STONES IN DANISH TILLS AS A STRATIGRAPHICAL TOOL A REVIEW

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Abstract. The composition and variation in the assemblages of boulders and pebbles in tills have been used for correlation and for determination of glacier movements. A number of factors, comprising at least flow in ice sheets, spreading and transportation of boulders and homogeneity of tills, are involved in these interpretations. An examination of these factors, as they appear in the Danish literature, has been carried out. Comparison with other investigations shows a high degree of disharmony.

It therefore seems to be inadvisable to use indicator boulders and stone-countings for regional stratigraphical interpretations in Danish Quaternary deposits.

INTRODUCTION

The theories concerning the movements of the ice in the Danish area through the last part of the Weichselian are to a considerable extent based on studies of the stone material in tills. For that reason, a fundamental condition must be that it is possible to correlate tills by means of their contents of stones.

Two analytical methods have been used—stone-counting and indicator-boulder analysis. In the first method, all the stones are washed out of a sample of the till. The stones in a certain size fraction (earlier 6—60 mm, today 1.4—4 mm) are then classified in rock-type groups (normally eight) and counted. The relative frequencies of the groups are finally calculated. If two samples show identical or fairly similar results, it is assumed that they were deposited by the same ice.

In the indicator-boulder analyses, only a few, characteristic types of rocks are taken into consideration. The grain-size fraction used is not defined, but in most cases it is probably equal to the stone fraction (2—20 cm).

The most common till in Denmark is clayey and in it the above-mentioned fraction forms only a very small part. For that reason, the majority of indicator-boulder analyses (90 % in Milthers, 1942) have been carried out at localities where secondary agents have concentrated the stones (on beaches and in meltwater material).

The absolute frequency of the indicator boulders is incompletely known. From the literature and from some investigations carried out on beaches in eastern Denmark, the frequency of the six indicator boulders used by V. Milthers (1932) and K. Milthers (1942) seems to be 0.4 % of the stones bigger than 2.8 cm and less than 20 cm. On the assumption that this fraction constitutes 1 % by weight in Danish boulder clay, it should be possible to find three of these boulders in every 2 tons of till.

The six boulders derive from two rock types from each of the following three areas in the central part of Scandinavia: the Oslo area, Dalarna in Sweden and a locality at the bottom of the Baltic which is presumed to be situated north of Gotland and south of the Åland islands.

Besides their use for simple correlations, Milthers and other authors think that from the indicator boulders it is possible to determine the route which the ice followed before it reached the Danish area. It is supposed that, if an ice came from the northeast, it would have a surplus of indicators from Dalarna, whereas an ice from the southeast would have a surplus of Baltic indicator boulders.

The model for the activity and flow of the ice on which these ideas are based includes at least the following assumptions:

1. From the area of accumulation, the ice particles move down to the bottom and then out to the margin faster (possibly at the same rate) than the particles higher up in the ice.
2. The ice picked up material and then transported it at least 1000 km.
3. The indicator boulders were of such a quality that they could stand the long transportation.
4. The ice only exceptionally picked up local material in the Danish area.
5. The material in a till forms a sufficiently homogenous mixture for comparing two samples.

In the following sections, these assumptions will be examined. It is not the author's aim to give an exhaustive explanation but to point out difficulties, as a contribution to further discussion on these problems.

THE SCANDINAVIAN ICE SHEET

The ice sheet which accumulated in the Scandinavian area during the Weichselian was asymmetrical and it is supposed that the ice divider was situated in the eastern part of northern Sweden and turned westward at its southern end (Flint, 1971). The outcrops of four of the indicator boulders used by Milthers are located in the most central part of the ice sheet.

Haefeli (1961) proposed a model for the movements of the particles in the ice caps of Greenland and the Antarctic. Investigations by Dansgaard (1961), Swinzow (1964) and Dansgaard and Johnsen (1969) seem to confirm this model. Fig. 1 shows the pattern of flow. Remarkable in this connection is the slow movement along the bottom, compared with the top.

