction, orientation of particles, presence of fractures and occurrence of sorted sediments. These factors are again dependent upon the till forming processes. Lodgement tills formed under active, temperate sliding glaciers are usually compact, rather homogeneous and in many cases they are fractured. Melt-out tills deposited in connection with stagnant ice are in most cases less dense, have a lower content of fine-grained particles and a higher abundance of sorted sediment lenses. Flow tills which are mainly formed by a secondary flow of supraglacial debris are commonly very variable, they may have a low content of fine-grained components, a low degree of compaction and they are often closely connected with sorted glaciofluvial sediments. Till genesis is in many cases difficult to interpret, and an objective description of all main characteristics of the till is important in hydrogeological studies. The lodgement till has a lower effective porosity than the melt-out and flow tills due to its finer grain-sizes and higher compactness. The saturated hydraulic conductivity is lower, and dependent upon the fracture pattern. In melt-out tills and flow tills the occurrence of well sorted sediments will in many cases control the hydraulic conductivity. In all till types the structural properties are most important for the saturated water flow.

Introduction

Tills may behave as aquifers or aquicludes, depending upon hydraulic conductivity (Dreimanis 1989). The nature of groundwater movement in tills is very difficult to assess because tills, in contrast to most other sediments, are poorly sorted and heterogeneous, and may vary considerably from place to place. Too little emphasis is therefore given to this subject in hydrogeological texts. Tills are most widespread, however, particularly in the northern hemisphere. In some areas, *e.g.* in the Nordic countries, tills are the main surface deposits, and are, therefore, impossible to ignore in regional studies of hydrogeology in such former glaciated terrains.

The characteristics of the tills which have the greatest influence upon the hydrogeological properties are the bulk porosity, the distribution of pores and fractures in a micro- and macroscale as well as the homogeneity and isotropy. These properties are controlled by the grain-size distribution, the spatial distribution and orientation of the particles, the structural properties, and the degree of compaction of the till. These properties, however, are again dependent on till source, distance of transport, mode of deposition and post-depositional modification.

This paper describes relation between the formation of till and the factors which control its hydrogeological properties.

Till Source and Distance of Transport in Scandinavia

The Fennoscandian Shield is dominated by different types of resistant Precambrian crystalline rocks which contributed large amounts of gravelly and stony materials to the glacial rock debris during the Pleistocene glaciations (Fig. 1). Another till source fringed the Fennoscandian Shield as a large sediment trough dominated by Mesozoic (mainly Cretaceous) and Tertiary, partly unlithified sediments facilitating glacial erosion.

The glacial transport of this wide spectrum of rock material was directed towards the marginal zones of the ice sheet, with predominantly glacial accumulation. The distance of transport varied from few kilometres to several hundred kilometres.

A summary of data on tills in Scandinavia shows that difference in source gives rise to differences in granulometric composition and thickness of tills (*e.g.* Lindén 1975, Lundqvist 1977, 1983, Hansen 1979, Haldorsen 1983 and Houmark-Nielsen 1987).

As a consequence of the predominant resistant bedrocks the Fennoscandian tills are generally coarse-grained with a low content of rock flour; the share of material coarser than 2 mm may be more than 50 per cent. The most fine-grained tills dominate in Cambro-Silurian bedrock regions while the crystalline rocks (Fig. 2) show a tendency to form a gravel-rich sandy till with large boulders (Lundqvist 1952, Jørgensen 1977).

