# Distribution and transport of Fennoscandinavian indicators

## A synthesis of data from the literature leading to a reconstruction of a pattern of flowlines and ice margins of the Scandinavian ice sheets

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Overweel, C. J., Distribution and transport of Fennoscandinavian indicators: A synthesis of data from the literature leading to a reconstruction of a pattern of flowlines and ice margins of the Scandinavian ice sheets. — Scripta Geol., 43: 1-117, 54 figs., 1 folding map, Leiden, October 1977.

Detailed indicator counts in the literature on areas south and east of the Baltic were revaluated on the basis of the main ice movement directions of the last glacial in Fennoscandia. This revaluation resulted in a distribution pattern of indicators which partially coincides with the general trends of ice movement. This holds for both the Weichselian and the Saalian. The other part of the indicator distribution is of Baltic origin.

The interrelationship found between flowline and distribution pattern was further analysed and elaborated, which led to a reconstruction of the directions of ice movement and outline forms of the Scandinavian ice sheets. The peripheral glacier-margin drainage was incorporated into the reconstruction, and the resulting possibility that drift ice could have transported indicators of Baltic origin through the Urstromtäler and the glacial lakes is discussed in some detail.

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## Introduction

In 1957 the study of Fennoscandinavian indicators became the author's concern as part of his assignment as the keeper of rocks at the Rijksmuseum van Geologie en Mineralogie (National Museum of Geology and Mineralogy) in Leiden. He began to acquaint himself with the indicators in the museum and those of some large, well-founded, private collections. With others and alone, he visited field occurrences of indicators in The Netherlands, West Germany, Denmark, and England, and also examined the outcrops in source areas in south Sweden.

During this introductory period it became clear that the investigation of Fennoscandinavian indicators was still in the stage of data collecting, and consisted mainly of the analysis of the indicator association per locality. Attempts had been made to correlate the results regionally on distribution maps, as exemplified by the chart of ter Wee (1962) of the Saalian ice front phases in The Netherlands. The localities of these counts are indicated here by Hesemann numbers. Although a distribution pattern can be distinguished, these numbers do not help us to visualize the relationship with the source areas. The distribution pattern is much more pronounced on, for instance, the porphyry map of Denmark: Table I of K. Milthers' publication (1942). Here, too, the relationship between the distribution pattern, ice movement, and provenance is difficult to grasp, but the zones of the tripartite indicator distribution in Lithuania given by Tarvydas (1960) trend toward their sources.

Thus, the quantitative approach of indicator investigation resulted in numberless counts, which are generally represented as separate, unrelated data. With the use of different procedures, some solitary regional correlations were made, but the overall picture remained one of separate and independant observations.

To advance indicator investigation, these loose entities needed to be fitted together. To achieve this, the counts based on different methods had first to be reduced to a common denominator. The Hesemann method and Lüttig's TGZ estimations were available, but these procedures did not yield a very clear picture of the indicator distribution pattern, perhaps because these approaches are too statistical since glacial control was not taken into account.

Therefore, I developed a new strategy, reckoning with glacial aspects. Thus, Part 1 of this paper gives a detailed regional analysis of the indicator distribution with reference to the traces of former ice movements in Fennoscandia. This analysis provides data from which a correlation was attempted of the published indicator counts of the circum Baltic. The resulting distribution pattern has two components, one corresponding to the Fennoscandian main ice flow trends, the other lacking this correspondence.

In the light of these findings, the relationships of the distribution pattern with glacial, periglacial, geomorphological, and geometrical features were investigated, as described in Part 2. The total forms a synthesis, a functional representation, of the Fennoscandinavian ice sheets.

## ACKNOWLEDGEMENTS

Foremost among those to whom I am indebted are Prof. J. D. de Jong and Prof. G. C. Maarleveld, who gave me their experienced guidance, constructive criticism, and valuable advice. Their aid when necessary, their encouragement, and their enlightening discussions contributed greatly to the ultimate result.

In 1957, the late Prof. I. M. van der Vlerk, in his capacity as Director of the Rijksmuseum van Geologie en Mineralogie, asked me to set up a section on northern crystalline erratics in the museum. He gave me full liberty in this commission for which I have always been grateful. He advised me to get in touch with the non-professional prominents in this field and to visit the parent rocks in Fennoscandia.

My contacts with the experts in crystalline erratics in The Netherlands have been very helpful indeed. Their cooperation, their readiness to communicate and to take me over their collections, will be always remembered. They contributed greatly to my present knowledge of indicator identification. Special mention in this respect should be made of the late Mr P. van der Lijn, Mr A. P. Schuddebeurs, and Mr J. G. Zandstra. The instructive excursions of the Nederlandse Geologische Vereniging, conducted by Messrs. W. F. Anderson and A. G. Koenderink, gave me a better understanding of the Quaternary geology of the countries adjacent to The Netherlands. My friend and colleague Mr M. W. ter Wee was so kind as to take me over the exposures in The Netherlands to acquaint me with the Saalian.

I am indebted to the Netherlands Organisation for the Advancement of Pure Research (Z.W.O.) for financial support to visit the southern part of Sweden to study the parent rocks of the indicators in 1959. Besides this opportunity to study the source rock, I benefited greatly from the help given me by, and the enlightening discussions with the Swedish geologists, especially Dr E. Åhman, Prof. S. Gavelin, and Dr P. H. Lundegårdh, who took me to the field and allowed me to join them on the excursions to the Vestervik archipelago in preparation for the 21 International Geological Congress in 1960.

I am indebted to Prof. E. den Tex and the other members of the Geologisch en Mineralogisch Instituut in Leiden for their hospitality. Prof. P. Hartman was kind enough to read the section on the geometrical aspects and gave me valuable advice. The most essential part of this paper are the figures, maps, and diagrams which elucidate the text, which were prepared by Messrs. J. Bult and F. J. Fritz. I am immensely grateful to them for their cooperation, skill, patience, and helpful advice. The librarians Messrs. C. H. Duvekot, O. J. Groot, and H. B. van der Meer gave me every possible assistance.

I am indebted to Mrs D. de Munter for correcting the English of large parts of the manuscript in its initial stage, and to Mrs I. Seeger for the final correction of the completed manuscript.

A word of special thanks is due to Prof. P. J. R. Modderman and his coworkers of the Instituut voor Prehistorie in Leiden for the way in which they accepted me in their midst, for the many instructive discussions about prehistory in particular and scientific inquiry in general, and for the chance they gave me to bring the present study to a close.

Finally, I cannot adequately express my gratitude for the aid and encouragement given by my wife, who undertook the preparation and typing of the manuscript. Without the support and loyalty of my wife and children, this study would probably never have been completed.

# Part 1. Areal distribution of indicators

## History and complexity of indicator investigation

To find out more about the shape and dynamics of the Quaternary ice sheets it is necessary to appraise the glacial deposits stratigraphically and to unravel the spatial trends of the ice stream movements. On this basis, the results of about two centuries of research on the dispersal of erratics will be discussed.

Each of the two objectives requires its own, specific approach, as shown by a discussion of Fig. 1. Figure 1a gives a schematic representation of a segment of an ice sheet flowing over outcrops of various parent rocks. An imaginary vertical plane has been indicated parallel to the direction of the stream and such that its line intersecting the subglacial surfaces marks an intervening boundary between different types of source rocks. On one side of this boundary line rock types A and B are present, on the other rock types C and D. Since the intervening boundary lies parallel to the direction of the stream, the highest densities of the indicators

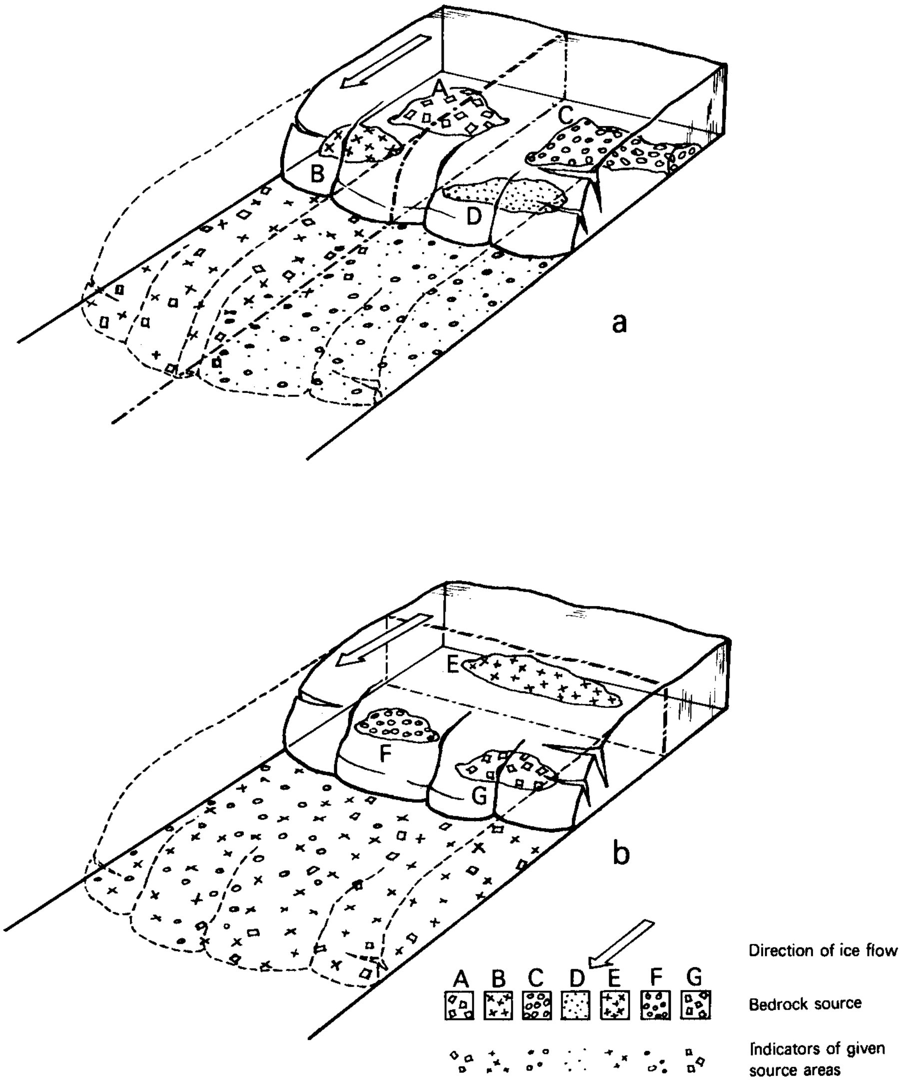

Fig. 1. Schematic representations of segments of an ice sheet. Source areas separated by lines parallel (a) and transverse (b) to the flow direction.

deriving from source rocks A and B will be found on one side of the produced part of the intersection line and the indicators deriving from source rocks C and D on the other side. Hence, when the respective areas of provenance are situated between lines running parallel to the direction of the ice movement, the distribution of the indicators in the area of deposition permits the drawing of conclusions concerning the general trend of the ice movement.

If, however, the source areas are separated by the base lines of vertical planes taken at right angles to the direction of flow (Fig. 1b), differences in the quantities of the indicators in areas situated far enough from the source, have a bearing on the duration and the rate of ice flow. The one region may have been covered during a relatively short period, the other region for a much longer period. This is closely related to such conditions as the duration of halts of the ice front and the rate of expansion or recession of the ice sheet. Thus, unless unknown factors played a role, the greater number of indicators derived from area E as compared with areas F and G (Fig. 1b) points to a longer period of ice erosion in area E.

In sum, the fact that the ice sheets in different glacials change in different ways means that provenances enclosed by lines at right angles to the direction of ice movement can be used for stratigraphic purposes. Contrarily, provenances contained by lines parallel to the direction of ice movement are required to unravel the trend of ice movement in relation to the area of deposition.

With these observations on the objectives of this field of research in mind, we are better equipped to evaluate the present state of affairs, which will be discussed in terms of the historical approach.

## INDICATOR IDENTIFICATION

The advance of research during the last hundred and forty years can be roughly divided into three phases, i.e., indicator identification, reconstruction of indicator fans, and application of the quantitative approach.

The initial stage, which started around 1830 and culminated in the early part of the twentieth century, is characterized by qualitative work. One of the pioneers in The Netherlands was S. J. Brugmans, who as early as 1781 proved in his doctoral dissertation that rock species occurring in the province of Groningen were related to Fennoscandia (Capadose, 1825). (This pioneer was brought to my attention by Professor L. D. Brongersma). The erratics found in the glacial deposits of northwestern Europe were described, classified, and compared with their possible counterparts from the solid bedrock in Fennoscandia. These investigations resulted in several standard works on the petrography of Fennoscandinavian crystalline indicators, such as those by Korn (1927), Hesemann (1936, 1939b, 1975), and van Calker (1912), as well as publications by Kruizinga (1918), Hucke (1917, 1967), and several articles by Martin published in the last quarter of the nineteenth century (brought to my attention by Professor L. D. Brongersma) concerning the sedimentary rocks. In this phase contributions of lasting importance were made by non-professional geologists who — working alone or as members of associations — collected, described, and compared erratics from the glacial deposits in their own region. It is worth mentioning here some of the periodicals issued by these enthusiastic societies: Grondboor en Hamer in The Netherlands and the Zeitschrift für Geschiebeforschung and Der Geschiebe Sammler in Germany.

Because indicator investigation is based on indicator identification, consideration must be given to the question of the extent to which a given indicator is a true specimen of the source to which it refers. Discussion of this problem will be more to the point if we start by asking ourselves what the main features of an ideal indicator are. By definition, an ideal indicator should be a unique, easily recognizable rock type whose area of origin is clearly defined. Good examples of this among the relatively small number of groups of Fennoscandinavian indicators, are the typical Oslo rocks and the group of rapakivi granites from Finland and the Åland islands. These externally striking specimens immediately catch the eye of a collector searching through the lag concentrates of till. Due to differential weathering of the component parts, the surface of the indicator is usually more vividly marked than that of the original source rock, but in any case the fresh fracture of a broken specimen bears comparison with the rough unweathered faces of the Fennoscandinavian equivalents.

The macroscopic similarity of indicator and possible source rock can be evaluated by microscopical examination. In addition to a macroscopic description, Hesemann (1936, 1975) also gave a microscopic specification of the indicator types he described. Van Calker and his school set a high value on the microscopical approach. Once the identity of an ideal indicator, e.g. as a rhomb-porphyry, is established both macroscopically and microscopically, macroscopic determination of other specimens of this kind suffices.

As mentioned by Korn (1927), another method of further verification of an indicator can be obtained by determining whether members of coexisting rock types in the source area of a certain indicator also occur as components of the indicator association. Thanks to Milthers' counts it is well known that the northern part of Jutland is strewn with rhomb-porphyries. Nonetheless, in visiting this region in the summer of 1971, the present author was impressed by the huge amount of these porphyries on the western beaches. In addition to the rhomb-porphyries there are many larvikites, albeit in distinctly smaller amounts. This indicator assemblage of typical Oslo rocks in the erratic association of northern Jutland confirms the identity of the rhomb-porphyries. On the other hand, the porphyries in their turn confirm the authenticity of the larvikites.

By reason of their rarity as rock types, the Oslo rocks and the rapakivis cause few problems as to their reliability as indicators. The distribution of the bedrock of the former is restricted to the Oslo area and that of the latter to the Åland islands, the sea-bed around these islands, and the southern part of Finland, so that the condition of a limited regional extension of the rock types is also satisfied, although this holds more strongly for the Oslo rocks than for the rapakivis.

Would further subdivision of these categories of indicators be useful? This depends on the problem under study.

1. For proving the authenticity of a given kind of indicator, collation of the divergences of the single specimens with variations of its source rock leads to greater certainty. However, use of this elaborate approach, especially when it requires microscopical investigation, will only make sense in some essential cases of dubious identity.
2. Subdivision into varieties of a kind of indicator whose main dispersal is confined to a restricted area of deposition, might provide more information about the directions and behaviour of movement of the ice streams that traversed the region. Hence, it could be useful to divide the rhomb-porphyries or the larvikites in northern Jutland into subgroups, but only if the source rocks of these varieties occur in separate, distinctly defined areas.
3. As opposed to local investigations where the main or overall features of the Scandinavian ice sheets are concerned, there is little need to carry out further subdivision of indicators to obtain information about areas outside of their centres of accumulation. For instance, subdivision of rhomb-porphyries or larvikites, outside their area of distinct concentration in northern Jutland, does not give much additional data about the general features of the ice sheet.

After these general remarks on the reliability of the identification of indicators from the Oslo area and the rapakivis, some other important groups of indicators will be dealt with. For more extensive and detailed information, the reader is referred to the publications of Hesemann (1936, 1975).

The third group of indicators to be considered are those from Dalarna. The Bredvad porphyries in the glacial deposits not only show macroscopic and microscopic correspondence with their source rock but also predominate over the other varieties of Dalarna porphyries and porphyrites, which strongly supports their reliability as indicator. V. Milthers (1909) pointed out that the Bredvad porphyry occurs more frequently than the other Dalarna porphyries in Denmark, which he explained by its greater distribution in the source area. According to Hesemann (1936) the Bredvad porphyry predominates in Germany too, and van der Lijn (1974) found it to be the most common of the Dalarna group in The Netherlands. The association of the Dalarna porphyries in the glacial deposits with the Jotnian sandstones, Grönklitt porphyrite, and Garberg granite porphyry, which also crop out in Dalarna, supports their reliability as well.

The Småland granites and porphyries form a fourth group of indicators. The average Småland granite is medium or coarse grained and has a yellowish to reddish-brown hue, determined by the colour of its conspicuous microcline-perthites. This granite is a characteristic indicator. The source area in the eastern half of the southern part of Sweden is roughly defined in the south by a line running slightly north of Karlshamn to Karlskrona; on the west by a line from Karlskrona to the Vättern lake, on the north from lake Vättern to Västervik, and on the east by the coast south of Västervik. Of the Småland porphyries, the granite-porphyries series from Påskallavic, Sjögelö, and Emarp, with their marked alkali-feldspar phenocrysts, measuring 1-3 cm, predominate as indicator.

A fifth group is formed by the so-called black and white granites from Stockholm and Uppland. The former is a fine-grained grayish-black, biotite-granite, of which there is also a red variety. The Uppland granites are granodiorites containing hornblende. The outcrops of the Bohuslän granite on the west coast of Sweden contain subordinate bodies of a granite variety that could be mistaken for the Stockholm granite. As indicator, the typical Bohuslän granite with its porphyric crystals of microcline is seldom found in The Netherlands or northern Germany. Consequently, the subordinate variety resembling the Stockholm granite should be even rarer in these countries and because of its rarity as erratic, there is little chance of confusion with indicators of the true Stockholm granite.

The easily recognizable, red-spotted granular gneis granites from the island of Bornholm may be mentioned as a sixth group of indicators.

## INDICATOR FANS

As qualitative stock-taking continued, several investigators began to relate the localities of these indicators with their source areas, which brings us to the second phase of the research, in which the sorting and reconstruction of indicator fans ranked above the qualitative classification of the individual rocks. A now famous compilation of these fans was given by Caldenius and Sandegren in a map in the Atlas of Finland (1910), which has been reproduced in many textbooks on Quaternary or glacial geology (e.g. Magnusson, Lundqvist & Regnéll, 1963). The reconstruction of these fans was the first logical attempt to unravel the general trends of ice movements of the Fennoscandinavian ice sheets. In a general sense the compiled directions on this map are radial, but strongly disturbed by fans intersecting the general radial pattern. The apices of most of these interfering fans are situated in the Baltic area. It is hardly surprising that the enigmatic configuration of the line-bundles of the indicator fans gave rise to controversy about the ice stream directions. In addition, the fact that these directions could be attributed not just to one but to several ice ages caused further confusion.

## THE QUANTITATIVE APPROACH

To find a way out, the problem was taken in hand by supporters of the quantitative approach, which characterizes the third phase of investigation. An enormous number of counts were made, but in three different ways, according to Madsen, Hesemann, and Milthers.

For Madsen's method (Madsen, 1928), a 10 kg dry boulder-clay sample is passed through a 6 mm-mesh sieve. The erratics in the residue are counted and subdivided into a number of major systematic groups such as crystalline rocks, limestones, dolomites, and flintstones, after which the proportion of flints to crystalline erratics is determined. This ratio or flint coefficient is used as an index to distinguish glacial deposits of different ages. Since the source areas are left out of consideration, Madsen's method may be considered purely stratigraphic.

In contradistinction to the methodology of Madsen, the source areas are a condition sine qua non in the counting procedures of Hesemann (1930) and K. Milthers (1942). Hesemann divided Fennoscandia into four areas, which he designated I to IV. The indicators from a given locality are grouped accordingly, and their percentages in tens are collocated in conformity with the identification numbering of the selected areas in what is called the Hesemann number. Milthers confined himself to porphyry counts from three source areas, namely the rhomb-porphyries of the Oslo district, the porphyries from Dalarna, and the Baltic porphyries. These instigators and their adherents performed numerous counts, and as a result we now have at our disposal a dense regional network of counts covering Denmark, West and East Germany, and The Netherlands.

Woldstedt and Duphorn (1974) made a general estimate of the stratigraphic value of different methods of indicator investigation. The counts after Milthers, and particularly those of Hesemann, proved to be useful, inasmuch as different glacials and subglacials are characterized by specific, prevailing Hesemann numbers. On the basis of Woldstedt (1955), east Fennoscandinavian indicators culminate in the Elster, the numbers fluctuating round 6310. Numbers such as 2170, 2260, or 1180, bear upon the Saalian moraines. Similar numbers of the first three source areas such as 4330 or 3340 are characteristic of the Warthe Stage. To a certain extent, the numbers of the Weichselian are the same as those of the Warthe, but considerable deviations occur frequently here.