In a boring at Camp Century in northern Greenland, Dansgaard and Johnsen (1969) found ice with an age of 100,000 years 30—35 m above the bottom. The locality is situated only about 100 km from the margin of the inland ice. The flow in the bottom layers must therefore be extremely slow.

There seems to be no objection to a comparison between the Scandinavian ice cap and the two recent ones. With the above-mentioned model of the flow, it will be obvious that no spreading of boulders to the margin will take place after the ice sheet has been established. Such spreading was a fundamental assumption made by V. Milthers (1932), K. Milthers (1942) and Wennberg (1949).

LONG-DISTANCE TRANSPORTATION

The possibility of stones being transported over very long distance cannot, of course, be excluded. However, investigations of tills show that the main part of the material in a till is normally of local origin (Gillberg, 1965, 1967, 1967; Holmes 1952; G. Lundqvist 1935, 1940, 1951; J. Lundqvist 1952, 1958, 1969). The local material is absolutely predominant and constitutes, on the average, 70 % (J. Lundqvist, 1970) of the material in a till. Locally and if the base is made up of a soft type of rock (for example, clay), about 90 % of the till may consist of the substratum (J. Lundqvist, 1969) and under special conditions close to 100 % (G. Lundqvist, 1940).

Downstream from the outcrop, the frequency decreases rather fast. Krumbein (1937) pointed out that the decrease follows an exponential function. A study of the spreading of the Cambro-Silurian sediments in southern Sweden by Gillberg has confirmed this. It was even possible for Gillberg to calculate some values for the constant a in the exponential function. This constant is supposed to be the sum of a series of constants, of which one of the most important refers to the durability of the stones.

By using Krumbein's formula and the values for the constant a found by Gillberg (1967), the half-distance values (the distance at which the frequency has been halved) for some rock types have been calculated:

Rock type	Half-distance, km
Cambro-Silurian limestone	5.1
Cambro-Silurian shale	8.6
Cambro-Silurian sandstone	14.0
Diabase	29.1
Dala porphyries	45.0

The figure for the Dala porphyries was determined from a map by G. Lundqvist (1951) on boulder-spreading.

The fact that the frequency of an actual boulder type decreases so fast downstream means that virtually nothing will be present at a distance of, for instance, twenty times the half-distance from the outcrop. If Krumbein's formula and the half-distance value are correct, the frequency of the Dala porphyries in the eastern part of Denmark is much too high and this figure should be expected in the area around Lake Vänern in Sweden.

THE DURABLE STONES

The main reason why the frequencies decrease so fast downstream may be the abrasion of the stones (Lundqvist, 1940). An unambiguous indication of this is that the half-distance value is six times as high for the hard diabase as for the soft limestone.

Even though the half-distance value for the porphyries is high, it is difficult to explain how they were transported over 1000 km. The possibility that the boulders started their journey as giant blocks appears to be unreliable, because it is possible to find specimens in Denmark of considerable size. If the abrasion was in accordance with the results of Erdmann's (1879)

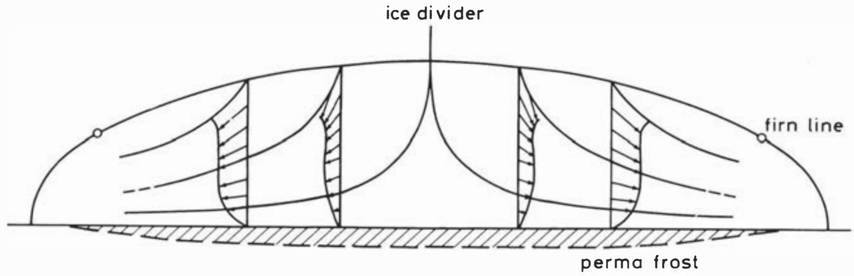


Fig. 1. Schematic cross-section through an ice sheet with flowlines and velocity profiles. Partly after Haefeli (1961).

experiments, as depicted by G. Lundqvist (1940), the big blocks found in Denmark would have been so enormous that it is questionable whether a glacier would have been able to move them.