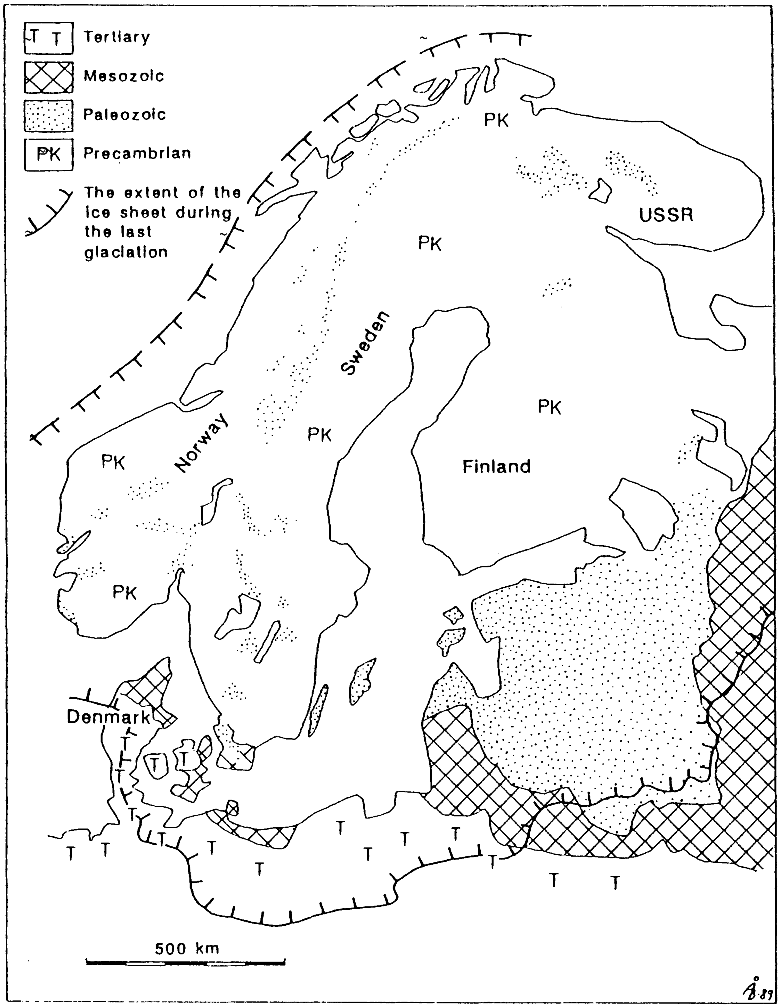

Fig. 1. Simplified bedrock map of Scandinavia and adjacent areas showing the maximum extent of the Scandinavian ice sheet during the last glaciation.

Contrary to the Fennoscandian tills the most common tills in Denmark and south-west Scania as well are clayey and sandy tills. The matrix of the tills is a mixture of long-distance transported rock flour and local fine-grained sediments of Mesozoic and Tertiary age (Hansen 1979). A share of material also comes from reworking of pre-existing glacial drift. Clayey till which dominates in the eastern part of Denmark contains more than 15 per cent of clay. Sandy tills are more widespread in the western and northern part of Denmark, where the high sand content is caused by glacial erosion of unlithified Tertiary or glaciofluvial deposits (Nielsen 1983) Fig. 3.

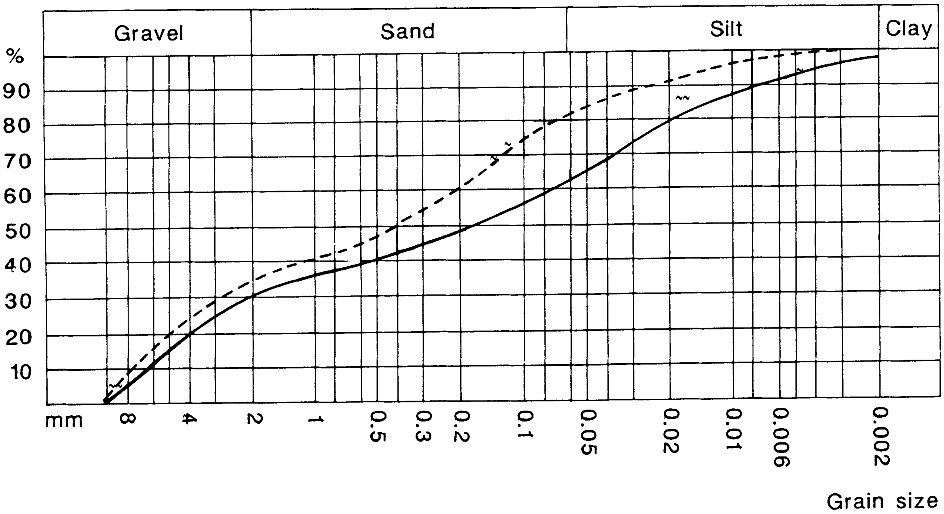

Fig. 2. Cumulative grain-size distribution curves of till from a Late Precambrian sandstone area in central southeastern Norway. Lodgement till, 51 samples (full drawn curves) and melt-out till, 31 samples (dashed lines). Only particles < 16 mm are included.