## DETERMINATION OF GENERALIZED MEAN TRENDS OF ICE FLOW

### *Hesemann's method*

We have seen that Hesemann's counts have stratigraphic value, and that provenances enclosed by lines perpendicular to the direction of ice movement are useful for stratigraphic purposes. Conversely, use of the common trend of the boundary lines of Hesemann's source areas should make it possible to arrive at an approximation of the direction of the ice flow toward The Netherlands and the western and eastern parts of Germany, where most of his counts were made. Since three of the four provenances proved to be involved, only the dividing lines between areas I, II, and III should be considered for the reconstruction. Because these lines are curved, straight lines were superimposed. In Fig. 2 the direction in question has been drawn perpendicular to these auxiliary lines, giving a generalized,

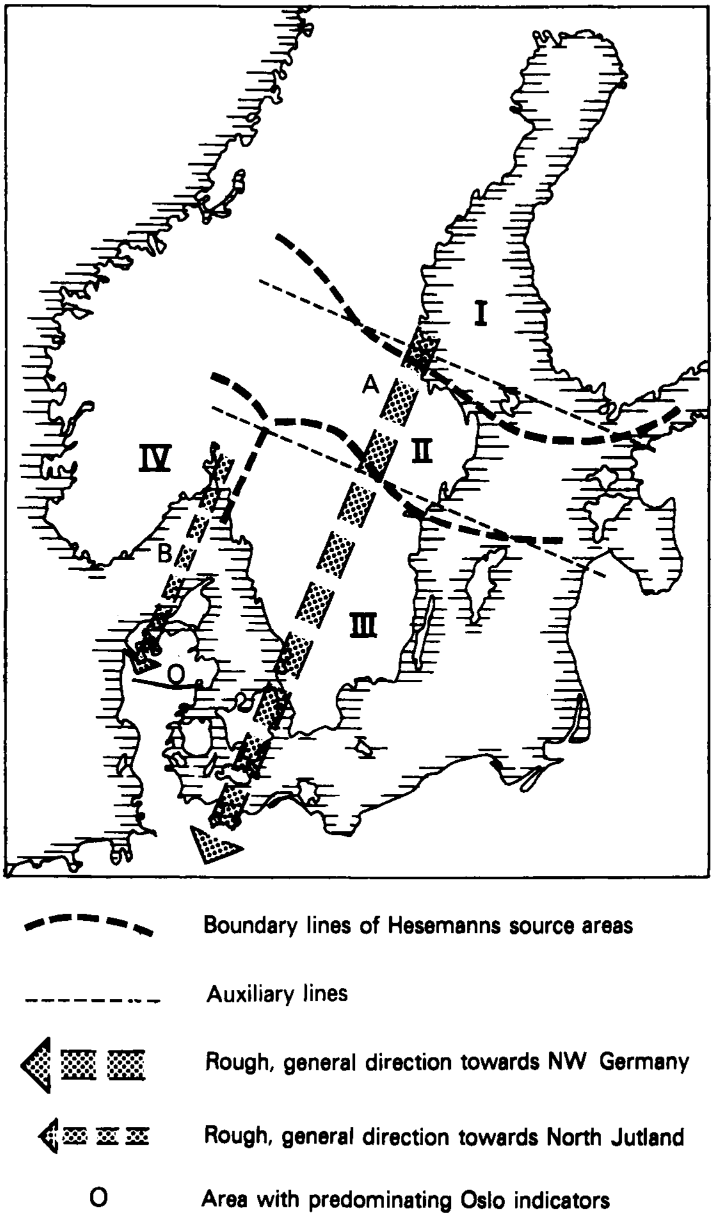

Fig. 2. Generalized mean ice stream directions tentatively reconstructed on the basis of the trends shown by the boundary lines of Hesemann's source areas.

mean ice flow direction running roughly from NE to SW. When source areas are separated by a line running parallel to the ice flow, the highest density zones of their indicator distribution are expected on either side of this line or its extension. Since the accumulation loci of the Oslo indicators lie on the west side of the extension of the line dividing Hesemann's areas IV and III and the main distribution of the Swedish indicators occurs on the east side, this dividing line should be parallel to the just estimated flow direction, which, as Fig. 2 shows, is in a general sense the case.

Hence, besides its stratigraphic merits, the Hesemann method yields an approximation of the general direction of ice flow in the southwestern part of the ice sheet. Nevertheless, his more or less W-E bearing stretches of source areas are too large for a more detailed analysis of the ice stream direction pattern.

### *Lüttig's TGZ estimations*

Lüttig (1958) reduced the size of Hesemann's hypothetic source areas by estimating the theoretical indicator centre (Theoretisch Geschiebezentrum, TGZ) of a large number of these counts. The longitude and latitude of the actual source of each indicator from a count of a given locality, were determined. The arithmetical mean of these longitudes and latitudes gives a geographical point that is the theoretical centre of the count in question. Working along these lines, Lüttig revised almost all of the published Hesemann counts, and some important points emerge from this approximation based on synthesis.

In the first place, Lüttig's TGZ characteristics provide greater stratigraphic

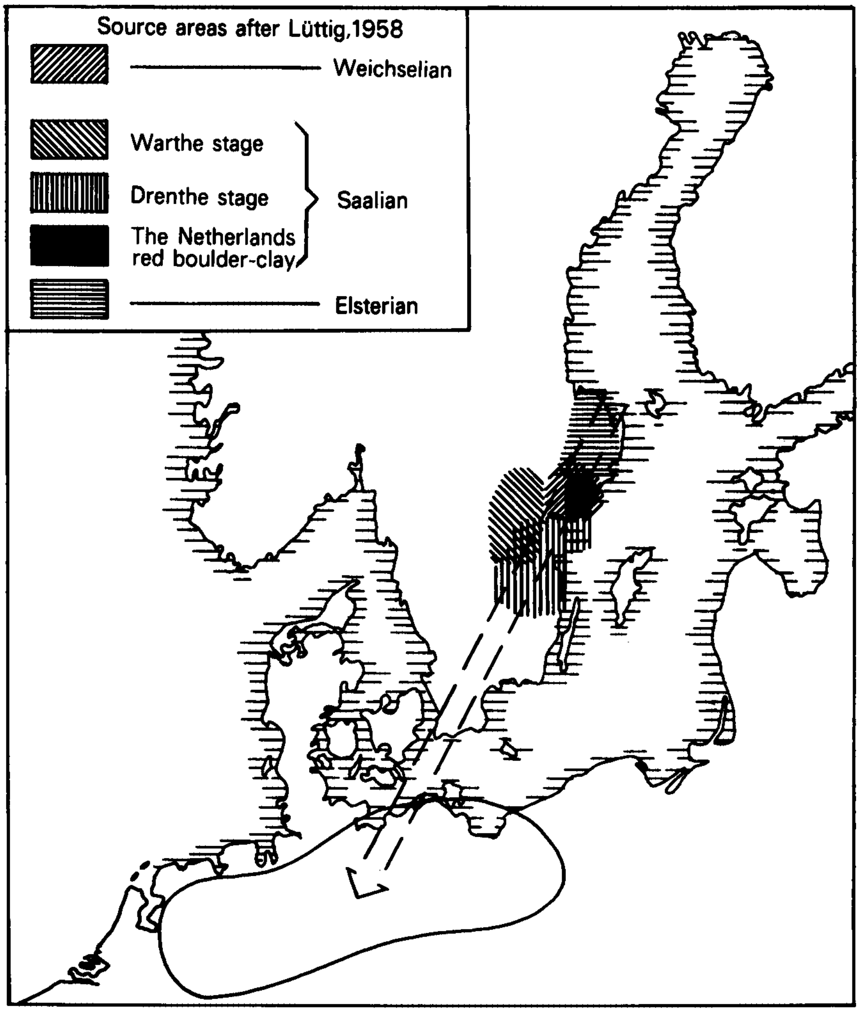

Fig. 3. The mean direction of ice movement toward the circumscribed area inferred from Lüttig's TGZ estimations.

refinement than the Hesemann numbers, because the conversion of the Hesemann counts into the TGZ estimations clarifies the stratigraphic positions and relations of glacial deposits in northern Germany and The Netherlands. The favourable effect of the application of Lüttig's method may have been due to the reduction of the vast Hesemann provenances to a restricted area. The situation of this synthetic mean, or rather an aggregate of its stratigraphical components, was established by Lüttig (1958) and is shown in Fig. 3. Since there is an interconnection between source area, direction of ice movement, and depositional area, the remaining elements have been added to Lüttig's original illustration (1958). For this reason, Figure 3 shows the additional outline, embracing the areas of deposition that Lüttig reconsidered. From the centre of this circumscribed region a line is drawn connecting and bisecting the related synthetic source area. In Fig. 3 this line, shown as an arrow, indicates the mean direction of ice movement looked for.

One of the main points to emerge from this sum total of Lüttig's synthesis is the stringent stratigraphic function of this method. It exposes an elongated mean ice flow with overlapping source areas upstream. Each of these source areas pertains to the predominant composition of indicators from a given glacial or stadial in the region of deposition. The backward and forward shifts along the stream direction of the locations of these provenances may be attributed to variations in the regimen of the diverse icecaps involved. A noteworthy factor here is the permanence of the mean ice stream direction, despite the different glacials and glacial phases.

It is of great importance that the mean direction runs about parallel to those which were roughly estimated on the basis of the locations of Hesemann's source areas. To reconstruct these directions, we began from two opposite starting-points, i.e. the source areas (by putting those of Hesemann to use) and the area of deposition (by taking advantage of Lüttig's TGZ estimations).

## CONSIDERATIONS

In spite of the inferred and confirmed general mean trend of ice movement, our review of the quantitative methods did not lead to a conception of the actual streamline forms. As we have seen, to determine the trend of ice movement with respect to an area of deposition on the basis of indicators, provenances are required that can be defined by lines running parallel to the ice stream direction, which means that the data we need are at the same time the relations to be deduced. In other words, we find ourselves in a vicious circle, which must be broken through in one way or another if our main objective is to attempt to unravel the ice stream pattern. In this respect it is of great advantage that the advocates of indicator counts and indicator fans have shown us how the land lies and have supplied us with a rich store of valuable information to draw upon.

Thus, although the indicators as modus operandi have put us in a fair way to gain some insight into the directions of ice stream, we have reached a deadlock and it is now time to adopt a different method of approach. When we strike the balance of the rich store of useful information available, our attention is drawn by the immense accumulation of data and facts concerning the direct and indirect glacial effects and features that have been carefully brought together by generations of geologists from Fennoscandia and the countries around the Baltic.

Of special interest, for instance, are the compilations on a regional scale of the directions of ice movement in Norway, Sweden, and Finland, the general outlines of the limits of the glacial phases of the diverse ice sheets, the inferred recession lines of the last glaciation, and the esker systems in Sweden and Finland. These features, which reflect the morphology of the former ice sheets, may provide additional information that lends itself to investigate the functional relationship between the location, the route or mode of transport, and the source of the indicators.

The first part of this report concerns the attempt to gain more insight into the regional distribution of indicators. It starts with an evaluation of the possible directions of ice flow in the source areas, to permit regrouping of these areas by lines that parallel the most plausible directions of the main ice movement. The indicator counts in the circum-Baltic area were rearranged accordingly, and the resulting distribution pattern is discussed in relation to the inferred design of ice flow in Fennoscandia.

## Regrouping of provenances

### CRITERIA FOR THE ESTIMATION OF THE DIRECTIONS OF ICE FLOW

To regroup the provenances, it is essential to know the former directions of ice motion in the source areas of the indicators. In this section, the methods used to determine these directions in Fennoscandia are commented upon. The flowline pattern proper will be discussed in the next section.

Different types of traces left by former ice movements are outlined in Table 1. The indicated characteristics and their possibilities and limitations for the assessment of ice flow directions are based mainly on data given by Charlesworth (1957), Flint (1971), and Embleton & King (1975). The relation of directional data to the sense of ice movement will be evaluated on the basis of Table 1.

To start with the striae, it must be kept in mind that changing ice flow directions may erase the earlier marks. Concerning this uncertainty, Flint (1971, p. 95) remarked that 'probably most of the striations that have been mapped were made near glacier margins during deglaciation and therefore do not indicate the direction of flow that characterized glacial expansion'. Here, in conformity with his cautious view — even though the striae could have been formed elsewhere under the ice sheet — they are considered to indicate glacial activities that took place toward the periphery of the ice mantle. The main glacial phase may be represented by well-defined striae, like those found by Bergersen & Garnes (1972) in the Gudbrandsdal area in Norway. Less well defined striations are younger, and there are strong differences in their trends. Because of variations from the main direction of the ice flow caused by the unevenness of the bedrock topography as well as the divergent direction of flow at the ice margin, Virkkala (1951, 1960) recommended that a statistical analysis of a large number of striae over a reasonably large area should be made to gain insight into the main trend of ice movement. The value of the results should be weighed against that of the measurements of other directional indicators such as grooves, fluted surfaces, and crescentic marks. Bergersen and Garnes (1972) found that lee-side plucklings and roches moutonnées had the same general orientation as the striae of the main glaciation phase. A

Table 1. Traces of directions of ice flow.

| Features | Mode of origin | Glacial distribution | Approach to interpretation of main ice flow directions | Deviations from main ice flow directions | Complications due to nonglacial processes | Scale of application in Fennoscandia |
|---|---|---|---|---|---|---|
| Glacial striae | Glacial basal abrasion | Toward periphery of the ice sheet | Statistical analysis of large numbers of striae | Unevenness of bedrock topography<br>Events at the ice margin | Striations made by:<br>drift ice<br>tectonic movements<br>mud flows<br>snow avalanches<br>rock avalanches | Regional |
| Roches moutonnées | Glacial basal abrasion | Throughout the ice sheet | Measurement of directions of the major axes | Slight deviations | | Local |
| Drumlins | Moulded at the base of the ice sheet | Throughout the ice sheet | Measurement of directions of the major axes | Slight deviations | | Local |
| Indicators | Dislodgement from the overridden bedrock<br>As loose fragments picked up by the ice sheet | Throughout the ice sheet | Statistical analysis of large numbers of indicators | Nonglacial events | Waterborne transport before or after their incorporation into the ice | Local |
| Fabric of till | Alignment in englacial or basal till by ice movement<br>Till flowage | Throughout the ice sheet | Fabric analysis of joints<br>Measurements of orientation of long axes of stones | Alignment depends on genetic till type<br>Till flowage<br>Slumping at ice edge | Disturbances by:<br>crustal rebound<br>drying up of till layers<br>geochemical processes<br>decalcification of till<br>cryoturbation | Local |

possible source of error for which we should be on our guard in dealing with striae are the non-glacial striae (Embleton & King, 1975). In Fennoscandia the measurement, plotting, and analysis of striae has been applied on a regional scale.

Roches moutonnées are rock masses which have been rounded off by glacial basal abrasion. They have been found in the area of the Scandinavian ice divide, on transfluence passes, and at the heads of valleys, but also at low levels or on flat ground, where they are best developed. The rather powerful abrasion action that must have shaped these bodies and the parallelism of the whaleback forms to inferred directions of ice flow, suggest that the overriding ice was active and had a persistent direction of movement. Consequently, the roches moutonnées are ideal criteria for the estimation of main directions of ice flow. Unfortunately, they are shown only locally on the Fennoscandinavian Quaternary maps.

The elongation of drumlins is generally considered to conform to the direction of the basal ice movement (Embleton & King, 1975). Accordingly, Aario et al. (1974) found that the majority of the striations in Koillismaa, Finland, lie parallel to the drumlin orientation. Flint (1971) thinks the drumlins to be more reliable indicators of former ice movement, because they are less influenced than striae by the local topography. Although it has been argued that drumlins are formed submarginally, Embleton and King state that they are also developed more toward the centre of the ice sheet. Therefore, they are considered here to be distributed throughout the ice sheet. In Fennoscandia they are recorded in local patches.

By definition, an indicator refers to its area of origin, or more precisely to the area where the source rock crops out as hard bedrock. However, the ice also removed clasts of the source rock around the source area proper. These disintegrated parent rock fragments were transported by non-glacial agencies. Of the non-glacial terrestrial agents (gravity, rivers, and wind), the rivers carry rudaceous rocks the farthest from their source, and fluvial transport may be called the leading non-glacial agency in the distribution of disintegrated source rock. Hence, preglacial rivers or river systems whose course through a source area was not parallel to the later direction of the main ice flow, tended to enlarge this provenance. The greatest effect can be expected where the river flowed at right angles to the ice stream direction.

Indicators in transit arriving at the edge of the ice could have been transported further, in a direction different to that of the ice, by proglacial rivers or river systems. Therefore, it is not inconceivable that the European ice-marginal streams carried indicator boulders from east to west. These boulders had a chance of being re-incorporated by an advancing ice sheet.

Consequently, preglacial and proglacial transport may be worth considering in attempts to explain cases of incongruity of indicator distribution with respect to inferred main ice stream directions.

Till is deposited throughout the ice sheet. There are several types of till. In the review given by Dreimanis (1976) they are subdivided genetically into two groups: superglacial tills and subglacial tills. Englacial till is assigned to the superglacial group. Another two-part classification mentioned by Dreimanis (1976) is based on the environment of deposition. Ortho-tills are deposited on land, para-tills in water. It is difficult to differentiate the genetic type on the basis of the lithologic character of a till.

In para-till, or water-laid till in the terminology proposed by Dreimanis, the alignment of clasts is found to be random. The alignment of boulders in basal till

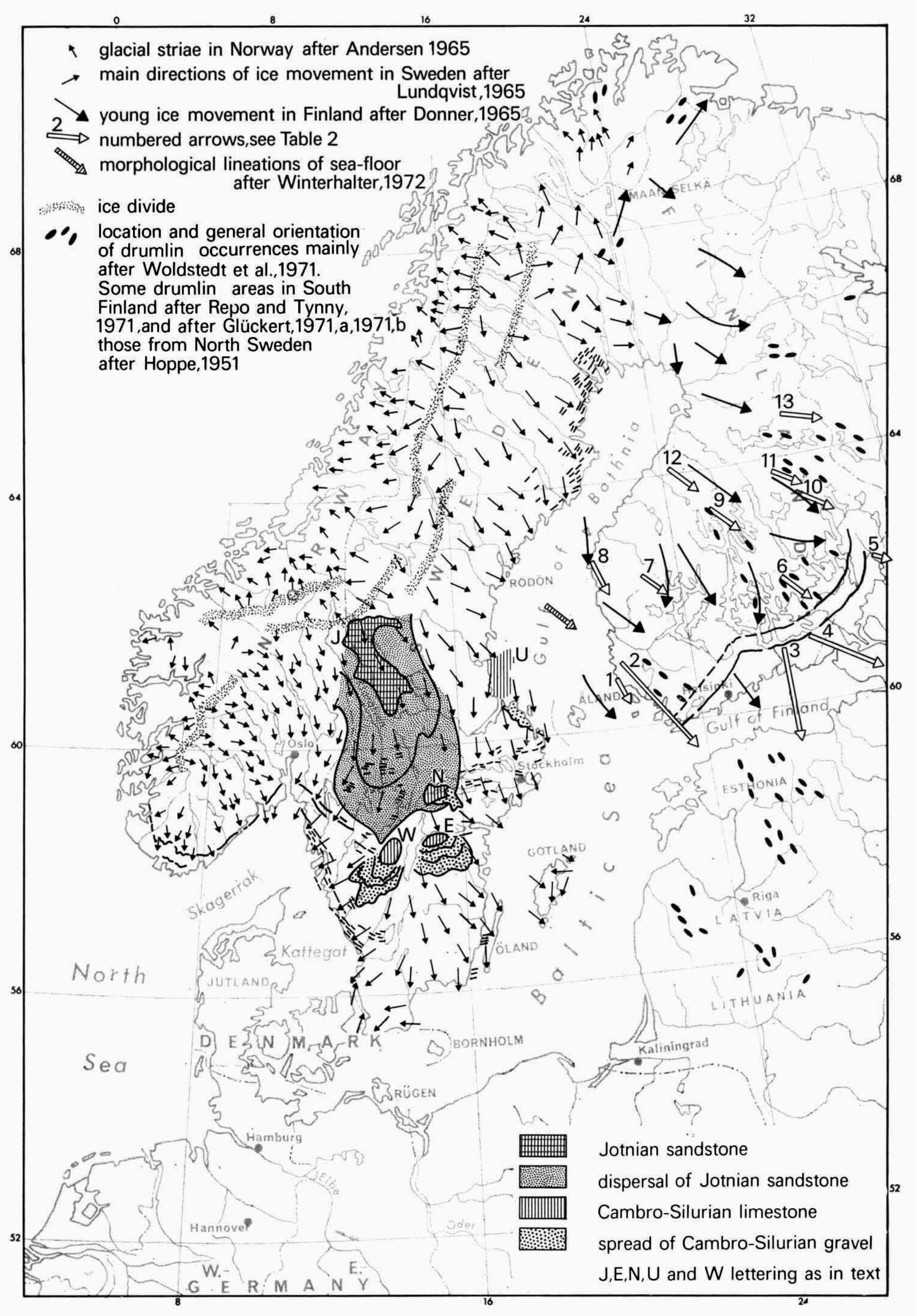

Fig. 4. Directions of main ice movement in Fennoscandinavia in relation to general orientation of drumlins, distribution of erratics in southern Sweden, and boulder trains in Finland.

may be either parallel or transverse to the direction of the ice flow. In englacial till the long axes of stones lie parallel to the direction of glacial movement. Evidently, the alignment depends on the type of the till in question, but the genetic type of till as sediment is hard to distinguish. Even water-laid till is seldom recognized as such (Dreimanis, 1976). Moreover, there are till fabrics which, according to Embleton & King (1975) are not directly related to the basal movement of the ice, but are determined by other processes such as till flowage due to hydrostatical pressure or the squeezing of water-soaked till from under the ice. Fabrics may also have been disturbed by slumping at the ice edge. This makes the interpretation of the results of fabric analyses very complicated.