THE LOCAL ORIGIN OF TILLS

As stated above, a till consist to a high degree of local material. In Denmark the pre-Quaternary deposits are composed of very soft sediments, such as Cretaceous limestone and Tertiary clay and sand. It seems reasonable to assume that before the last glaciation the surface was like the one we have today, consisting mainly of till, meltwater deposits and possibly marine clay. In this way, the Danish area was a very easy object for glacial erosion and it is most likely that the bulk of Danish tills is re-worked material from the area.

The mapping of the southernmost part of Sweden by Ekström (1947, 1960, 1961, 1961) shows a close connection between the lithological composition of the stone material in the tills and the lithology of the substratum. Of special interest is the apparent congruence between the clayey till from the so-called Baltic ice (*lågbaltiska isen*) and the soft Mesozoic sediments.

It seems unquestionable that the last ice in Denmark dug up older tills. In this way boulders which today are a part of the youngest till were previously incorporated in one or more tills in the area from earlier glaciations.

THE HOMOGENEITY OF THE TILLS

An imperative condition for correlations must be that the properties implicated in the correlations can be reproduced in repeated analyses of the same till. Correlations by means of indicator boulders have been used to demonstrate a glacier from the Baltic moving north through the Store Bält. For these correlations, the so-called Baltic indicator boulders were used. Fig. 2 indicates the relative frequency of these boulders in the above-mentioned area. However, the greatly varying values do not make it feasible to draw isofrequency lines which have any relation to the movement of the glacier.

Two explanations are imaginable. Either it is not possible to correlate by means of indicator boulders in this way or the theory of the glacier movement is wrong. But since no other patterns of isofrequency lines can be drawn, at least the first alternative must be accepted. The reliability of the theories for explaining the movements of the glaciers in the Danish area will not be discussed in this article.

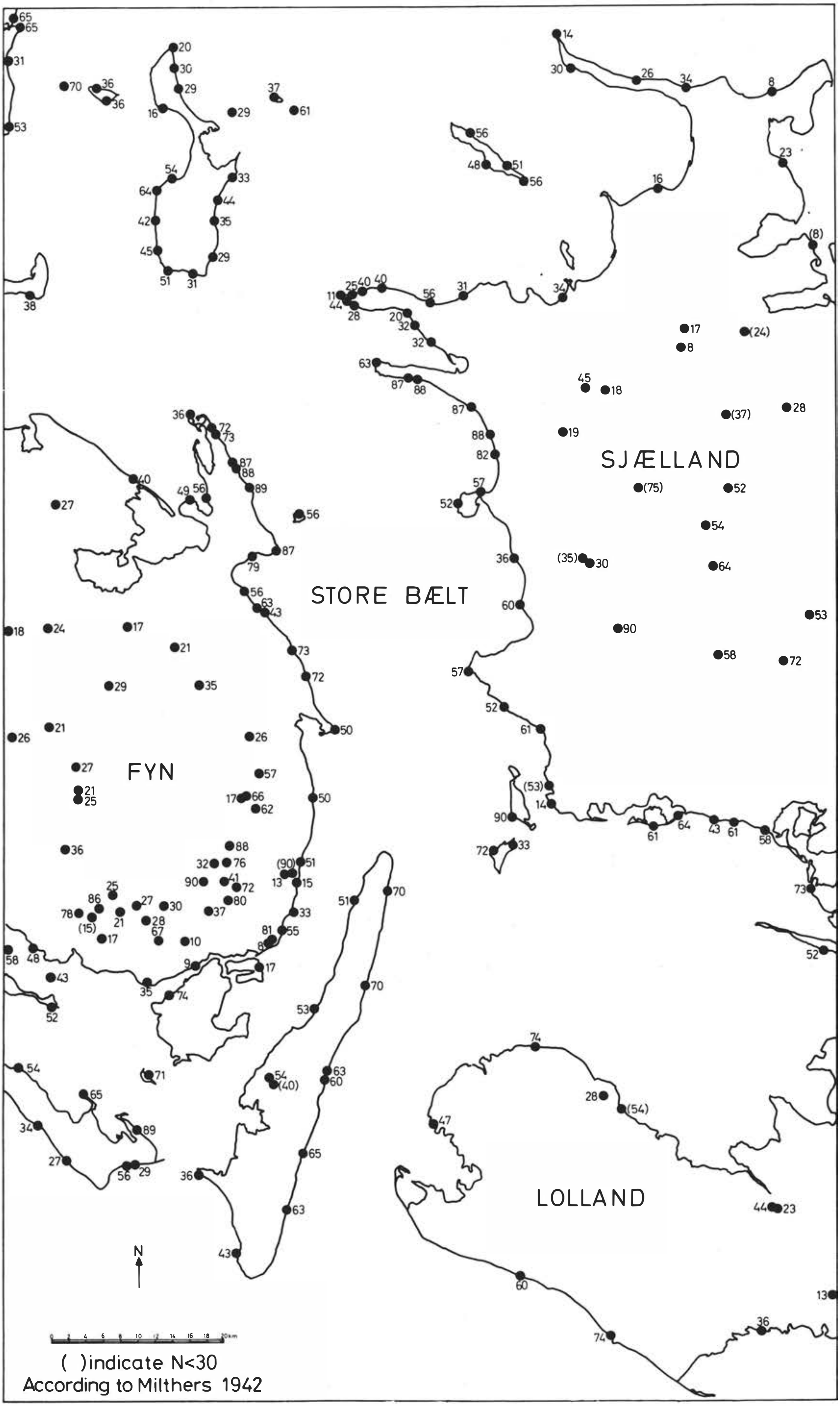
Correlations in which all the stones in a fraction are considered seem to be founded on a better basis. The stone-counting method fulfils this condition. The question of the unambiguity of the results is difficult to answer in a simple manner. Investigations by Gillberg (1969) and Bahnson (1972) indicate that it really is possible to reproduce results by repeated analyses in the same till. This means, consequently, that the till is homogeneous.