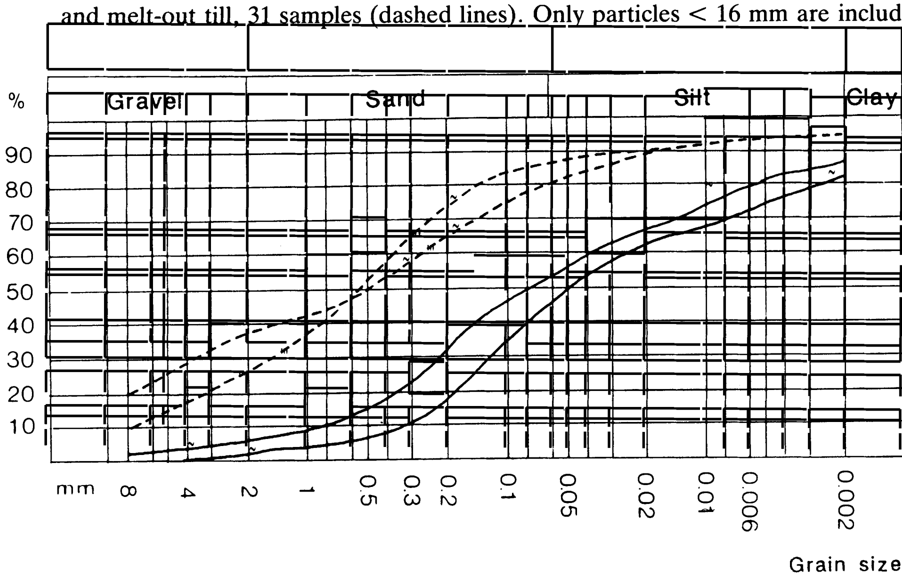

Fig. 3. Cumulative grain-size distribution curves of typical Danish tills from southern Sjælland. Lodgement tills (full drawn curves) and flow tills (dashed curves).

In the higher relief areas in Norway and northern Sweden the till cover is mostly discontinuous and its thickness only locally exceeds 2 m. In the central parts of Sweden the thickness of the till cover decreases from some tens of metres in low areas to zero on the highest ground (Lundqvist 1983). In Denmark the recorded thickness mostly refers to complex sequences of deposits including several till units interbedded with glaciofluvial deposits. In general, the thickness is some tens of metres, but it varies greatly, from about zero on the Stevns peninsula in the east to more than 100 m in central Sjælland.

These regional differences in till distribution and granulometric composition affect the hydrogeology of the tills. There are for instance great differences in the pore-size distribution. The silty-sandy tills which are so typical for central Scandinavia may have a great content of pores of size 10-40 μm (Haldorsen *et.al.* 1983), while in the clayey tills in southern Scandinavia considerably smaller pores dominates.

Till Genesis

In a local scale many variables which affect the efficacy of groundwater movement in tills are controlled by the mode of till deposition. Comparative studies at modern glaciers have contributed with much information on working sedimentation processes in different glacial environments (Boulton 1968, 1970, 1972, Mickelson 1973, Sudgen and John 1976, Shaw 1977, Lawson 1979, Krüger 1979, 1983, 1984, Krüger and Humlum 1981, Humlum 1981). On the basis of general environment these processes are: lodgement beneath sliding glaciers, melt-out from beneath stagnant ice masses and from the upper surface of down-wasting dead-ice and finally a considerable redeposition of the material may take place by sliding and secondary flow during and after the ice has melted.

The outlined different origins of tills result in different characteristics which are likely to affect the hydraulic properties. For hydrogeological purposes it is therefore useful to base a description of till-sediments on mode of genesis. Most glacial geologists still adhere a classification by Boulton (1972):

Supraglacial tills:	Flow till
	Melt-out till
Subglacial tills:	Melt-out till
	Lodgement till

Below some important properties of the resulting mode of till deposition are summarized (see Dreimanis 1976, 1989 and references therein).

Deposition by lodgement results in a dense lodgement till (Boulton 1970, 1978, Krüger 1979, 1988, Krüger and Thomsen 1984) Fig. 4. Lodgement till is preconsolidated; its compactness moderate to very high.