Post-depositional non-glacial forces add to these complications. Grisak et al. (1976) mention a crustal rebound after glacial loading, the drying up of till layers, and geochemical processes during various periods of ground-water circulation. To these may be added cryoturbation and solution of limestones. Consequently, the younger the drift under investigation, the less chance of post-depositional disturbances. Hence, a fabric study of a Weichsel drift could carry more weight than an analysis of the fabric in a Saale till. Richter (1932, 1933) examined a large number of exposures of the Weichselian in the northwestern and eastern parts of Germany, Poland, and Denmark, and estimated the alignment of boulders and the sense of joint patterns in the till. The general impression given by the results is one of orderliness. The main regional tendency of the longitudinal position of the boulders in the vicinity of Rügen is northeast. The further toward the east, the more long axes trend north-south, resulting in a roughly north-south sense just beyond the meridian of 16° E (Richter, 1936).

The outcome of fabric analyses of Saalian till in The Netherlands is not order but disorder. This led Boekschoten and Veenstra (1967) to point out that this method of estimating the direction of ice movement falls short here. Despite the promising results obtained in the Weichselian in Germany, the limited applications so far and the inadequacy with respect to altered and older strata make the estimation of orientations of indicators inadequate to approximate the regional directions of ice flow for the Scandinavian ice sheets.

Because we are primarily concerned with the main directions of active ice, the roches moutonnées and the drumlins are the most reliable direction indicators for the present purpose. Unfortunately, these features have only been recorded locally. The striae were mapped on a regional scale, but their formation towards the periphery of the ice sheet and their susceptibility to local variations of ice flow mean that their reliability is uncertain. The dispersal of indicators gives an over-all view of main ice stream directions, but even so, the non-glacial events may lead us astray here.

In view of all this, we must exercise the greatest care, and weigh one directional feature against another, in judging main directions of active ice flow.

## FLOWLINE PATTERN IN FENNOSCANDIA

In 1965 Andersen published two glacial maps, one of southern and the other of northern Norway, on which the direction and location of numerous striae of the last glaciation are shown. Lundqvist (1965) compiled the main directions in Sweden, on the basis of the directions of striae and boulder transport, and here and there on rock forms. A map of the more recent movements of the ice in Finland was given by Donner (1965). In the defining of the general movement of the ice in Finland, striae have been used almost exclusively.

Because the main directions in Sweden were not derived from striae only, but also from boulder transport and rock forms, they have been defined on a sounder basis than those in Norway and Finland. Nevertheless, if the directional data from these three maps are combined, the pieces fit well together in the general sense. The result is shown in Fig. 4.

Although the regional consistency of the streamline features suggests a certain reliability, these features should also be evaluated by more trustworthy direction indicators, say drumlins, which, as we have seen, only occur locally. Compiled from various sources (mentioned in the legend), the locations and general orientations of drumlin occurrences are also shown in Fig. 4. Their directions agree with those of the ice movements.

The same holds for the direction of spread of some Swedish indicators. Magnusson et al. (1963) provided us with a representation of the dispersal of Jotnian sandstones (J). (Capital letters between parentheses refer to Fig. 4). Instances of the glacial distribution of Cambro-Silurian gravel on the east (E) and west (W) sides of Lake Vättern were given by Gillberg (1965). The same author published the results of investigations of the dispersal of Cambro-Silurian gravel in Närke (N) and Uppland (U) in 1967. Figure 4 indicates that the southward trends of the more or less tongue-shaped frequency distributions lie parallel to the pattern of the inferred ice flow.

The directions of boulder trains and trace element concentrations in Finland are given in Table 2 and are also depicted by numbered arrows in Fig. 4.

Table 2. Boulder trains in Finland.

| number of arrow | area | lithology | author |
|---|---|---|---|
| 1 | Laitila | rapakivi | Sauramo (1929) |
| 2 | Satakunta | olivine diabase, sandstone | Sauramo (1929) |
| 3 | Viipuri | rapakivi | Sauramo (1929) |
| 4 | Viipuri | rapakivi | Sauramo (1929) |
| 5 | Ladoga | rapakivi | Sauramo (1929) |
| 6 | Virtasalmi | ore boulders | Hyvärinen (1969) |
| 7 | Seinäjoki | plagioclase porphyrite<br>antimony bearing blocks | Pääkkönen (1966) |
| 8 | Korsnas | | Hyvärinen (1967) |
| 9 | Kolima | trace element concentrations | Kauranne (1967) |
| 10 | northern Savo | diabase | Sauramo (1929) |
| 11 | Paukkajanvaara | | Wennervirta (1967) |
| 12 | Ylivieska | | Mutanen (1971) |
| 13 | Moisionvaara | quartzites | Virkkala (1951) |

These directions are in reasonable agreement with the general tendency of the young ice movements. As a result, the flowline pattern is linked up at its north, east, and south ends with swarms of drumlins and the dispersal of certain indicators. This could be taken as confirmation of the traces of ice movements under consideration.

Drumlins are shaped and indicators are transported by ice in motion. Hence, the flowline pattern must reflect the directions of ice movement. This is obviously the case for advancing ice, but it is not as self-evident for receding ice. Flint (1971) mentions the pronounced shrinkage of most of the present ice bodies in the first half of this century. In spite of the retreat of their termini, however, these glaciers are still in motion, as shown by an illustrative case cited by Bischop, to which Flint (1971) refers. Here, a zone near the terminus of the ice sheet near Thule in northwestern Greenland stagnates while the ice flow upstream proceeds, and in this case the stagnant ice is even overridden by its mobile counterpart. Embleton and King (1975, p. 93) remarked that: 'A dynamically active glacier is one which is flowing fast, whether it is retreating or advancing at its snout'.

It is therefore uncertain whether the Fennoscandinavian flowline pattern was formed at the beginning or the end of the last glaciation, but the chances are that, in the main, the present directional remnants are related to mobile ice of the final regional recession of the last ice sheet.

## SOURCE AREAS ADAPTED TO ICE FLOW DIRECTIONS

As stated at the outset of this chapter, unravelling of the general trends of an ice flow pattern on the basis of the distribution of indicators requires provenances contained by lines running parallel to the directions of ice movement. Since these directions bear roughly north to south in southern Sweden, the source areas should be chosen such that they are consistent with a north-south trend. In the eastern part of Sweden the source areas have to be consistent with the general southeasterly direction.

To fulfil these conditions, twelve compound source areas which could be combined into five rows, were chosen in Fennoscandinavia. These north-south trending arrays are represented in a west to east sequence and are indicated by Roman numerals (see Fig. 5) in ascending progression. In this way, the left side of a paper refers to west, the west to east order is maintained when the numbers are put in writing in regular succession. The component parts of the north-south trending arrays are designated by the same number as the unit to which they pertain. Arranged according to the five major units, the twelve source areas are: I: Oslo, and the Swedish west coast including the provinces of Västergötland, Bohuslän, and Dalsland; II: Scania, Småland, and Dalarna; III: Bornholm and Blekinge; IV. Stockholm and Uppland; V: Ångermanland, forming a single group with the island of Rödön and the Ragunda area, the Baltic and the Gulf of Bothnia, Åland, and Finland.

On the south side of the circum-Baltic area the rapakivis and Baltic quartz porphyries account for the lion's share of the indicators from unit V. As a result this large unit may be narrowed down to a more restricted zone comprising the coastal parts of southern Finland, the Åland islands, and a southwestward extension including the areas where the Baltic porphyries may crop out. The compound source areas and units are shown in Fig. 5. It must be kept in mind that these groups are adjustable and can be rearranged into other units should the need arise.

Although the eastward-trending increase of north Baltic elements in the coastal areas bordering the south Baltic, at the expense of the southern Swedish indicators (Woldstedt, 1955) supports the proposed approach, a more detailed analysis must be carried out to evaluate this new strategy properly.

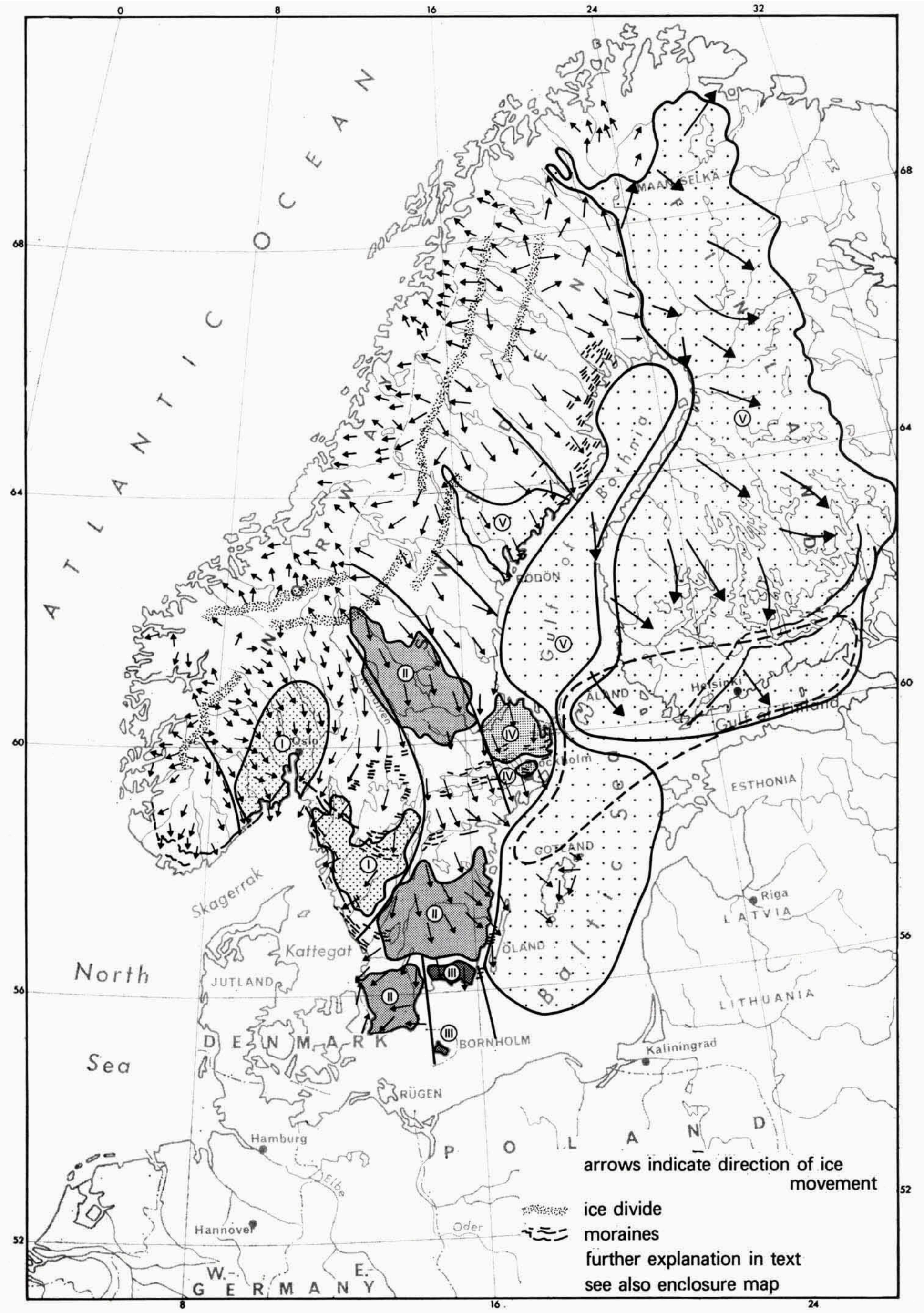

Fig. 5. Source areas chosen according to directions of ice flow. For geographic names, see folding map.

## Rearrangement of indicator counts

Whether or not the Fennoscandinavian flowline pattern should be ascribed to ice movement of an advancing or receding ice sheet, one thing is certain — it belongs to the last glaciation. Therefore, the indicator distribution of that time should be considered first. Hence, diverging current practice, our investigations will be carried out from young to old, and begin with the Weichselian.

### THE WEICHSELIAN

#### *Denmark (Milthers, K.)*

K. Milthers (1942) made an extensive and systematic investigation into the

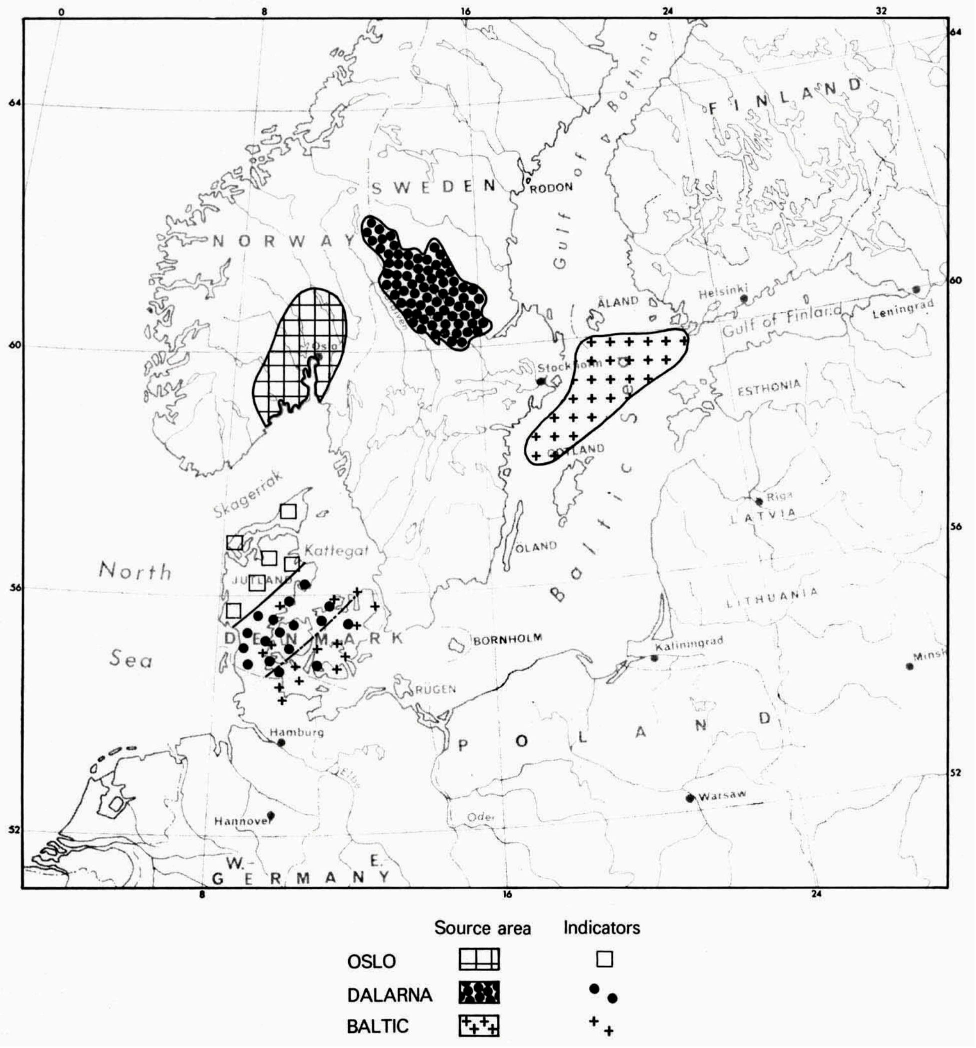

Fig. 6. Indicator distribution of the Weichselian in Denmark. Counts of K. Milthers (1942).

distribution of indicators throughout Denmark. To obtain statistically comparable results, he confined himself to rhomb-, Dalarna, and Baltic porphyries. These are tough and easily recognizable indicators, but in addition their resistance to mechanical wear and disintegration is comparable. Schematic representations of their source areas are given in Fig. 6.

The three-component system allows grouping of the results into three categories, i.e. localities with prevailing Oslo, Dalarna, and Baltic indicators. To characterize these categories on his porphyry distribution map, Milthers indicated the locations of his counts by distinctive symbols. On referring to this map (Table I in Milthers' publication) we find that localities with predominantly Oslo indicators are concentrated in and virtually restricted to the northern half of Jutland. A sharp, slightly curved, southern boundary line can be drawn that separates the area in which rhomb-porphyries predominate from an area characterized by Dalarna porphyries. North of this line, the localities of the counts are indicated on Milthers' distribution map by one symbol only, i.e. the one for the prevailing rhomb-porphyries. South of this line, however, next to the symbol for predominance of Dalarna porphyries, which occurs the most frequently, the symbol for counts with predominance of Baltic porphyries occurs, especially on the present coastlines. Toward the south, this mixed zone in which Dalarna porphyries predominate can be delimited by a more or less straight line, which runs parallel to the northern boundary line through Jutland and from the southeasternmost part of Jutland to the northern end of the Öresund.

Counts in which Baltic prophyries predominate abound south of this line. In some places there is, however, an occasional locality in which Dalarna porphyries predominate.

Figure 6 shows the over-all porphyry distribution pattern in Denmark. A north-east-trending belt in which Dalarna porphyries predominate is flanked on its northern side by a major distribution zone of rhomb-porphyries and on its southern side by an area where the Baltic porphyries predominate. North of the dividing line through Jutland, the rhomb-porphyries average 80%. Between the lines through Jutland and the Danish archipelago the average percentages of the Dalarna, Baltic, and rhomb-porphyries are 50, 40, and 10, respectively. South of the line through the Danish archipelago, the average ratio of Baltic to Dalarna porphyries is 75 : 25, and almost no rhomb-porphyries occur here (less than 1%).

### *An area west of the Oder (Hesemann)*

Hesemann (1932, 1938) made about 70 counts in a tract south of the island of Rügen and west of the Oder. He drew his indicator samples from the following stretches of moraines: Barth-Grimmen (1); Greifswald-Zirchow (2); Gnoien-Rosenthal (3); west Oder end moraine of the Pomeranian Stage (4); Gransee-Rüdnitz (5) (see Fig. 7). For each of these areas I combined the localities and regrouped their indicators according to the twelve newly chosen compound source areas. The resulting percentages per combination of localities are shown in Table 3A.

It is obvious that the indicators from Småland and the Baltic unit are in the majority. This is shown diagrammatically in Fig. 7, where the average shares of these areas in the total indicator association of the 70 counts for the west side of the Oder are shown superimposed on the corresponding source area. The density shading indicates that the indicator distribution is split into two groups, the Småland and Baltic indicators falling in the 41-60% range and those from Dalarna,

Table 3. Rearranged Hesemann counts in the Weichselian glacier area west of the Oder (in percentages).

| Regional combinations of count localities (see Fig. 7) | | A. Source areas | | | | | | | | | Total of unit V | 100 – total of V | B. Source areas without V; the remaining percentages brought up to 100 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | I | II | | III | | IV | | V | | | | I | II | | III | | IV | | |
| | | Oslo<br>Västergötland<br>Bohuslän<br>Dalsland | Småland | Dalarna | Bornholm | Blekinge | Stockholm | Uppland | Ångermanland, Ragunda, Rödön | the Baltic + Gulf of Bothnia | Åland + Finland | Bothnian-Baltic | | Oslo<br>Swedish W. Coast | Småland | Dalarna | Bornholm | Blekinge | Stockholm | Uppland | |
| Barth-Grimmen | 1 | — | 40 | 3 | 3 | | 2 | | 1 | 21 | 30 | 52 | 48 | — | 84 | 6 | 6 | | 4 | | |
| Greifswald-Zirchow | 2 | — | 37 | 3 | 1 | | | 2 | | 10 | 47 | 57 | 43 | — | 86 | 7 | 2 | | 5 | | |
| Gnoien-Rosenthal | 3 | — | 37 | 3 | 1 | | 3 | | | 6 | 50 | 56 | 44 | — | 84 | 7 | 2 | | 7 | | Hesemann, 1932 |
| West Oder end moraine Pomeranian Stage | 4 | — | 68 | 5 | 8 | | 1 | | | 5 | 13 | 18 | 82 | — | 83 | 6 | 10 | | 1 | | |
| Gransee-Rüdnitz | 5 | — | 58 | 8 | 1 | | | 1 | | 5 | 27 | 32 | 68 | — | 85 | 12 | 1 | | 2 | | Hesemann, 1938 |

Uppland, Stockholm, and Bornholm in the 1-5% range. Indicators from the Oslo area and the Swedish west coast are lacking.

Figure 7 visualizes the relationship of the indicator association to the twelve compound source areas, but is not equally suitable for the evaluation of the distribution of the five major units. To overcome this drawback, the data from Table 3A have been incorporated into Fig. 8 as an indicator diagram in which the twelve source areas are combined in the five major units as indicated. The units are set out geographically from west to east. The indicator diagram shows that the individual line-graphs for the various stretches of moraine are comparable. They emphasize the supremacy of the Småland-Dalarna and the Bothnian-Baltic units with respect to the others, which from a quantitative point of view are rather thin.