An examination of a large number (67) of double samples seems to some degree to show the opposite. A double sample means two or more samples from the same till. In the literature, 64 double samples from the Danish area are listed and three more have been taken by the author.

It is required that the stone assemblages in such a double analysis shall be parts of the same population, in such a way that there are no real differences between the samples. For this purpose, a statistical examination, using the χ^2-test, was used. Only 41 % of the 67 double countings showed a statistically significant agreement between samples.

The conclusion concerning the stone-counting method must be that, although two samples are different in their contents of rock types, they may still originate from the same till. The opposite is probably also the case. In general, the conclusion seems to be that correlation is possible under some conditions but impossible in other cases.

Per cent baltic indicator boulders



GENERAL DISCUSSION

Indicator boulders have successfully been used in North America and Sweden to determine the direction of movement of glaciers over a short distance (about 150 km) from the outcrops of the boulders. The spreading of boulders, like the formation of stria, takes place in the marginal zone of an ice cap, and the above-mentioned investigations deal with such marginal phenomena. Denmark is situated so far away from the outcrops of the normally used indicator boulders that it seems unrealistic to make any comparison with the above-mentioned investigations.

Since the transportation takes place in the marginal zone of an ice cap, it is reasonable to imagine that the Scandinavian boulders travelled to Denmark step by step at the beginning and end of each glaciation. However, the non-durability of the stones seems to contradict this theory, but in connection with englacial transportation it may nevertheless be part of a possible explanation.

An idea which immediately suggests itself is transportation by drift ice. The resulting aquatic sediment may then later have been incorporated in a real till.

CONCLUSION

It seems to be rather uncertain whether the indicator boulders from the central part of Scandinavia were transported to Denmark exclusively in the last glaciation. The courses of the boulders were possibly complicated and other forms of transportation than glaciers are quite conceivable.

Some heterogeneity in Danish tills appears to make both the stone-counting analyses and the indicator-boulder analyses unreliable for regional correlations.

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Fig. 2. Map of the Store Bält region in central Denmark, showing the relative frequency of indicator boulders from the Baltic.