In lodgement till the content of fine-grained material is usually high compared with that in other till types. Pre-sorted sediments that have been incorporated in the till may affect the grain-size distribution considerably. The compactness and

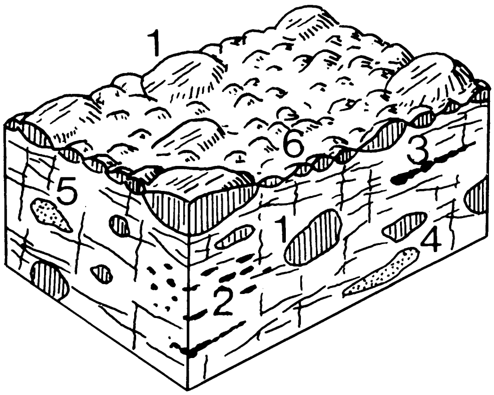

Fig. 4. Surface and sub-surface features in recently exposed lodgement till in front of an Icelandic glacier.

high content of fine-grained material is usually accompanied by high bulk density and low effective porosity. In sandy-silty unweathered Fennoscandian lodgement tills the effective porosities usually lie between 5 and 10 % of the volume, while in clayey lodgement tills of Scania and Denmark the values are considerably lower. The low porosity retards percolation downwards, but on the other hand, an upward movement of water from the groundwater zone may be high due to capillary rise. The studies by Haldorsen *et al.* (1983), showing that pore sizes 10-40 μ are prominent in sandy-silty Fennoscandian tills, were carried out in areas with lodgement tills; and illustrate that this till type is quite favourable for a fast capillary transport.

Normally lodgement till is relatively homogeneous, but a consistent orientation of the various elements of fabric, such as alignment of rock particles and lenses of sorted sediments parallel to the former ice flow, creates an anisotropy (Fig. 4) which may play a role for the hydrogeological properties, and may for instance give a higher hydraulic conductivity in horizontal than in vertical direction.

However, the dense fracture or joint pattern, which commonly occur in lodgement till is a more important property, because groundwater may move faster along these discontinuities than in massive till in between them. There are three main types of joints (Fig. 5): A subhorizontal fissility or foliation of closely spaced joints is very common, particularly in clayey and silty lodgement tills. Together with the horizontal alignments described above, this fissility creates an anisotropy with the highest conductivity in horizontal direction (Haldorsen *et al.* 1983). A second type of joints comprises subhorizontal shear joints often marked by thin layers of incorporated sand or silt and extending laterally for some tens or hundreds of metres, Fig. 5 (see also Krüger in Krüger and Marcussen 1976). The third joint type comprises vertical shear joints. They frequently occur in conjugate pairs and extend continuously down to several metres depth. These are not syndepositional structures, however, but they merely originate from deformation by the

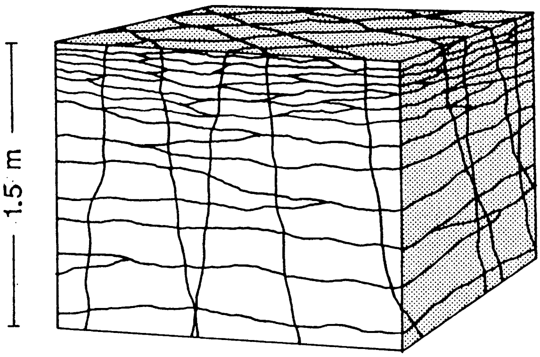

Fig. 5. A dense network of subhorizontal and vertical joints in Danish lodgement till.

overriding ice after deposition. It has been shown that close to vertical shear joints clasts often have been re-oriented and show a dispersed or preferred orientation parallel to the strike of the joint system; in the massive till in between the joints elongated clasts still parallel the direction of former ice movement.

Lodgement tills are very common in the Scandinavian countries and in Denmark they are especially related to till plains and more or less undulating ground moraine landscapes.

Tills which are classified as melt-out tills are in most cases formed by a subglacial melting from stagnant ice masses. The orientation of long axes of particles are as in lodgement till. In many cases where a till is identified as melt-out till there is a presence of well sorted sediments in the till units (Fig. 6) but a melt-out till may also have a massive appearance (Haldorsen and Shaw 1981). If there has been a removal of fines by melt-water, the till may be very sandy (Fig. 2). A diffuse lamination with poorly defined boundaries is very common. The degree of compaction is usually lower than in lodgement till. Due to the lower compaction and coarser grain sizes the melt-out tills normally have a higher effective porosity and