Since the west side of the Oder is in a direct line with the flowline pattern in Dalarna and Småland but far from the conceivable extension of the flowlines through the Bothnian-Baltic unit, the values for the latter were omitted from Table 3A and the remaining percentages recalculated to total 100. The results shown in Table 3B are represented schematically in Fig. 8. Now the percentages of the Scania, Småland, and Dalarna unit lie in a narrow range of 89 to 97%. As a result, the lines connecting the percentages of this compound source area with those of the Bornholm-Blekinge unit almost coincide.

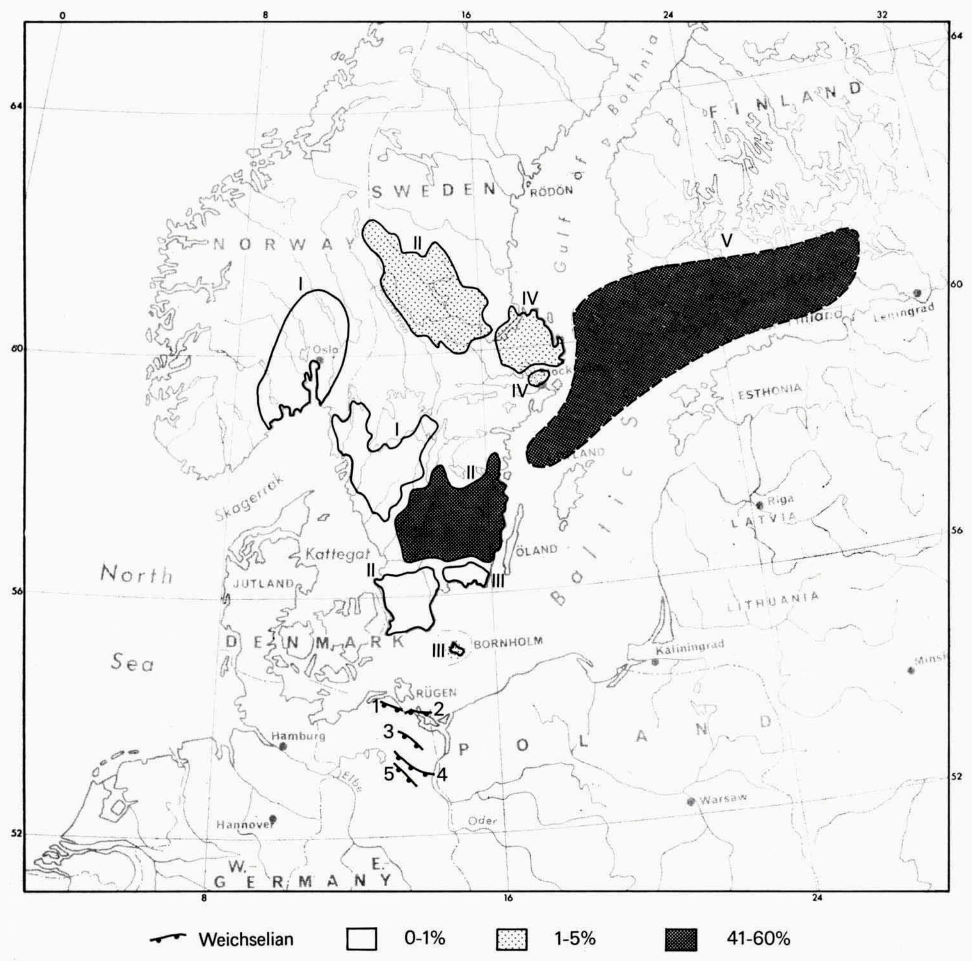

Fig. 7. Schematic representation of indicator associations of the Weichselian of an area west of the Oder. For numbered stretches, see also Table 3.

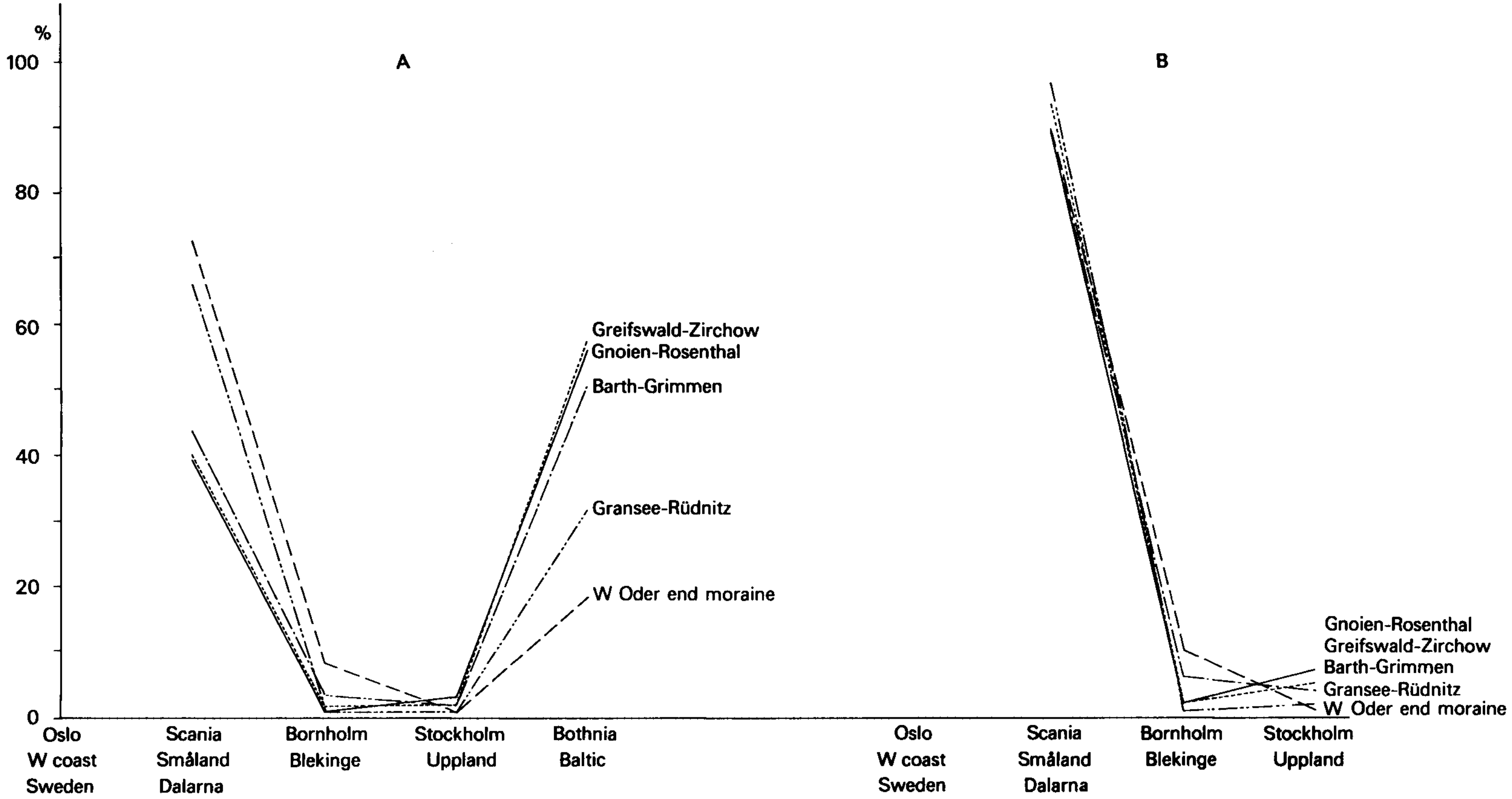

Fig. 8. Indicator diagrams of rearranged Hesemann counts for the Weichselian west of the Oder.

### *An area east of the Oder (Hesemann)*

As can be seen from Fig. 9, the Weichselian area east of the Oder is situated between two lines, one of them a NNE-SSW-bearing line that passes through the Lower Oder, and the other the 16°E meridian. Hesemann (1932, 1937, 1938) made 140 counts in this area, which are subdivided in Table 4A into four regional sections: the N-S trending stretch of the east Oder end moraine of the Pomeranian Stage (6), the eastern section of the W-E track of the Pomeranian end moraine (7), the Züllichauer Bogen (8), and an area between Zossen and Unruhstadt (9).

The percentages in Table 4A clearly reflect the deficiency of the Bornholm indicators as opposed to the demonstrable quantities on the west side of the Oder. This could mean that Bornholm lay in the path of ice movement towards the west side of the Oder but outside the course towards the east side of the river. In accordance with this, Bornholm is tentatively placed to the left of the Småland-Dalarna groups in Table 4, in order to maintain the west-east arrangement of the source areas for a given region.

The values for the Bothnian-Baltic and the Småland groups stand out again,

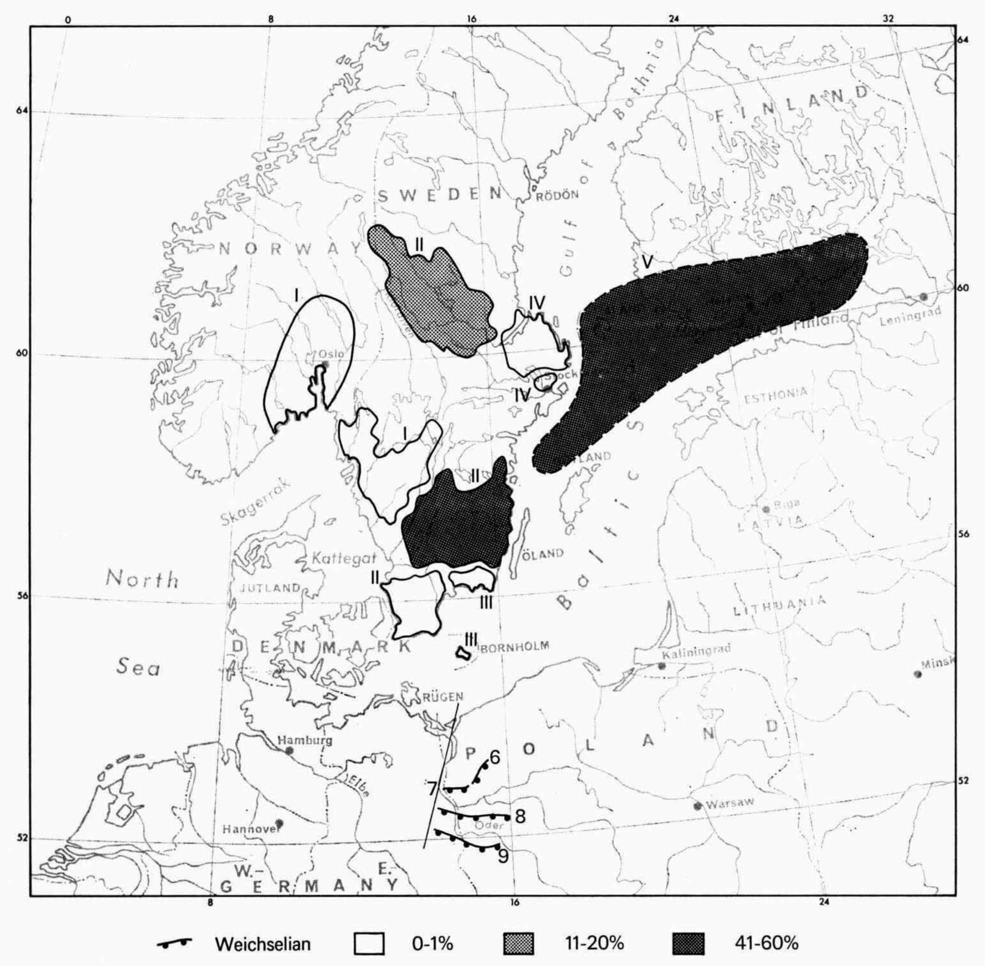

Fig. 9. Distributional features of the Weichselian indicator associations of an area east of the Oder. For numbered stretches, see also Table 4.

Table 4. Rearranged Hesemann counts for the Weichselian glacier area east of the Oder (in percentages).

| Regional combinations of count localities (see Fig. 9) | | A. Source areas | | | | | | | | | Total of unit V | 100 – total of V | B. Source areas without V; the remaining percentages brought up to 100 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | I | III | II | | IV | V | | | | | | I | III | II | | IV | |
| | | Oslo<br>Västergötland<br>Bohuslän<br>Dalsland | Bornholm | Småland | Dalarna | Stockholm<br>Uppland | Ångermanland, Ragunda, Rödön | the Baltic + Gulf of Bothnia | Åland + Finland | | Bothnian-Baltic | | Oslo<br>Swedish W. Coast | Bornholm | Småland | Dalarna | Stockholm<br>Uppland | |
| East Oder end moraine N-S arm Pomeranian Stage | 6 | — | 2 | 26 | 15 | 2 | | 12 | 43 | | 55 | 45 | — | 4 | 58 | 34 | 4 | Hesemann, 1932 |
| East Oder end moraine E-W section Pomeranian Stage | 7 | — | | 40 | 12 | 2 | | 10 | 36 | | 46 | 54 | — | | 74 | 22 | 4 | Hesemann, 1932 |
| Züllichauer Bogen and area to the north as far as the end moraine of the Pomeranian Stage | 8 | — | | 55 | 9 | 1 | | 4 | 31 | | 35 | 65 | — | | 85 | 14 | 1 | Hesemann, 1937 |
| Area south of Züllichauer Bogen between Zossen and Unruhstadt | 9 | — | | 42 | 15 | | 1 | 4 | 38 | | 43 | 57 | — | | 74 | 26 | | Hesemann, 1938 |

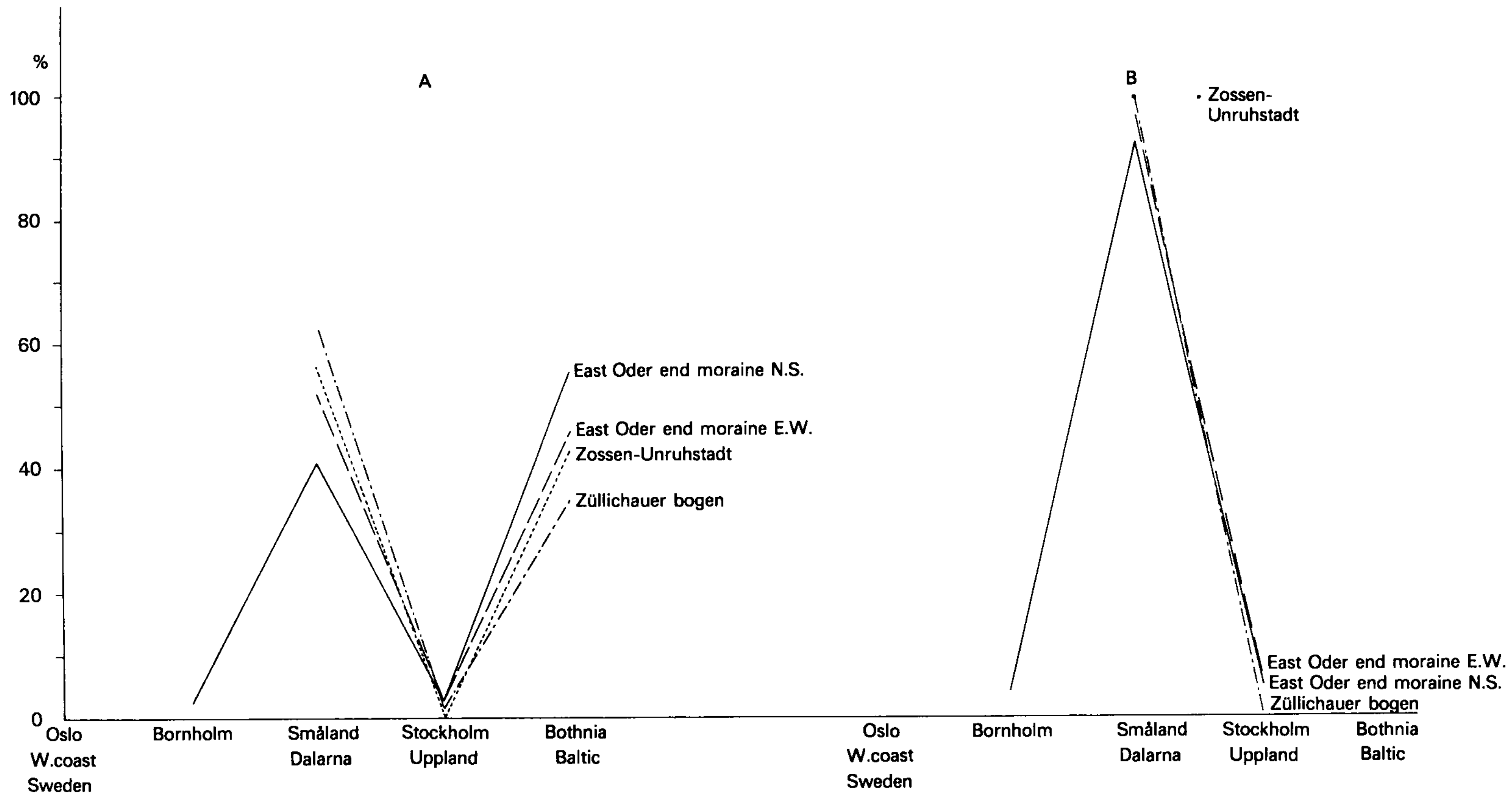

Fig. 10. Indicator diagrams of rearranged Hesemann counts for the Weichselian east of the Oder.

but those for Dalarna are better represented on the east than on the west side of the Oder. These three groups predominate as can be seen from Fig. 9. The indicator diagram (Figure 10), shows that the Småland-Dalarna unit ranges from 41 to 64% and the subdivisions on either side, i.e. the Bornholm and the Uppland-Stockholm groups, do not exceed 2%. At first sight the Småland-Dalarna unit seems on the wane as compared with the corresponding values in the western Oder area, but when the Bothnian-Baltic unit is subtracted and the remaining values recalculated to 100 (Table 4B), the Småland-Dalarna unit on the east side of the Oder outranges the same association on the west side, due to the higher content of Dalarna indicators.

### *Lithuania (Korn and Tarvydas)*

No Hesemann counts have been carried out in Lithuania, but Korn (1895)

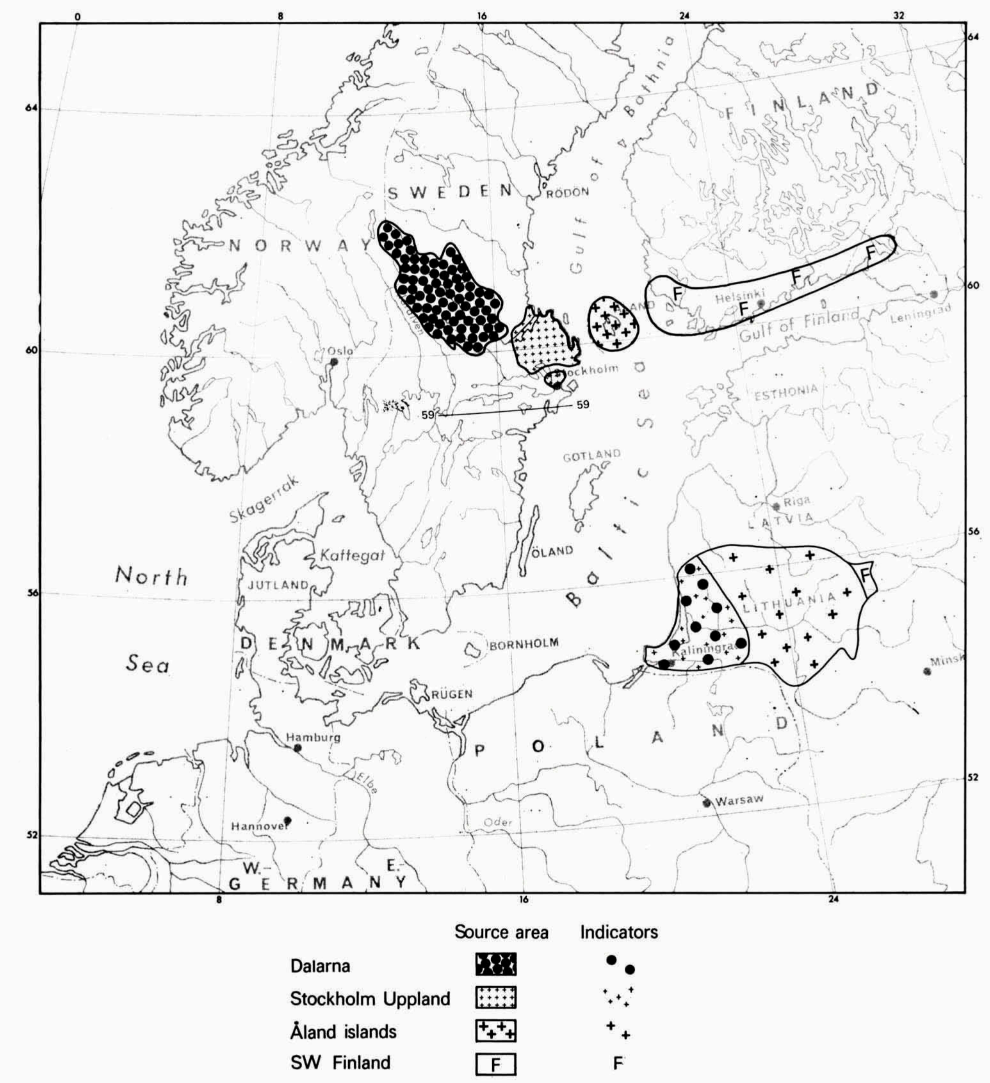

Fig. 11. Lithuania: the tripartite indicator distribution given by Tarvydas (1960).

investigated the erratics in material collected by drilling in Kaliningrad and surroundings. He found that the Swedish indicators in east Prussia appear to originate from areas lying north of the 59° parallei, because the material lacked Scanian basalts and indicators from Småland, but contained indicators from Stockholm, Uppland, Dalarna, Jämtland, Ångermanland, and Norrland. The same tendency is evident from the percentages published by Tarvydas (1967). In the Kaliningrad region the Swedish indicators total 46%, including south Swedish ones accounting on average for 7%, whereas no south Swedish indicators are encountered in the Lithuanian areas east of this region.

An over-all picture of the erratic distribution of the Pomeranian Substage in Lithuania is given by Tarvydas (1960). In west Lithuania, indicators from Sweden and the bed of the Baltic predominate; in the centre, indicators from the Åland islands and SW Finland, and in NE Lithuania, indicators from SW Finland, Vyborg and neighbouring regions of Karelia. His representation of the three areas of distribution is reproduced in Fig. 11.

Thus, two boundary lines divide Lithuania into three indicator zones. One of these lines delimits the dispersal areas of some central-Swedish indicators, including the Dalarna porphyries, as well as the Uppland and Stockholm granites to the east. The other line separates an area in which Åland indicators predominate from a corner in the northeast of Lithuania, where south Finnish indicators prevail.

### *Latvia (Eskola)*

Eskola (1933), who identified 961 erratic boulders from the environs of Riga, came to the conclusion that they originated from southwest Finland, including the Åland islands. He drew his conclusion on the basis of the percentages of the different groups of the total association in relation to their distribution in Finland.

Because his enumeration is not divided into the usual indicator categories, it is not possible to compare his values with those of the Hesemann counts. Fortunately, however, the Åland indicators and the Baltic porphyries are exceptions. Since Eskola also took into account the Dalarna porphyries, which were absent, the three groups of indicators necessary for a Milthers count are available. The result is shown in Table 5. These percentages have been recalculated to give a total of 100 in the last column.

The Baltic porphyries and the Åland rapakivis seem to add up to 45.1%, but in reality this is only a minimum value because, according to Eskola, a large

Table 5. A Milthers count derived from Eskola's tabulation of erratic boulders from Riga.

| | percentages (from Eskola, 1933) | percentages recalculated to 100% | |
|---|---|---|---|
| Dalarna porphyries | — | | — |
| Red Baltic porphyries | 0.7 | | 7.5 |
| Brown Baltic porphyries | 1.5 | | 16.1 |
| Åland rapakivis | 2.0 | 21.5 | 76.4 |
| Rapakivis unspecified | 5.1 | 54.9 | |
| | | | 100.0 |

part of the unspecified rapakivis shown in Table 5 may be ascribed to the Åland islands and the sea bottom south of these islands. If this share (in Table 5 in the column on the right) is greater than 5%, which in view of the low verge is likely, the indicators from the Åland islands and the bottom of the Baltic will prevail in Riga. It therefore seems plausible to assign Riga to the central Lithuanian indicator zone defined by Tarvydas.

## THE SAALIAN

### *The Netherlands (Hesemann counts)*

In 1972, Zandstra reviewed all of the published Hesemann counts from The

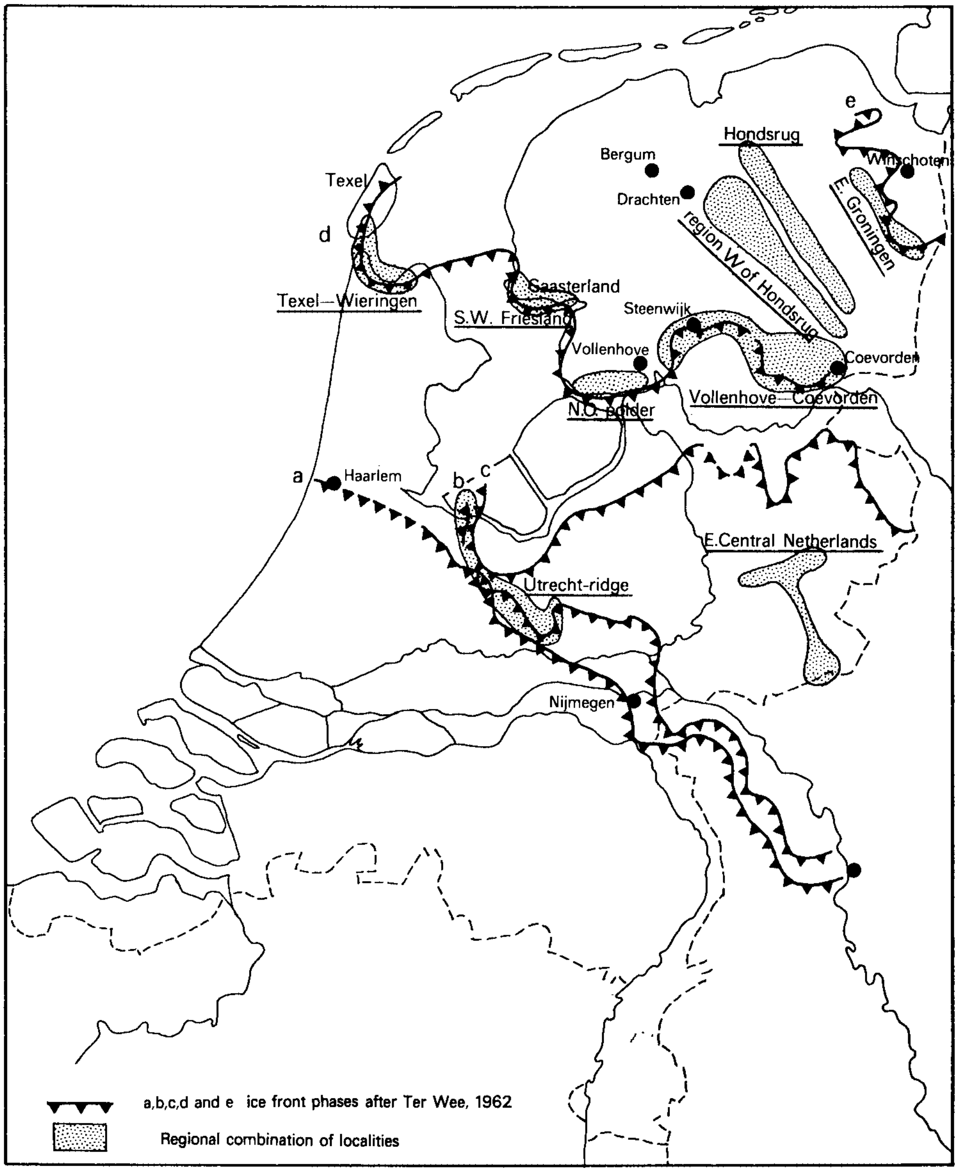

Fig. 12. Regional grouping of the Hesemann counts in The Netherlands.

Netherlands, at that time amounting to 53. To this number we can now add 5 which are counts made by Zandstra (1974), who was also kind enough to place at our disposal the results of two more, which were made in Emmerschans and will be published in 1977.

Thus, there are 60 counts to consider, the localities being placed in nine regional combinations roughly analogous to the subdivision made by Zandstra (1972). The indicators of the lenses of the red boulder clay were assigned to a tenth assemblage. These regions are indicated in Table 6 and Figs. 12 and 13.

In Table 6A (leaving out of account the Hondsrug, the region west of it, and the lenses of red boulder clay, because of their high quantities of Baltic material) the cumulative percentages of the Scania, Småland, and Dalarna groups lie higher than 29%. At the same time, except for the Utrecht ridge where the Bornholm-Blekinge indicators amount to 13%, the shares of this unit do not exceed 10% and those of the Oslo-Swedish west coast 2%.

We should pause here to consider an aspect of the distribution of Oslo indicators that does not find expression in the general mean value just mentioned,

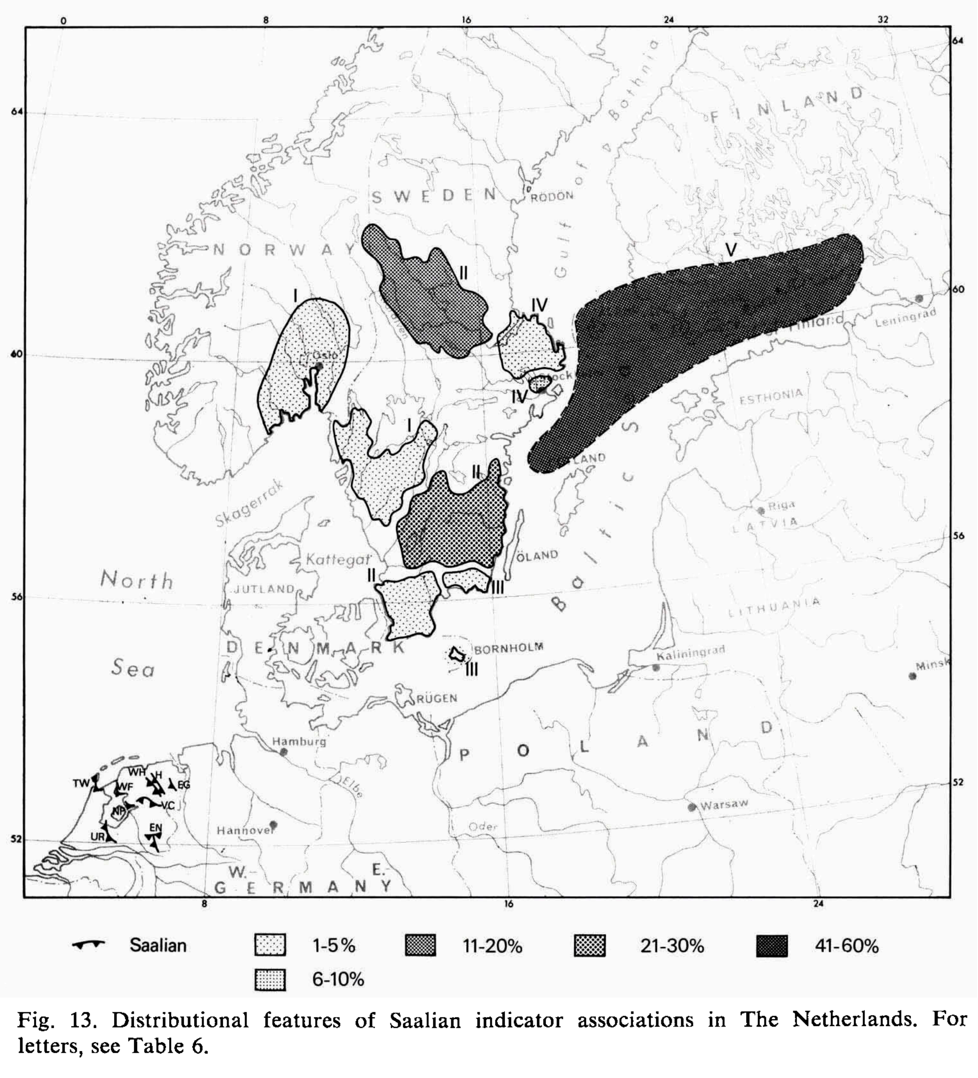

Fig. 13. Distributional features of Saalian indicator associations in The Netherlands. For letters, see Table 6.

Table 6. The Netherlands, percentages of rearranged Hesemann counts.

| Regional combinations of count localities (see Fig. 13) | | A. Source areas | | | | | | | | | | | | Total of unit V | 100 – total of V | B. Source areas without V; the remaining percentages brought up to 100 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | I | | II | | | III | | IV | | V | | | | | I | | II | | | III | | IV | |
| | | Oslo | Västergötland<br>Bohuslän<br>Dalsland | Scania | Småland | Dalarna | Bornholm | Blekinge | Stockholm | Uppland | Ångermanland, Ragunda, Rödön | the Baltic + Gulf of Bothnia | Åland + Finland | Bothnian-Baltic | | Oslo | Västergötland<br>Bohuslän<br>Dalsland | Scania | Småland | Dalarna | Bornholm | Blekinge | Stockholm | Uppland |
| Utrecht ridge | UR | | | 1 | 20 | 8 | 6 | 7 | 13 | 14 | 1 | 24 | 6 | 31 | 69 | | | 1 | 29 | 12 | 9 | 10 | 19 | 20 |
| E Central Netherlands | EN | | | 1 | 34 | 14 | 8 | 2 | 8 | 1 | 3 | 6 | 23 | 32 | 68 | | | 1 | 50 | 21 | 12 | 3 | 12 | 1 |
| *Phase d - ter Wee* | | | | | | | | | | | | | | | | | | | | | | | | |
| Texel-Wieringen | TW | | | 1 | 20 | 10 | 6 | | 5 | 3 | 1 | 6 | 38 | 45 | 55 | | | | 56 | 19 | 11 | | 9 | 5 |
| SW Friesland | WF | | 1 | 1 | 28 | 20 | 4 | | 7 | 2 | 2 | 5 | 30 | 37 | 63 | | 2 | 2 | 44 | 32 | 6 | | 11 | 3 |
| NE Polder (normal boulder clay) | NP | | | | 23 | 15 | 3 | 1 | 12 | 6 | 3 | 6 | 31 | 40 | 60 | | | | 38 | 25 | 5 | 2 | 20 | 10 |
| Stretch Vollenhove-Coevorden | VC | 1 | 1 | 2 | 18 | 18 | 7 | 1 | 5 | 3 | 3 | 5 | 36 | 44 | 56 | 2 | 2 | 4 | 31 | 31 | 13 | 2 | 10 | 5 |
| Arithmetic mean of phase d | | | 1 | 1 | 24 | 16 | 5 | 1 | 7 | 4 | 2 | 6 | 33 | 41 | 59 | | 2 | 2 | 40 | 27 | 8 | 2 | 12 | 7 |
| Region west of Hondsrug | WH | 1 | 1 | 2 | 14 | 12 | 3 | 1 | 4 | 2 | 2 | 8 | 50 | 60 | 40 | 3 | 3 | 5 | 34 | 29 | 8 | 3 | 10 | 5 |
| Hondsrug | H | 1 | 1 | 1 | 12 | 10 | 3 | | 1 | 2 | 2 | 5 | 62 | 69 | 31 | 3 | 3 | 3 | 40 | 32 | 10 | | 3 | 6 |
| E Groningen | EG | 1 | | 2 | 22 | 19 | 3 | | 2 | 4 | | 4 | 43 | 47 | 53 | 2 | | 4 | 41 | 35 | 6 | | 4 | 8 |
| Lenses of red boulder clay | | | | 9 | 4 | | 1 | | 13 | 4 | 3 | 3 | 63 | 69 | 31 | | | | 29 | 13 | | 3 | 42 | 13 |

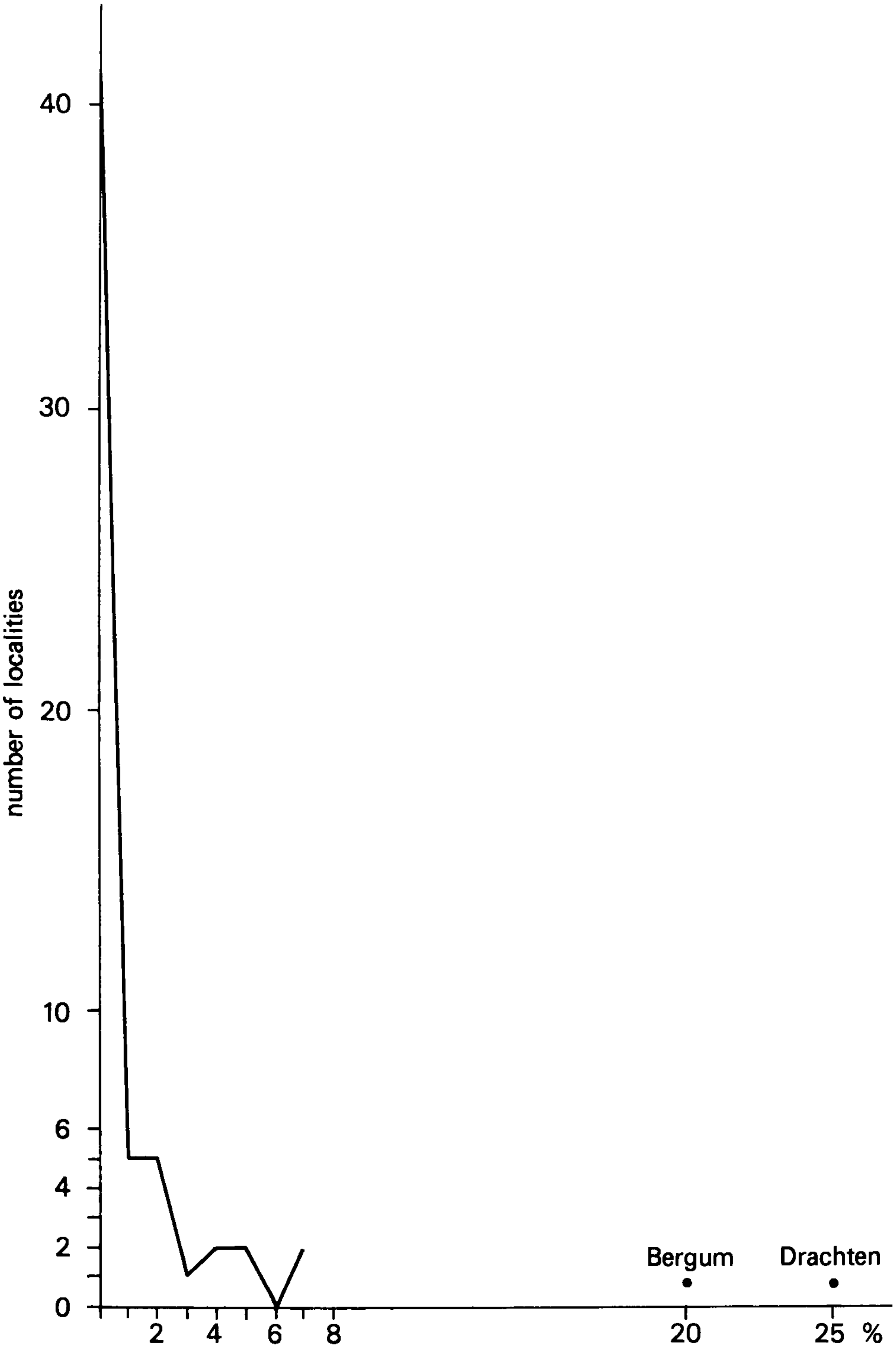

Fig. 14. Distribution of the Oslo indicators in The Netherlands.

i.e. the combined percentage of the Oslo-Swedish west coast unit. The Oslo group itself accounts for one per cent and a half at most (see Table 6A). To show these values more clearly, the grouped frequencies of the percentages of the counts are given by region in Table 7A, from which it can be seen that the regional means range from 0.00 to 1.44%. The percentages above 1.00 are found in the middle of the eastern part of The Netherlands, i.e. in the Hondsrug, the area west of it, and a stretch between Vollenhove and Coevorden. The remaining regional averages are distributed more randomly.

The regional scarcity of the Oslo rocks in The Netherlands is expressed in Table 7B. Since no Oslo indicators have been found in more than 43 of the 60 investigated localities or two-thirds, the mode is 0. The arithmetic mean is 0.83%. There are two exceptions to the homogeneous pattern of indicator associations with hardly any Oslo indicators, but due to the lack of complete counts, these cases could not be included in Table 6. For an association with 20% rhomb-porphyries near Bergum in Friesland, van der Lijn (1941) mentioned the Hesemann number only. These walnut-sized porphyries were found in a ground moraine, which became accessible during the reclamation of some lakes. In spite of the large amount of Oslo rocks, Schuddebeurs (1959) did not count the indicator association brought up by dredging work near Drachten as it underwent an essential change. The larger pieces of stone were separated out and transported by ship to be dumped elsewhere. The smaller fraction that remained had an appreciable content of Oslo indicators, roughly estimated by Schuddebeurs at some 25%.

These two cases have three things in common: the amounts are so divergent from what would be expected that they may be regarded as isolations, they form part of a smaller fraction, and their location is in the middle of the eastern part of The Netherlands where Oslo indicators occur in percentages above 1%. The isolation is brought out clearly by Fig. 14, a graphical representation of the general distribution of the Oslo indicators in The Netherlands. If these exceptional cases are added to the 60 complete counts, the total number of counts becomes 62 and the arithmetical mean percentage of Oslo indicators 1.53, which means that despite the unusually high amounts of Oslo rock around Bergum and Drachten, the average still falls within the 1 to 5% category.

The density shading in Fig. 13 shows five indicator categories in the over-all distribution pattern in The Netherlands. The mean percentages of the indicators fall in the following ranges: Bothnian-Baltic: 41-60%, Småland: 21-30%, Dalarna: 11-20%, Stockholm: 6-10%, and Oslo, the Swedish west coast, Scania, Blekinge, Bornholm, and Uppland: 1-5%. Four groups stand out: the Bothnian-Baltic, the Småland, the Dalarna, and the Stockholm.

In Fig. 15A, the values from Table 6A are represented as an indicator diagram in which the twelve source areas are combined into the five major units indicated on the base line. From west to east, the distributions of the first three units exhibit symmetry, their lines hardly intersecting, as opposed to the more irregular configuration of the two remaining units. The indicator diagram has two peaks, one reflecting the Scania-Småland-Dalarna unit, the other the Bothnian-Baltic. Apart from these peaks, there is the less pronounced Uppland-Stockholm combination.