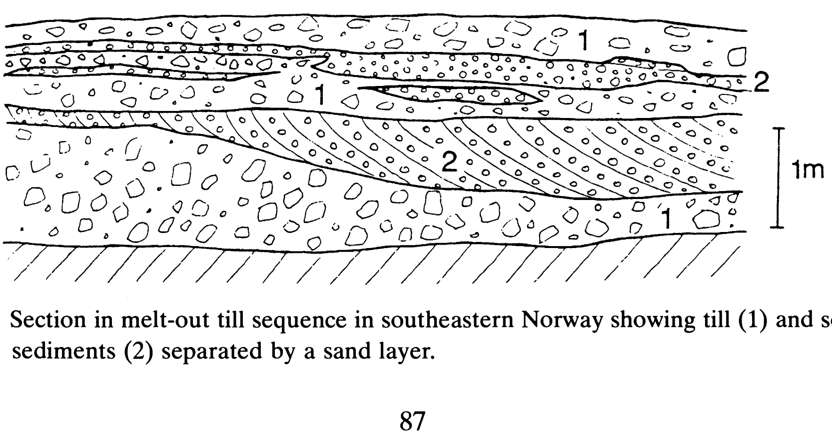

Fig. 6. Section in melt-out till sequence in southeastern Norway showing till (1) and sorted sediments (2) separated by a sand layer.

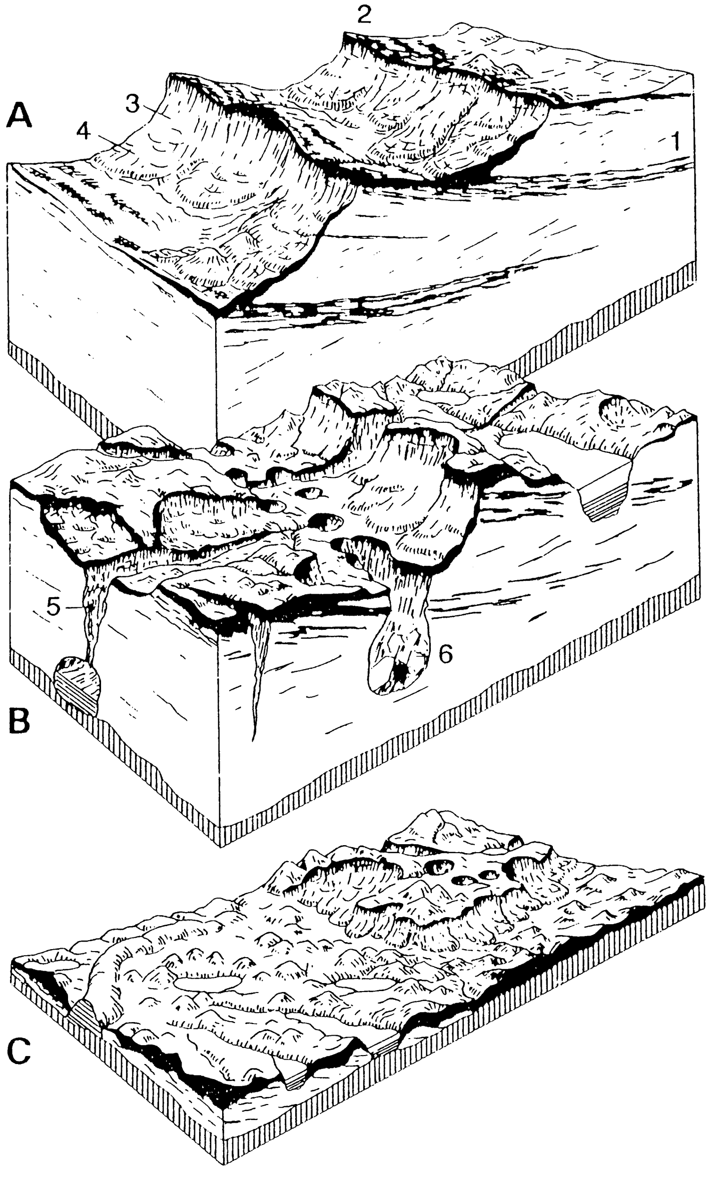

Fig. 7. Deposition of flow tills from the surface of a glacier on Iceland. A) A section showing the surface of a 30-50 m thick active ice. The material is transported in debris bands (1) up to the surface of the ice (2), where it flows down along the steep ice cliffs (3) and forms flow till lobes (4). B) In the mature stage when the ice has become more stagnant. Crevasses (5) and sink-holes (6) create an irregular ice surface. The flow processes are active, and flow tills are deposited in close combination with glaciofluvial material. C) In the old stage only remnants of the ice remain, and an irregular surface with flow till is the result of the continuous melting.