For Table 6A the Bothnian-Baltic unit was omitted and the remaining percentages recalculated to 100. The results (see Table 6B) are represented schematically in Fig. 15B. In eight of the Dutch regional categories, the distribu-

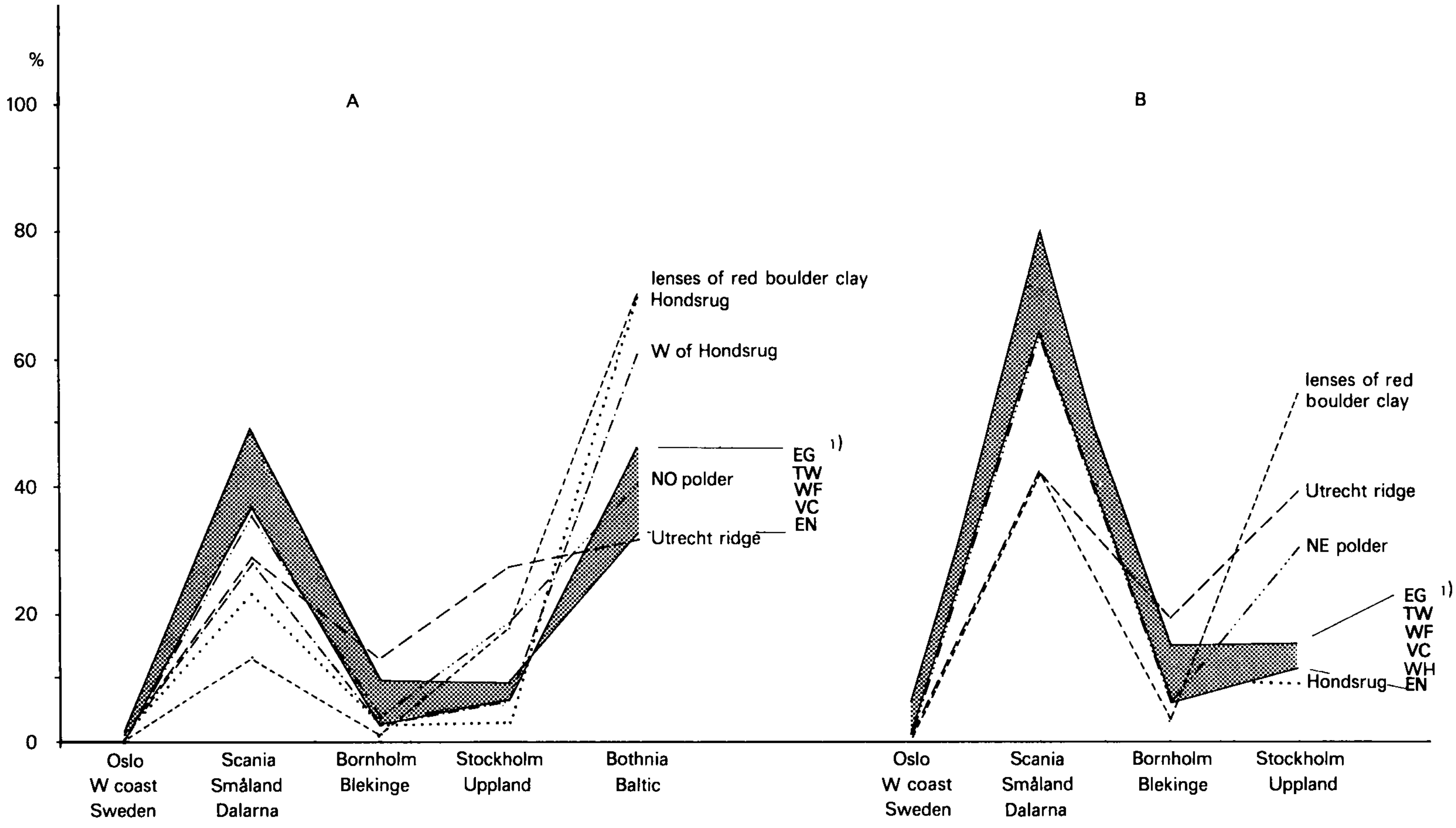

Fig. 15. Indicator diagrams of rearranged Hesemann counts in The Netherlands. [1]) See Table 6.

Table 7. Percentages of Oslo indicators in The Netherlands.

A. Regional frequency distribution

| Regional combinations of localities | frequency × percentage | regional mean in % |
|---|---|---|
| Utrecht ridge | 8 × 0% | |
| | 1 × 7% | 0.78 |
| E Central Netherlands | 3 × 0% | 0.00 |
| Wieringen-Texel | 3 × 0% | |
| | 1 × 3% | 0.75 |
| SW Friesland | 3 × 0% | 0.00 |
| NE Polder, normal boulder clay | 6 × 0% | |
| | 1 × 2% | 0.29 |
| Vollenhove-Coevorden | 5 × 0% | |
| | 2 × 1% | |
| | 1 × 4% | |
| | 1 × 7% | 1.44 |
| Region W. of Hondsrug | 7 × 0% | |
| | 1 × 1% | |
| | 2 × 5% | 1.10 |
| Hondsrug | 5 × 0% | |
| | 1 × 1% | |
| | 4 × 2% | |
| | 1 × 4% | 1.18 |
| E Groningen | 2 × 0% | |
| | 1 × 1% | 0.33 |
| Lenses of red boulder clay | 1 × 0% | 0.00 |

B. General frequency distribution

| | frequency × percentage | totals in % | general mean % |
|---|---|---|---|
| | 43 × 0% | 0 | |
| | 5 × 1% | 5 | |
| | 5 × 2% | 10 | |
| | 1 × 3% | 3 | |
| | 2 × 4% | 8 | |
| | 2 × 5% | 10 | |
| | 2 × 7% | 14 | |
| subtotal | 60 | 50 | 0.83 |
| Bergum | 1 × 20% | 20 | |
| Drachten | 1 × 25% | 25 | |
| total | 62 | 95 | 1.53 |

tions of the first three Scandinavian units bear a stronger resemblance to each other than is the case in the initial indicator diagram. They comprise more than 60% of the Scania-Småland-Dalarna unit, whereas the Oslo-Swedish west coast and the Bornholm-Blekinge units do not exceed the 10 and 15% limit.

The indicator associations of the two remaining categories, i.e., the Utrecht ridge and the lenses of red boulder clay, also seem to correspond to each other, as suggested by the striking parity of the percentages of the Scania-Småland-Dalarna unit and the higher amount of Uppland-Stockholm granites relative to the other regional categories. This is in accordance with the correspondence of the gravel association of the 3.5 mm fraction of boulder clays in the environs of the Utrecht ridge and Lunteren with that of the decalcified clay of red boulder clay lenses in the Noordoost Polder (Overweel & Zandstra, 1967).

### *The area between the Rhine and the Elbe (Hesemann)*

In an area adjoining The Netherlands and lying between the Rhine and the Elbe, Hesemann (1939a) performed 71 counts which can be geographically subdivided

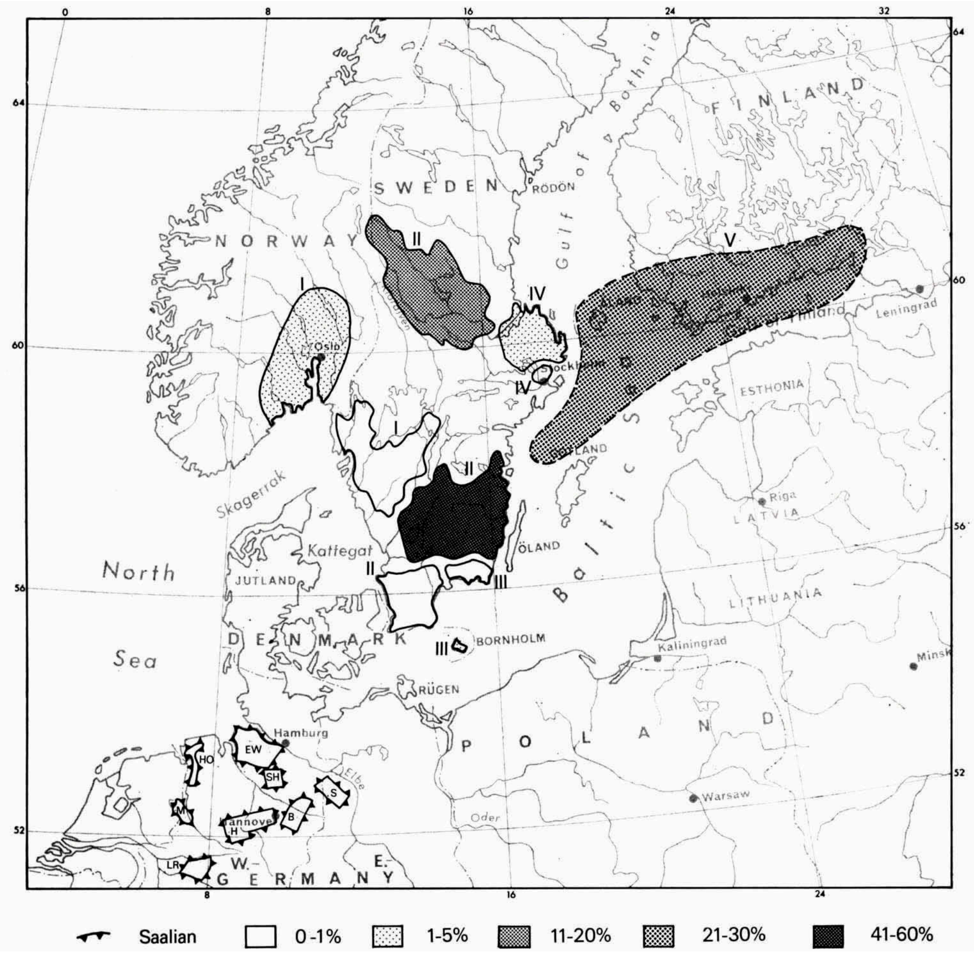

Fig. 16. Indicator distribution of the Saalian between the Rhine and the Elbe. For letters, see Table 8.

as follows: a stretch south of Hamburg (SH), and area indicated in Fig. 16 as Münsterland (M), the drainage areas of the Lippe and the Ruhr (LR), and regions encompassing Hannover (H), Braunschweig (B), and Stendal (S). Schuddebeurs (1959, 1967) made 10 counts in the Hümmling and in Ost Friesland (HO in Fig. 16). The Saalian erratic boulder assemblages have been rearranged and averaged in the same way as for the Dutch counts shown in Table 8A and Fig. 17. The counts in the area south of Hamburg and in the Stendal region belong to the Warthe Stage. Figure 16 shows that in the over-all distribution of the counts in this area, the indicators from Småland, the Bothnian-Baltic, and Dalarna again predominate. As usual, the indicator diagram (Fig. 17) is double-peaked, but this time the Småland-Dalarna unit predominates over the Baltic-Bothnian unit. Except for the large amount of Oslo indicators, the Hümmling-Ost Friesland curve is consistent with the other diagrams.

If the Bothnian-Baltic unit is excluded and the remaining percentages recalculated, so they again amount to 100, the sum total of the Scania-Småland-Dalarna unit ranges from 97 to 100% in six of the eight regions. Except for the Hümmling and Ost Friesland, the recalculated percentages of the Småland granites between the Rhine and the Elbe range from 59 to 90, lying above 70 in five of the eight regional categories (see Table 8B). The large amount of Oslo rocks in the Hümmling and Ost Friesland stands out; these rocks even reach 50% at Werpeloh, Fresenburg, and Langefeld. Schuddebeurs (1959, 1967) pointed out that the exceptional abundance of these indicators belongs to part of a fraction (smaller than some 8 to 10 cm) of deposits underlying the boulder clay.

Although Marczinski (1968) did not specify the individual indicators in his counts made in an area between the Lower Elbe and the Lower Weser (EW in Fig. 16), he classed them in some of the same source area groups and units as are used here. He denoted the Bothnian-Baltic unit as rapakivi rocks, the Stockholm-Uppland unit as black-white granites, the Småland group as blue quartz granites and porphyries, the Dalarna group as Dalarna porphyries, and the Oslo group as rhomb-porphyries.

Notwithstanding the fact that the remaining source areas were not taken into consideration, Marczinski's values are comparable to the Hesemann counts in nearby areas. Marczinski subdivided the Saalian of the area he investigated into a series of three strata. His percentages contained in the total for crystalline erratics, have been recalculated to total 100% for each stratum in Table 8. The resulting values with their relatively small share of indicators of the Bothnian-Baltic unit approach those of the Warthe Stage south of Hamburg and of the Saalian of the Hannover area. Compared to the other counts for the area between the Rhine and the Elbe, the percentages of the Småland-Dalarna groups predominate here too, but not to the same degree. The decrease might result from the suppletory copresence of indicators of the Stockholm-Uppland unit, which are absent in the Hesemann counts.

The inclusion of this unit in the counts made by Marczinski (1968) facilitates comparison with the Dutch association. If the Bothnian-Baltic unit is left out of account, the percentages in both areas are approximately the same except for the Småland group (compare Table 8 with Table 6).

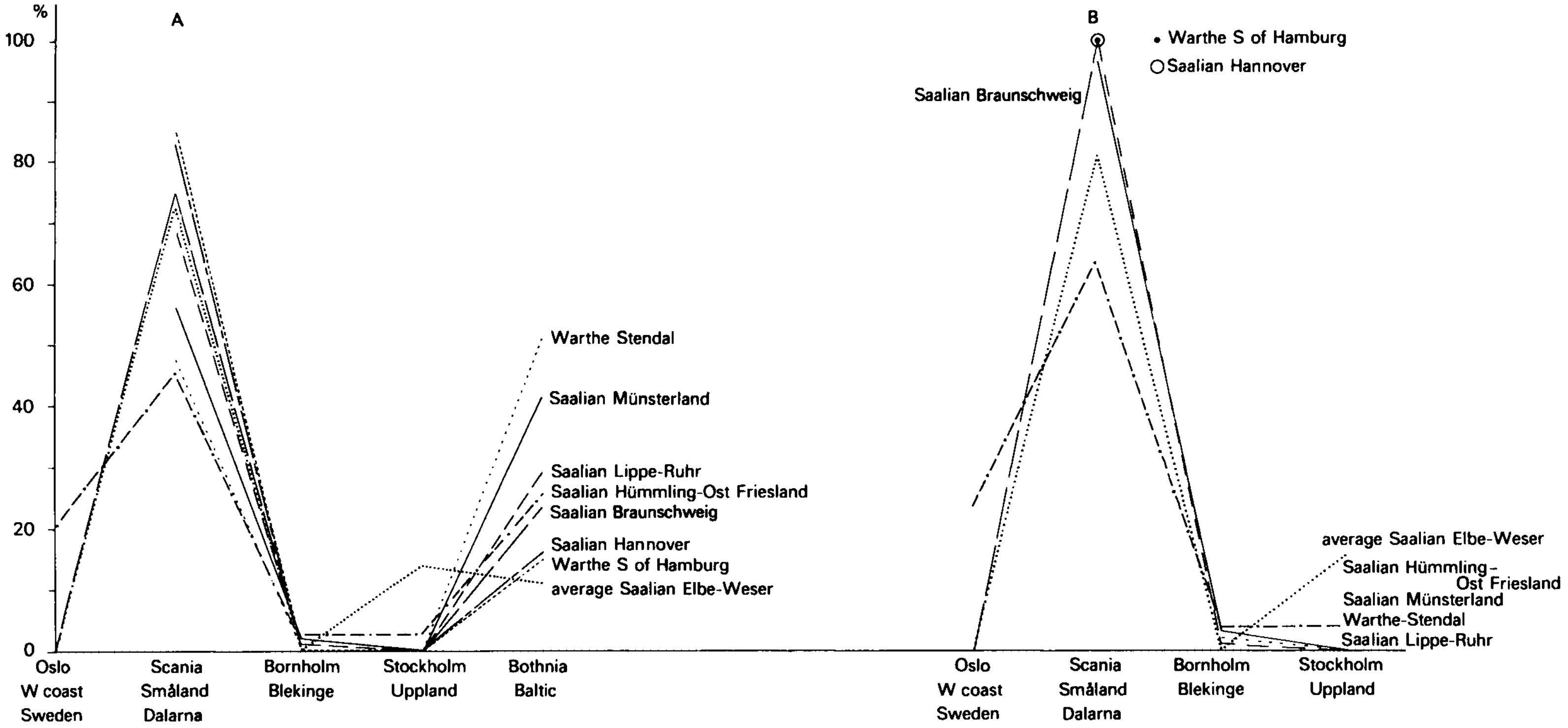

Fig. 17. Indicator diagrams of rearranged Hesemann and Marczinski counts of Saalian erratic associations between the Rhine and the Elbe.

Table 8. Rearranged Hesemann counts in the area between the Rhine and the Elbe (in percentages). Marczinski counts in the area beween the Lower Elbe and the Lower Weser (in percentages).

| Regional combinations of count localities (see Fig. 16) | | A. Source areas | | | | | | | | | | | | Total of unit V | 100 – total of V | B. Source areas without V; the remaining percentages brought up to 100 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | I | | II | | | III | | IV | | V | | | | | I | | II | | | III | | IV | | |
| | | Oslo | Västergötland Bohuslän Dalsland | Scania | Småland | Dalarna | Bornholm | Blekinge | Stockholm | Uppland | Ångermanland, Ragunda, Rödön | the Baltic + Gulf of Bothnia | Åland + Finland | Bothnian-Baltic | | Oslo | Swedish W. Coast | Scania | Småland | Dalarna | Bornholm | Blekinge | Stockholm | Uppland | |
| Warthe Stage south of Hamburg | SH | | | | 71 | 14 | | | | | | 2 | 13 | 15 | 85 | | | | 83 | 17 | | | | | |
| Saalian Münsterland | M | | | 2 | 49 | 5 | 2 | | | | 2 | 2 | 38 | 42 | 58 | | | 3 | 85 | 9 | 3 | | | | |
| Saalian Lippe-Ruhr | LR | | | | 63 | 6 | 1 | | | | | 4 | 26 | 30 | 70 | | | | 90 | 9 | 1 | | | | |
| Saalian Hannover area | H | | | | 72 | 12 | | | | | 1 | 3 | 12 | 16 | 84 | | | | 86 | 14 | | | | | Hesemann, 1939 a |
| Saalian Braunschweig | B | 1 | | | 56 | 19 | | | | | | 1 | 23 | 24 | 76 | | 1 | | 74 | 25 | | | | | |
| Warthe Stage Stendal area | S | | | | 29 | 19 | 1 | | | | | 8 | 43 | 51 | 49 | | | | 59 | 39 | 2 | | | | |
| Saalian Hümmling-Ost Friesland | HO | 20 | | 3 | 24 | 19 | 3 | | 3 | | 1 | 2 | 24 | 27 | 73 | | 24 | 4 | 34 | 26 | 4 | | 4 | 1 | Schuddebeurs, 1959, 1967 |
| Saalian Elbe-Weser: | EW | | | | | | | | | | | | | | | | | | | | | | | | |
| stratum 3 | | 1 | | | 59 | 18 | | | | 9 | | | 13 | 13 | 87 | | 2 | | 68 | 20 | | | | 10 | |
| stratum 2 | | 4 | | | 43 | 21 | | | | 21 | | | 11 | 11 | 89 | | 4 | | 48 | 24 | | | | 24 | |
| stratum 1 | | 1 | | | 58 | 21 | | | | 12 | | | 8 | 8 | 92 | | 1 | | 63 | 23 | | | | 13 | Marczinski, 1968 |
| — | | — | | | — | — | | | | — | | | — | — | — | | — | | — | — | | | | — | |
| Average | | 2 | | | 53 | 20 | | | | 14 | | | 11 | 11 | 89 | | 2 | | 60 | 22 | | | | 16 | |

### *Poland and White Russia - Belo Russkaya - (Milthers & Milthers)*

Except for those in the eastern Oder area, and those made by Ladwig (1938), there are no Hesemann counts for Poland, but fortunately V. and K. Milthers (1938) performed a systematic study based on porphyry counts of Saalian deposits in an area roughly circumscribed by latitudes 50° and 54° N and meridians 19° and 29° E of Greenwich. The larger, western part of this area lies in Poland, the remainder in White Russia (see Fig. 18). These investigators divided their study area into 6 regions, which I have adjusted slightly. Figure 18 shows not 6 but 5 regions, which are numbered I to V from west to east. The recalculated percentages of the erratic associations of these regions are given in Table 9, where the source areas are shown in the same sequence.