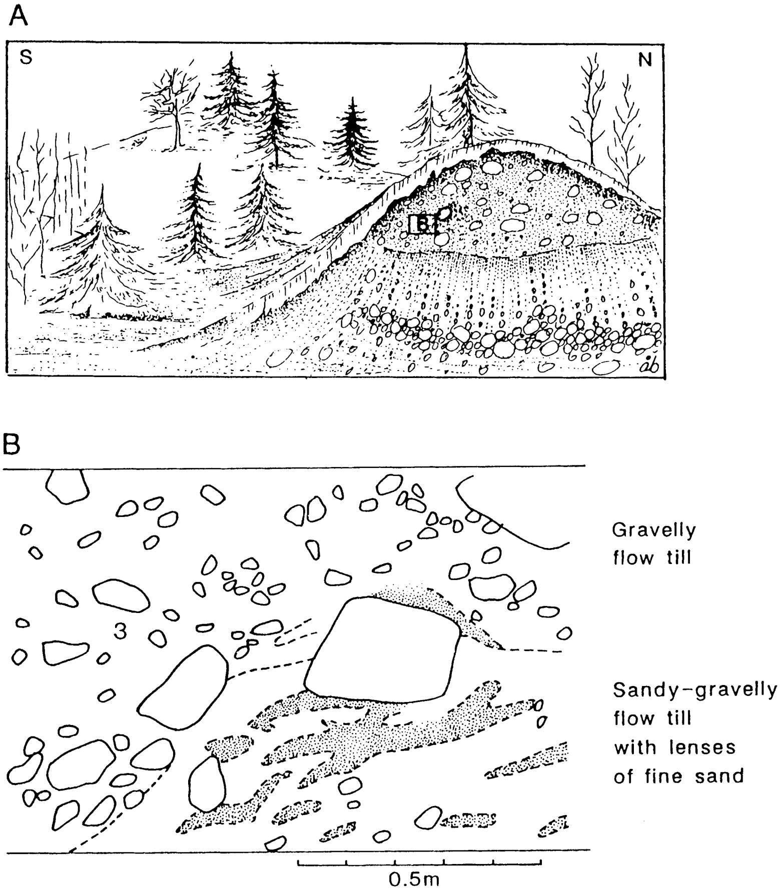

Fig. 8. Hummocky area in Åstdalen, southeastern Norway showing flow till horizons with abundant sediment lenses.

hydraulic conductivity than the lodgement tills. Pore drainage is more important for the vertical water movement, and the presence of better sorted sediment lenses in many cases control the water movement. There may be a fissility, but this is not as common as in lodgement till and is not so important for the water movement in the till. Melt-out till is believed to be a usual till type in the central part of Scandinavia.

The flow till resulting from redeposition processes at the surface of the ice (Fig. 7) is deposited in an area where melt-water is abundant, and the flow till is usually found closely connected with sorted water transported sediments (Fig. 8). The content of fine-grained material may be lower than in other till types due to a removal of fines by water (see Fig. 3). The flow till units are usually very variable over short distances and are according to Lawson (1979) often characterized by:

1) rapid lateral and vertical variations in grain-size distribution, 2) individual sedimentary units of varied geometry, 3) weakly defined, bi- to multimodal fabric, 4) laterally discontinuous stratification, 5) cut and fill structures, and 6) randomly dispersed subparallel alignment of single – pebbles-thick – layers. The compaction is normal, and lower than for lodgement till. The hydrogeological properties of the flow tills are similar to the melt-out tills. However, flow till sequences are commonly more inhomogeneous and anisotropic than the other till types because of the mixture with waterlain sediments. In Scandinavia flow till is commonly connected with the deglaciation period after the last glaciation. In most areas with hummocky moraines flow till is an important component (Fig. 8).

It is in many cases difficult to distinguish between the three described till types in the field without detailed investigations. The genesis may vary in short distances. The genetical groups have therefore been regarded as end members, where many tills in a regional scale consists of components of all the genetically different groups (Dreimanis 1989).

In Denmark the hydrogeological properties of tills are also seriously affected by the broad occurrence of large-scale dislocations of glacial drifts as a result of several glacier advances as well as minor readvances during the general recession of the ice. Such glacitectonical features may create an anisotropy which is very difficult to describe without detailed investigations of vertical and lateral variability.

Lithological Descriptions of Tills for Hydrogeological Purposes

In many hydrogeological studies of tills a good description of the till is lacking and it is difficult to know for which areas the results are applicable. It must be aimed at that the tills are described in such a way that the later investigators as well as readers of hydrogeological literature may use the results as reference for other studies.

As mentioned above, the genesis of tills is often difficult to interpret, and considerable variations may exist within one genetical group. The average regional variations due to the bedrock differences are in many cases not detailed enough to be used directly in hydrogeological studies. There is in many cases need for additional data. It is recommended that only the parameters of major significance for the hydrogeology are observed and that the observations are as objective as possible so that different observers will describe them in the same way.

The most actual descriptions are based on vertical sections, which may be combined to give an areal description of the till. The use of a general code appropriate just for tills would make it easier to carry out such vertical and areal descriptions. A lithofacies code for studies of tills have been proposed by Eyles *et al.* (1983). The code was, however, mainly made for sedimentological and not for practical pur-

Lithofacies code for description of glacial till

APPEARENCE	FRACTURES	GRAIN SIZE	COMPACTION	SORTED SEDIMENTS	CLAST ORIENTATION	
M						Massive, homogeneous
G						Graded
S						Stratified
H						Heterogeneous
	L					Lacking
	I					Irregular
	H					Subhorizontal
	V					Subvertical
		C				Coarse grained, gravelly
		M				Medium grained, sandy silty
		F				Fine grained, clayey
			1			Loose, not compacted
			2			Moderate, easy to excavate
			3			Compact, difficult to excavate
			4			Very compact
				C		Continuos layers
				L		Lenses
					✳	No marked orientation
					→	Significant long axis orientation

Fig. 9. Code system for description of till for hydrogeological purposes (modified from Krüger *et al.* 1989).

poses, and it is not easy to apply in hydrogeological studies. Jenssen and Køhler (1986) modified this system and made a lithofacies code suitable for infiltration studies in glacial sediments in general. The part which concerned tills did, however, include only a part of the properties of importance for the hydrogeology.

Krüger *et.al.* (1989) designed a lithofacies code especially for tills and related sediments. It can be applied for very detailed studies as well as for more general surveys. Fig. 9 shows a simplified version of this code which may serve as a guide for descriptions of tills for hydrogeological studies. The general appearance is defined as massive (M), graded (G), stratified (S) and heterogeneous (H). Visible fractures, which may have a dominating influence upon the water movement are described in terms of irregular (I), subhorizontal (H) and subvertical (V). The bulk grain-size properties are described in terms of gravelly (coarse C), sandy-silty (medium M) and clayey (fine F). The typical Fennoscandian tills will in most cases be classified as coarse or medium, while Scanian and Danish tills usually will be described as medium or fine. The tills are grouped according to the degree of compaction too, which has a great influence upon the bulk porosity. Loose (1), moderate (2), compact (3) and very compact (4) are the proposed coding. Flow till will in most cases relate to group 1 while lodgement tills usually will gain the codes 3 or 4. The occurrence and extension of sorted sediments, which have proved to be of great importance for saturated water flow, is noted as continuous (C) and lenses (L). The need of this notation is obvious for melt-out till and flow till. Finally, the orientation of clasts may be indicated as lacking or by an arrow which indicates the direction of orientation with north pointing vertically upwards. When such a code is used in the field, most of the factors which are of importance for the hydrogeology of the tills below the soil horizon are observed and described. A lodgement till in southeastern Norway got the following lithofacies codes: Massive (M) with subhorizontal fractures (H), medium grained (M), compact (3) and with a significant long axis orientation. The hydraulic conductivity was measured in the field by an infiltration test which gave values of 10^{-6}-10^{-5} m/s. Laboratory tests carried out on undisturbed samples showed that the horizontal conductivity was significantly higher than the vertical, due to the fracturing and clast orientation. Flow till in the same area was described as stratified (S), lacking fractures (L), medium to coarse grained (M-C), loose (1) with continuous layers of sorted sediments (C) and had no marked clast orientation. The hydraulic conductivity was calculated to 10^{-5}-10^{-4} m/s. The higher values are explained by the sorted sediments and the lack of compaction. The measured differences in hydraulic conductivity were thus indeed explained by the observed lithofacies characteristics. It is, therefore, our conclusion that such lithofacies descriptions are of great importance for future hydrogeological studies of tills.

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