Strictly speaking, there are only two relevant source areas: the Baltic-Bothnian and Dalarna. The Baltic-Bothnian group is represented here by the brown and red Baltic porphyries and the Åland indicators. Since the variance of the Baltic porphyries (i.e. the sum of the brown and red porphyries) is limited to a narrow range of 2% (between 7 and 9%), marked differences in the Baltic-Bothnian must be due to variations of the Åland indicator percentages. Figure 18 shows an

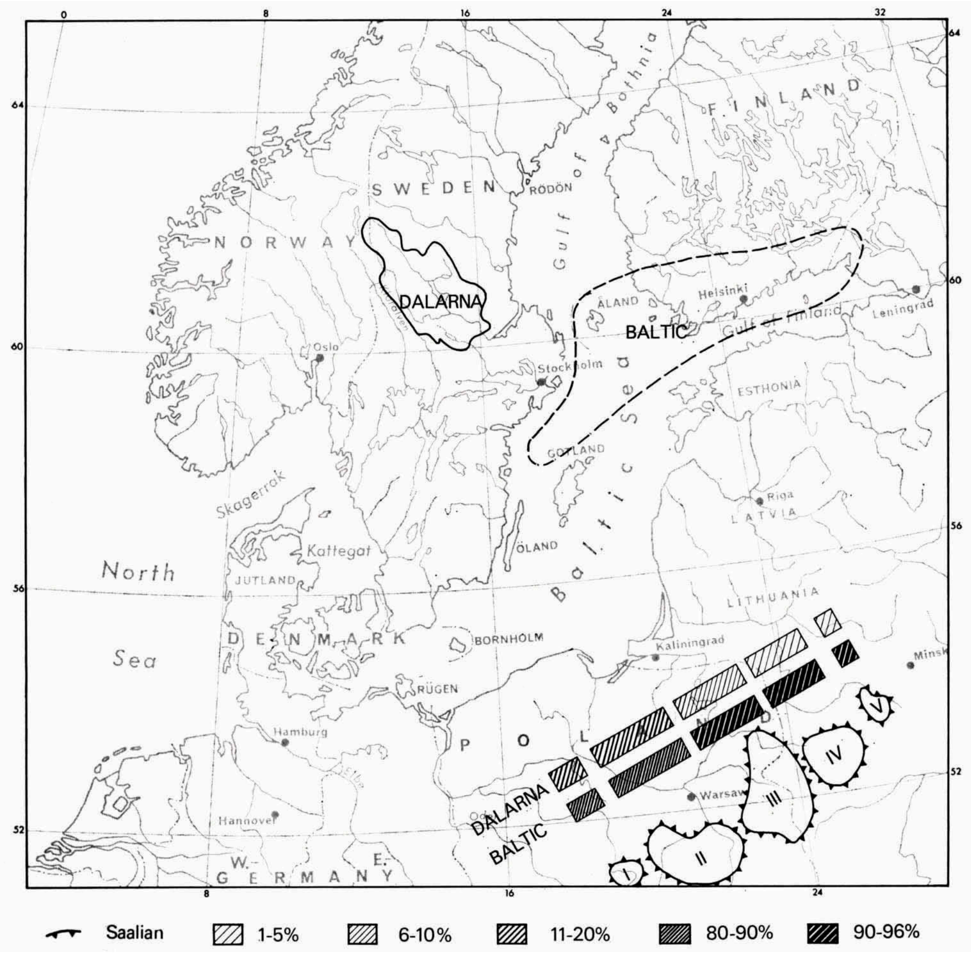

Fig. 18. The eastward trend of the Saalian indicator distribution in Poland and White Russia. For Roman numerals, see Table 9.

Table 9. Milthers counts in Poland and White Russia (in percentages).

| | Regional combinations of count localities | Indicator type | | | |
|---|---|---|---|---|---|
| | | Dalarna porphyries | Brown Baltic porphyries | Red Baltic porphyries | Åland indicators |
| I | Area southwest of Lodz | 20 | 4 | 3 | 73 |
| II | Area south of Warsaw | 13 | 5 | 4 | 78 |
| III | Siedlce area | 7 | 3 | 6 | 84 |
| IV | Area south of Grodno | 4 | 1 | 6 | 89 |
| V | Area south of Vilna | 4 | 1 | 7 | 88 |

increase of the Baltic indicators and a decrease of the Dalarna indicators, both from west to east, the latter dropping from 20 to 4%. Compared with the 15 to 60% Baltic indicators in the Hesemann counts to the west of this area, the 80% in region I, south of Lodz, is certainly higher. From there to region IV, the percentage of the Baltic indicators rises from 80 to 96%.

In Milthers' method of boulder counting, only the porphyries are used. The percentages in Table 9 would have been much lower, favouring other groups, if the remainder of the indicators had been included as well. The interesting question is, which of the other major groups of indicators besides these porphyries occur in Poland? Kreutz and Glowinska (1932) offer an answer in their statement that the indicators from the Stockholm and Uppland areas are second in importance, after those from Finland.

## Resulting distribution pattern of indicators

### CORRESPONDENCE BETWEEN THE WEICHSELIAN AND THE SAALIAN DISTRIBUTIONS

Of the twelve basic source areas from which we started, four stand out in the indicator distribution on the south side of the circum-Baltic. This is especially clear from the Hesemann counts where, in contrast with the method of Milthers, there is no restriction on the choice of the species of crystalline indicators.

Thus our new approach reveals four main groups of indicators, i.e. the groups of Oslo, Dalarna, Småland, and the Baltic. In the regional distribution of the Weichselian, which is shown in Fig. 19, the predominance of the Oslo group

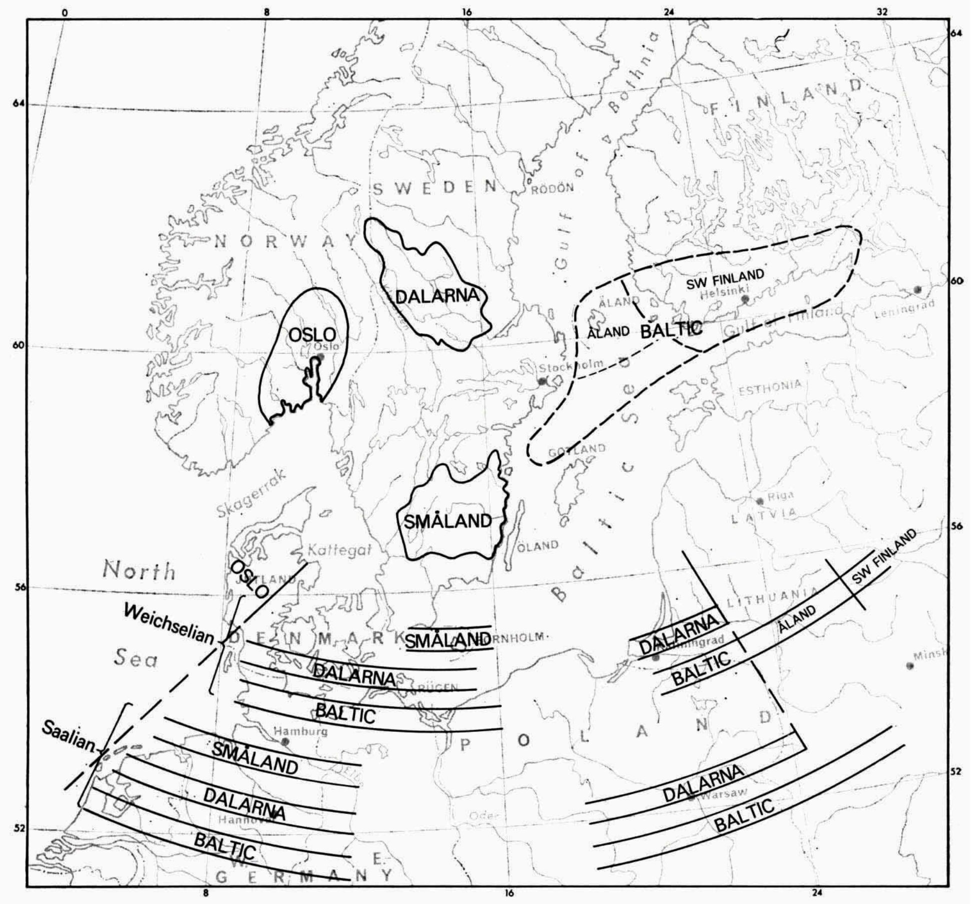

Fig. 19. Distribution of predominant indicator groups of the Saalian and the Weichselian.

is restricted to the northwestern half of Jutland. On its east side lies an area where Dalarna and Baltic indicators prevail. The main dispersal of the Dalarna indicators extends to the dividing line in Lithuania separating the zone of central Swedish indicators from the zone of the Åland indicators. The distribution of the Baltic indicators, however, continues further eastward, although those from the Åland islands predominate in the central part of Lithuania and those from southern Finland in the northeastern part.

Although in almost every location in north Jutland where a Milthers' count has been made, the rhomb-porphyry content amounts to 70 to 80% or even more, there are some instances where Baltic or Dalarna porphyries predominate. The transition between the zone of the outranking rhomb-porphyries and the zone characterized by the Dalarna-Baltic groups is abrupt. The Oslo rocks lie within the 0 to 25% range comprising most of the cases of indicator associations in a 100 km belt on the southern side of the boundary line. With a few exceptions, the Oslo indicators do not exceed 50% here, which means that in almost every locality in this belt the combined Dalarna-Baltic components are in the majority. Farther to the southeast, the rhomb-porphyry percentages decrease to 0. In short, the area with mainly Oslo rocks in north Jutland is dotted with some localities where Dalarna or Baltic porphyries predominate, particularly close to the boundary line. Conversely, the homogeneous area where the Dalarna-Baltic combination predominates shows some specks with predominantly Oslo indicators.

The zone of the Weichselian distribution characterized by Dalarna and Baltic indicators shows a gap between the western border of Lithuania and 16° longitude where no counts have been performed. Further westward, on both the east and west sides of the Oder, Småland indicators show up in addition to the indicators from the Baltic and Dalarna.

The same three main groups stand out in the Saalian distribution of The Netherlands and in the area between the Rhine and the Elbe. No counts have been made in the Saalian deposits between the Elbe and the Warthe, but east of the Warthe the association of Dalarna and Baltic porphyries is encountered again in the area investigated by Milthers & Milthers (1938). As can be seen from Table 8, the Dalarna porphyries decrease here from west to east.

To compare the Saalian with the Weichselian we return to the delimitation of the Dalarna indicators of the Weichselian to the east. This lateral limit is the western boundary of the central Lithuanian zone. Where this line is extended southwards, it intersects the Saalian deposits south of Grodno, roughly between the regions III and IV (see Fig. 18). From region III to region IV the Dalarna porphyries decrease from 7 to 4%. The latter percentage, which is in fact a Dalarna-Baltic porphyry quotient, would have been lower if it had included other kinds of indicators as well, say the Stockholm and Uppland granites. The reduction to less than 4% suggests that here we have reached the margin of the main Saalian distribution of the Dalarna porphyries. If this is really the case, the horizontal extension to the east of the Dalarna indicators of the Saalian would coincide with that of the Weichselian.

To the west, the dispersal of the Dalarna porphyries of the Weichselian is distinctly bounded by the area of predominance of rhomb-porphyries in the northwestern part of Jutland. Figure 19 shows that the southward extension of this boundary line of the Weichselian distribution pattern is located in the North Sea, west of The Netherlands. This location is not only consistent with the predominance of the Dalarna-Baltic combination in The Netherlands and the western part of Germany but also with the absence of a coherent group of localities with more than 70% rhomb-porphyries. Just as in the Weichselian of the Danish archipelago, the area characterized by the Dalarna-Baltic combination of the Saalian is dotted by some localities in which Oslo indicators predominate, i.e. near Drachten in The Netherlands and near Werpeloh, Fresenburg, and Langefeld in the northwestern part of Germany.

In general, therefore, the distribution patterns of the Weichselian and the Saalian are similar. In the first place, the width of the dispersal area of the Dalarna porphyries of the Weichselian, although not yet completely investigated, is distinctly delimited to the west and the east. The southward extensions of the boundary lines seem to comprise the Saalian distribution of the Dalarna indicators as well. This holds more clearly for the east than for the west side, where the extended boundary line is in the North Sea.

Secondly, in both the Weichselian and the Saalian, the Dalarna indicators are accompanied as far as their eastern limits, by the Baltic suit, which in both stages extends beyond the Dalarna porphyries farther to the east.

Thirdly, where Hesemann counts have been made the Småland indicators stand out in the Weichselian and the Saalian alike. Topographically, the Saalian distribution of the Småland, Dalarna, and Baltic groups in The Netherlands and in the area between the Rhine and the Elbe seems to link up with the Weichselian west and east of the Oder. There seems to be a continuous distribution of these groups roughly from the North Sea as far as 16° longitude, but since no Hesemann counts have been performed either in Denmark or in Poland and Russia, we are still in the dark as to the actual dispersal of these indicators.

### THE DOUBLE-PEAKED CHARACTER OF THE INDICATOR DIAGRAMS

Unlike the counts of Milthers, which comprise only a limited number of indicator categories, the Hesemann method includes a wide selection of the crystalline indicators and therefore lends itself to the compilation of indicator diagrams.

These diagrams are distinctly double-peaked. Irrespective of whether they are from the Saalian or Weichselian, one peak reflects the Scania-Småland-Dalarna unit and the other the Bothnian-Baltic. Although the indicator diagrams are on the whole similar, there are some differences in detail which deserve further attention.

The Weichselian distribution of Oslo indicators in Denmark drops from

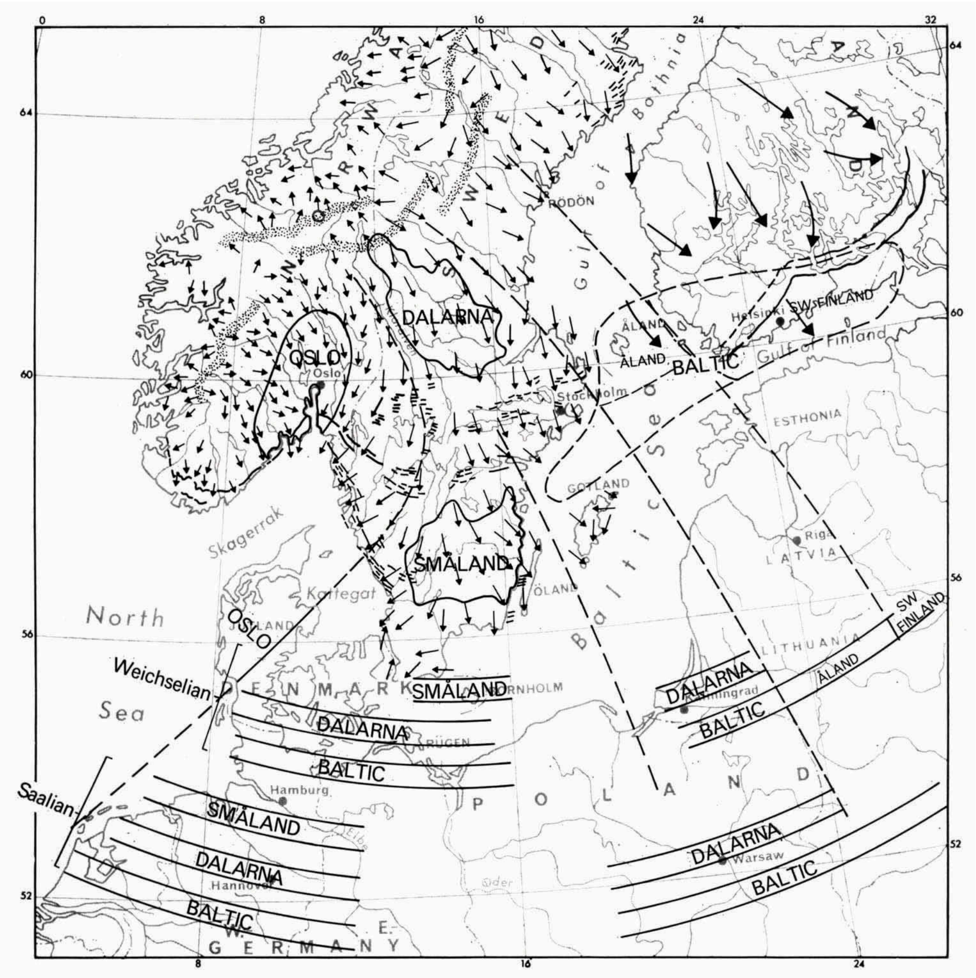

Fig. 20. Indicator distribution in relation to flowline pattern.

80% in Jutland to less than 1% in the eastern islands of the Danish archipelago. This tendency seems to persist, because hardly any Oslo indicators have been found on the west or the east side of the Oder. In the Saalian the distribution of Oslo indicators in The Netherlands is comparable with that in the area between the Rhine and the Elbe.

When the percentages of the Bothnian-Baltic unit are omitted and the remaining values recalculated to total 100, the percentage of the Scania-Småland-Dalarna unit ranges from 42 to 84 in The Netherlands, from 97 to 100 in the area between the Rhine and the Elbe, from 89 to 97 on the west side of the Oder, and from 92 to 100 on the east side. The wide range of the recalculated values for The Netherlands contrasts with the narrow range of the percentages in the other areas. Since the area between the Rhine and the Elbe refers, as in The Netherlands, to the Saalian, the nature of the contrast cannot be stratigraphic.

## THE WEICHSELIAN DISTRIBUTION AND FLOWLINE PATTERN IN FENNOSCANDIA

When source areas are delimited by a line running parallel to the ice movement, the highest densities of their indicators will be found at the corresponding sides of the extension of that line. Figure 20 shows the boundary line in Jutland separating the area with predominantly rhomb-porphyries on its west side from an area on its east side characterized by Dalarna porphyries. When the northeastward extension of this dividing line is adjusted to the course of the striae, the provenance of the Oslo rocks will lie to the west and the line will pass between this source and that of the Dalarna indicators. Similarly, another boundary, i.e. delimiting the areas of the central-Swedish and Åland indicators in Lithuania, can be extended across the Baltic. On reaching the Swedish coast, the extension is drawn parallel to the general trend of the striae. The Åland islands then lie on one side of the line and the provenance of the Dalarna indicators on the other. The area with predominantly Åland indicators in central Lithuania is separated from the area in which south-Finnish indicators predominate. When the parting is extended northeastwards, it will pass between the Åland islands and the southwest coast of Finland.

Thus, the dividing lines of the Weichselian indicator distribution pattern link up with equivalent features in the flowline pattern. The over-all structure shows a central more or less fan-shaped part encompassing the provenance and the main distribution range of the Dalarna indicators. This fan-like area is flanked on the west by the source area and main distribution area of Oslo clasts. On the east, it is true, it is flanked by a broad strip covering the Åland islands and the central Lithuanian zone in which Åland indicators predominate, but these erratics, together with others from the Baltic, are also in evidence in the major distribution zone of the Dalarna indicators.

In addition, the major distribution zone of Dalarna indicators includes representatives of the Småland group. The lateral extension of the spread of this group is not yet known, but the distribution of the Småland indicators, like their provenance, seems to fall within the fan-shaped range of the Dalarna clan. The western margin of the Dalarna suit approaches both of the source areas, but the eastern margin, although still close to the provenance of the Dalarna porphyries, lies far from that of the Småland indicators. Therefore, to approximate the lateral margin of the distribution of the Småland group on the east, an additional line has to be drawn parallel to the trend of the striae and close to the bedrock source. Passing through the Baltic, the extension of this line crosses the coast in the Gulf of Gdansk, west of Kaliningrad, and then lies just in the gap in the Weichselian distribution pattern where no counts have been performed. If the extension of this line really denotes the roughly drawn easternmost limit of the major distribution zone of the Småland indicators, these specimens should be scarce farther to the east. This is consistent with the counts done by Korn (1895) because he found no indicators from Småland in the surroundings of Kaliningrad. Moreover, Tarvydas (1967) found only 7% south-Swedish indicators in the Kaliningrad region and no indicators from southern Sweden in the Lithuanian areas east of that region.

So far, the double peak of the indicator diagrams seems to recur in the over-all distribution pattern, because the latter falls into two parts. One part conforms to the Fennoscandinavian ice flow pattern. The other, which does not, is a unit of Baltic origin. At the circum-Baltic south and southwest sides the divergence of the Baltic constituent from the flowline pattern is distinct, but toward the southeast the component parts of the Baltic indicator association of the Weichselian conform to the directions of ice flow in central Sweden and southern Finland.

## CORRESPONDING DIRECTIONS OF ICE MOVEMENT IN THE WEICHSELIAN AND THE SAALIAN

In the preceding section the relationship between the Weichselian distribution and the flowline pattern emerged. But earlier in this chapter we saw that the distribution of indicators of the Weichselian and the Saalian correspond. The same groups stand out in the Saalian distribution as in the Weichselian. The indicator association of the Saalian is also bipartite, one half being characterized by Baltic and the other by Småland and Dalarna indicators. Furthermore on p. 45 we saw that the southward extensions of the boundary lines of the distribution zone of the Dalarna porphyries of the Weichselian seem, in spite of the gap where no counts have been performed, to include this equivalent of the Saalian as well. Since the source areas of the Dalarna and Småland indicators lie in the same sector of the flowline pattern, the erratics from Småland are also included in the distribution zone of the Dalarna porphyries, in both the Weichselian and the Saalian (see Fig. 20). These source areas can, however, be separated by a line running perpendicular to the former direction of ice flow. Because, as shown above, provenances enclosed by lines lying at right angles to the direction of the ice flow may be stratigraphically useful, the ratio between the Småland and Dalarna indicators could have stratigraphic value.

Here, at the end of the first part of this paper, some conclusions may be drawn. Firstly, because the distributions of Weichselian and Saalian indicators are not contradictory, there is no reason to assume that in a general sense the directions of ice movement differed in these stages. This is consistent with the permanence of the mean directions of ice movement for the Saalian and the Weichselian inferred from Lüttig's TGZ estimations (see p. 12), and also with the results of the investigation of Veenstra (1963), who studied the Bryozoa enclosed in various boulder clays from The Netherlands and other regions, and came to the conclusion that in both glacials the main direction of the ice in NW Germany was the same, 'as it must have passed the Danish archipelago to pick up similar microfaunal assemblages'.

Secondly, reference to the Fennoscandinavian flowline pattern shows the importance of the Småland indicators for a comprehensive picture of the distribution pattern. Furthermore, the general approach shows where no counts have been performed.

Thirdly, the indicator distribution on the south side of the circum-Baltic area has two main components. One of these, whose regional distribution harmonizes with the flowline pattern, will be referred to as consistent, and the other, which holds the Baltic indicators, will be called inconsistent. The wide-spread inconsistent Baltic distribution being the larger (see Fig. 19), it will be dealt with first in the following discussion.

# Part 2. Interpolation of indicator transport between distribution and source areas

Agents of the transport of indicators and the pattern of ice movements stand central in the second part of this paper. They are viewed in the light of the two classes into which the indicator distribution of the southern circum-Baltic region falls: the consistent unit, with its distribution showing correspondence with the flowline pattern, and the inconsistent, with indicators from the Baltic predominating. After considering the origin of the inconsistent distribution, I shall give a further elaboration of the streamline pattern on the basis of the consistent unit, which will result in a geometric approximation of the outlines and lines of flow of the ice sheet. Further adjustment and completion of the theoretical picture will lead to an integration of the hypothetical reconstructions of the consistent and inconsistent distribution processes.

## The inconsistent distribution unit

### THE FORCE OF THE CONSISTENT AND INCONSISTENT ICE MOVEMENTS

During the revision of the indicator counts, little attention was paid to the processes and agents of transport which underlie the dispersion of indicators. Because the consistent distribution agrees with the pattern of ice flow in Fennoscandia, the ice movement tendency belonging to it may be denoted as consistent too. Because the Baltic distribution unit is intersected by the trend of the Fennoscandinavian flowline pattern, the transport of the Baltic indicators is defined inconsistent.

Since the second half of the nineteenth century it has been generally assumed that the Baltic indicators were dispersed by an ice stream flowing through the Baltic basin. Since this basin is now submerged, most of the traces of the Baltic ice stream are covered by water and pretty well inaccessible. Denmark and Scania form an exception due to their location in the outlet of the Baltic. There, the central axis of flow of the huge ice stream through the Baltic depression must have lain straight across the Danish archipelago; but Denmark was also crossed by the consistent ice. Consequently, it is possible to compare here the consistent and inconsistent ice streams of the last glaciation.

### *Indicator distribution in Denmark*

The Danish geologists not only accumulated ample information but also represented the data in a way making them highly accessible. In this connection the porphyry distribution map (table I) given by K. Milthers in 1942 is of special interest. On first inspection, the introduction of Baltic elements from east to west is obvious from the significant percentages of Baltic porphyries throughout the Danish

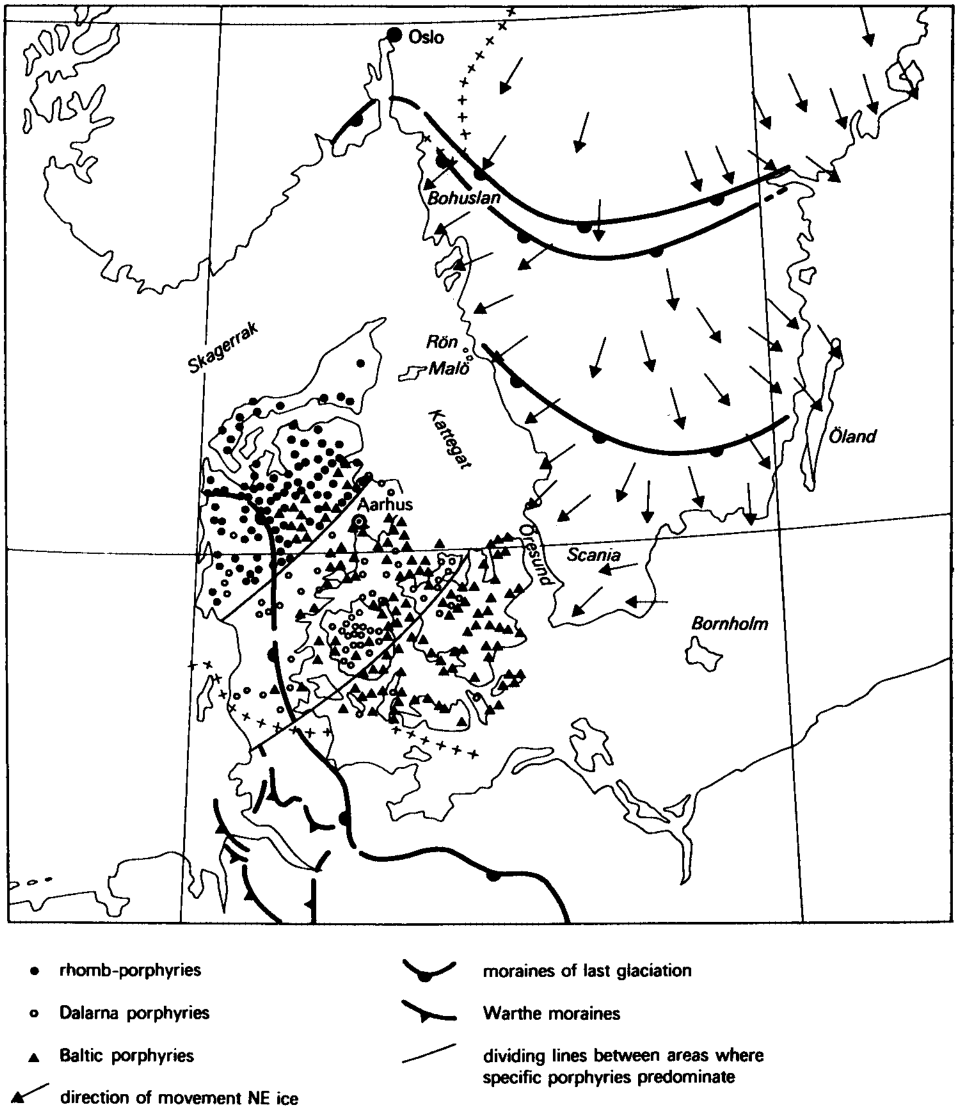

Fig. 21. Indicator distribution in Denmark, modified after K. Milthers (1942).

archipelago as far as an area northwest of Aarhus in Jutland, for which many porphyry counts show a composition with 50% (or slightly more) Baltic elements.

But, as we have seen, some essential dividing lines can be drawn on this distribution map between areas in which rhomb-, Dalarna, or Baltic porphyries predominate (Fig. 21).

The ratios for porphyry distribution in Denmark are fairly consistent in the areas separated by the dividing lines. In other words, there is a consistency in the porphyry distribution in a NE-SW direction over a distance of roughly 400 to 500 km. In a SE-NW direction, within a distance of 250 km, the distribution undergoes a distinct change from an area with an absolute majority of Baltic porphyries, via an area with Dalarna porphyries predominating, to an area with an absolute majority of rhomb-porphyries.

From the consistency of the porphyry distribution in the NE-SW direction in all three areas it follows that the main Weichselian ice movement in Denmark was also from NE to SW. This direction is consistent with the NE-SW trend of the boulder train of the Cyrena and Katholm erratics and the sense of the dispersal of Kinnediabaas (Baartman & Christensen, 1975). The consistency in the NE-SW direction, together with the inconsistency of the porphyry distribution in the SE-NW direction, indicates that the effect of any Baltic ice stream was very small during the Weichselian.

The moderate force of the Young Baltic ice stream as compared with the vigour of the NE flow is confirmed by the comprehensive reports by Hansen (1965) and Lundqvist (1965). Hansen's publication shows that whereas the islands of the Danish archipelago were hardly real obstacles for the NE ice stream (which must have ridden roughshod over them on its way to Jutland), those same islands were virtually insurmountable obstacles for the Young Baltic ice stream, which only succeeded in passing through the channels the Little Belt, the Great Belt, and the Öresund. The impotence of the Young Baltic ice stream is also evident from the 1965 paper by the Swedish geologist J. Lundqvist, who saw the Young Baltic ice stream, which was surrounded by melt-water, as the result of a shortliving effort of an advance of the inland ice during the deglaciation of Scania.

### *Striae in Denmark and the surrounding region*

According to Charlesworth (1957), Torrel's recognition in 1865 of a Younger Baltic ice stream was based partially on the double systems of striae of Scania, Bornholm, Gotland, and northern Germany. There are NE striae which are consonant with the consistent ice stream and others which are attributed to the inconsistent stream.

As far back as the second half of the nineteenth century the striae deviating from the NE direction in southern Scania and Bornholm, and from the N to NW trends in Öland and Gotland, intrigued the Swedish geologists. In 1885, G. de Geer made a comprehensive study and pointed out that the divergent striae post-date the retreat of the land ice and occur only below the 70 m mark above present sea level. Detailed striae analyses made by Mattsson (1960) confirmed that the aberrant striae in Scania and Bornholm were made during or after the retreat of the NE ice. According to Hillefors (1967), the same holds for the divergent striae on Rön and Malö, two islands lying a few miles offshore halfway between Göteborg and Varberg (see Fig. 21).

Both Mattsson and Hillefors point to the force of the NE ice, which can be judged from the glacial rock sculpture and the wide-spread distinct NE striae. However, the divergent striations occur phantomlike, point in various directions, and are superficially scratched on those rock faces only that dip against the trend of the striae.

In sum, here we obtain the same picture as was given by the indicator distribution, i.e. an energetic and forcible NE ice stream as compared with an inert and very weak Young Baltic stream.

## THE ENIGMATIC BALTIC ICE STREAM

### *Factors supporting the concept of Baltic ice streams*

On what factors is the idea of a Baltic ice stream based? The answer comprises five main points:
*Firstly,* the distribution of Baltic indicators, as shown by the double-peaked indicator diagrams of the rearranged Hesemann counts (see Chapter 3 of Part 1). The amounts of indicators from the Baltic and Gulf of Bothnia are of the same order of magnitude as those of the indicators of the consistent ice streams.
*Secondly,* the double system of striae (see the foregoing section).
*Thirdly,* the distinctly different types of boulder clay in southern Scania, which have puzzled Swedish geologists for about a century.
*Fourthly,* the geomorphological features in Denmark pointing to ice movements from the east or even the southeast.
*Fifthly,* the postulated guidance of the Baltic glaciers by the Baltic depression (Kummerow, 1950/1951).

### *Enigmatic features*

In spite of these points favouring the Baltic ice stream concept, some problems remain:
*Firstly,* the extensive distribution of the Baltic indicators and the weakness of the Young Baltic ice stream are contradictory.
*Secondly,* since the southeast coast of the Baltic must have been situated along the concave bank of the ice stream, the indicators from the Devonian, Permian, and Jurassic outcrops in the Baltic States and Poland could be expected as common members of the erratic associations in the moraines flanking the southern border of the presumed ice flow. Contrary to these expectations, Kruizinga (1918) established that hardly any indicators from the southeastern Baltic coast are present in the Dutch moraines.
*Thirdly,* there is the question of how the red lenses of boulder clay in The Netherlands, whose origin is also Baltic, remained fairly free of allochthonous material during transport over a thousand odd kilometres, and what is more, via a route leading through source areas of easily identifiable indicators. These lenses, which were studied thoroughly by de Waard (1949), contain mainly erratics from Åland and Finland together with Silurian limestones and quartz-porphyries, and according to Veenstra (1963) the microfaunal assemblage of this boulder clay consists chiefly of Silurian fossils. Red boulder clay characterized by rapakivis and Silurian limestones occurs not only in The Netherlands but also in NW Germany,

Denmark, and Poland, as shown by both of the authors just mentioned and an outline map of deposits of red boulder clay in The Netherlands and Germany prepared by Maarleveld (1956). A 50 km wide strip rich in red boulder clay extends southwest from Oldenburg (Germany) toward the Dutch border (Richter, 1958). The Saale moraines described by Cepek (1969) in many locations throughout Mecklenburg in the northern part of the G.D.R. may also be instances of red boulder clay, because of their high percentages of Palaeozoic limestones and crystalline erratics of Baltic origin.

*Fourthly,* the spatial relations of the consistent and inconsistent ice stream raise doubts concerning Faber's (1960) suggestion that the lenses of red boulder clay in The Netherlands could have been transported by a riding glacier that was pulled to pieces by the carrying one. If the glacier, conveying the Baltic indicator association was riding on the radially spreading consistent ice streams, it would have continued in the direction of its carrier after the confluence. In that case, the red lenses of boulder clay would have been carried southeast instead of southwest.

*Fifthly,* the floor of the Baltic rises from an average depth of 200 m on both sides of Gotland to a depth of 20 m close to the Danish archipelago. Thus, instead of a depression that would have directed the Baltic ice stream toward the Danish islands, the Baltic glacier had to climb an ascending slope. If the bathymetry of the Baltic had been the main determinant of its course, the Baltic ice stream would probably have flowed toward Gdansk rather than toward the Danish archipelago. It is, however, a question whether the differences in relief of the Baltic sea floor could have controlled the direction of ice movement on a regional scale. Because the greater part of the Baltic sea bottom lies above the level of the -200 m contour line, and the major part of Sweden and Finland as well as large areas in Poland, Lithuania, Latvia, and White Russia lie below the +200 m contour line, the relief of the Baltic floor is similar to that of the circum-Baltic region. Since the topography of this landscape could hardly have restrained the consistent ice streams, how did the Baltic depression come to promote the flow direction of the Baltic ice streams. The weakness of these glaciers might offer an explanation but conflicts with the resistance of the rising Baltic floor, which the Baltic ice stream had to overcome on its way toward the Danish archipelago.

## *An interpretation*

The extensive distribution of Baltic indicators in association with the lack of strength and short duration of the Baltic glaciers indicates that there is something peculiar about the Baltic ice streams.

In approaching this problem, we will start with the last retreat of the north-European ice mantle. The main feature of the detailed accounts given by Finnish and Swedish geologists is the body of water in the Baltic basin growing whereas the ice sheet with its margin across the Baltic, was shrinking as visualized by Magnusson et al. (1963). However, this picture, although it is a plausible approximation, seems to refer to the situation in the summer, because in the winter the whole body of water must have been frozen over.

How would such a growing water body have affected the distribution of Baltic indicators? Since calving is known to have occurred during the last deglaciation, icebergs and floes must have moved about in the open water during the summer intervals. Hence, ice rafting must be taken into account as one of the modes of conveyance of the Baltic indicators.

In case the ice advanced, however, the body of water in the Baltic basin became smaller and smaller. Icebergs and floes were pushed southward and incorporated into the progressing ice front — for instance by being frozen into it during the winter or by becoming attached to the ice margin, as happens today in the Antarctic (Schell, 1966). Consequently, lenses of red boulder clay, indicators from the Åland islands, and Silurian limestones may have been partially transported by floating ice.

When a partially waterborne transport is taken into account, the enigmatic features of the Baltic ice stream become explicable.

*Firstly,* this mechanism could have contributed to the wide distribution of Baltic indicators despite the weakness of the Baltic ice streams.

*Secondly,* the arrival of a Baltic glacier beyond the ice mantle proper at the end and beginning of a glacial is a prerequisite for the concept of a partially waterborne transport.

*Thirdly,* till-rafting occurring over the greater part of the distances to be covered could explain the authigenous character of the lenses of red boulder clay.

*Fourthly,* the difficulties attached to the supposition that the Baltic depression was a guiding element with respect to the Baltic ice streams, are overcome if this depression is considered as a receptacle for the variable bodies of water at the beginning and at the end of a glaciation.

But even so, how does a partially waterborne transport fit in with the direct evidence supporting the Baltic ice stream concept?

*Firstly,* as we have seen, a partially waterborne transport could explain the extensive distribution of the Baltic indicators.

*Secondly,* the aberrant striae might reflect the action of floating ice, to which we will return below.

The different types of boulder clay found in southern Scania and the geomorphological features seen in Denmark seem yet to favour the Baltic ice stream theory. These complications will be evaluated in this chapter (see below).

## WATERBORNE TRANSPORT

The idea that Baltic indicators and other material were transported by drift ice is not new. A century and a half ago, floating ice was thought to be the only agent responsible for the transport of glacial boulders. Because in the controversy between the adherents of the iceberg and the glacial theories, the latter proved to be right, transport by floating ice fell into discredit. It became, as it were, taboo. This may have been one of the main reasons why in the last seventy years hardly any attention has been paid to this important mode of transport during the Glacial Epoch. Kummerow (1930, 1935, 1954) was one of the exceptions, since he attached great value to waterborne transport, but even in his opinion the Baltic ice stream was the leading element in the distribution of the eastern indicators toward the southwest.

### *Ice-rafting in Fennoscandia*

#### *At present*

A review on sea-ice formation and melting in the Gulf of Bothnia from 1899 to 1905 was given by Hellström (1913). In a paper published in 1922, he dealt with the ice conditions in this area throughout the severe winter of 1916. Strübing (1970) illustrated the course of the ice distribution in the northern Baltic in the winters of 1967, 1968, and 1969 by nine satellite pictures, from which it is evident that even in our time drift and pack ice are common features in this region.

From the foregoing it follows that the conditions in the Baltic are favourable for ice-rafting, but does this also mean that waterborne transport takes place even now?

According to Roemer (1885), in the spring large ice floes transport granite boulders from the north to the south coast of the Finnish Gulf. Another instance of present-day debris transport by ice in the Fennoscandinavian waters has been given by Winterhalter (1967). During underwater investigation of the Sylen shoal in the southwestern part of the Gulf of Bothnia, he found a 0.5 m high pile of limestone boulders which were dislodged and moved by pack-ice in the severe winter of 1965-1966. Even large boulders with a diameter of more than 1 m had been shifted over distances of several metres.

Gripp (1975) described the formation and shifting of small pressure ridges of beach sand and pebbles by wind driven sea-ice along the backshore at Amrum in March of 1962. König (1976) observed the transport of ice-bound sediments in the Wadden Sea after periods of frost in the winter.

Hurtig (1971), who described current ice conditions between Mecklenburg and the island of Rügen, pointed out that here too not only smaller specimens but also boulders measuring a cubic metre had been shoved along by ice pressure. Among others, Rudowski (1972) studied present-day ice-rafting along the Polish shore. Over distances of a few kilometres, ice-floes transport large pebbles and blocks of cohesive deposits, which are redeposited on the Baltic beaches. He emphasized that: 'the existence of ice-rafted transport has been neglected even in studies dealing with beach pebbles as indices of shore development'.

Of great interest are Reinhard's (1967) observations on the freighting of boulders by ice-floes in the litoral zone of Koos, an island situated between Greifswald and Rügen. He studied this phenomenon from 1959 to 1967 and found that boulders, even those measuring several cubic metres, are displaced in three ways: 1) by the kinetic energy of wind-driven ice-floes that are thrown against the huge boulders; 2) the floating off of boulders frozen in by ice-floes subject to wind propulsion; and 3) the movement of ice-shoved ridges which override the beach in stormy weather, pushing rock and beach material even beyond the edge of a cliff.

### *In the past*

Since ice-rafting in the Baltic occurs at present, it must have taken place on a larger scale in the colder climate at the end of the Weichselian. This view is supported by the regions of calving indicated on G. de Geer's map of the last deglaciation in south Sweden and Denmark. According to this map, which was published by E. H. de Geer in 1961, calving occurred in a sector of the south Baltic adjoining the east coast of Scania, the south coast of Blekinge, the southeast coast of Öland, and the northwest coast of Bornholm. In addition, Ringberg (1971) drew attention to some small calving bays that must once have existed in eastern Blekinge. Another region lies northeast of Uppland between Sundsvall and Gävle (Järnefors & Fromm, 1960). Sauramo (1929) found traces of calving in the Tampere district in Finland.

Calving took place not only in the coastal belt of the Baltic but also in the subaquatic areas during the retreat of the ice sheet in Finland and Sweden. The observations made by Sauramo (1923) on calving in southern Finland are particularly informative. On the basis of detailed fieldwork, Frödin (1916) concluded that calving occurred near Holmestad between lakes Vänern and Vättern.

But what of ice-rafting in the strict sense? G. de Geer (1885) pointed out that the Cretaceous limestones and flints which are common erratics in Bohuslän, were carried there by drift ice. He even found such ice-rafted boulders at Hästfjord in Dalsland, 63 m above the present sea-level. In 1957, E. H. de Geer considered transport by icebergs to explain the occurrence of erratic flints along the Swedish west coast and the Norwegian fjord valleys. She pointed out that since the Öresund opened in the midst of the Bölling interstadial, the icebergs were able to slip through this channel into the Kattegat. In this connection the investigations of Reite (1967) are worth mentioning. Radiocarbon dating of marine shells between Trondheim and Bergen showed that this area was ice-free in 11 620 ± 120 years B.P. These findings establish a route for ice-rafting of the Oslo rock and chert found in this region. According to Spjeldnoes (1973), floating coastal ice probably transported the flint and rhomb-porphyries on the Norwegian shelf. In side-scan sonar pictures, Belderson and Wilson (1973) found iceberg plough-marks on the shelf and slope of the Norwegian trough. G. de Geer argued that the Baltic boulders on the southwest coast of Norway, listed by V. Milthers (1911), were imported by icebergs drifting westward from the Åland sea (E. H. de Geer, 1963).

Several occurrences of ice-rafted boulder clay, which G. de Geer (1919, 1932, 1938) came across in Södermanland, Uppland, and Västmanland, confirm these observations. The close resemblance between these till-rafts and the lenses of red boulder clay in The Netherlands is remarkable. Both are plate-like bodies in an almost horizontal position, their dimensions are of about the same order of magnitude, and the till-rafts too contain Cambro-Silurian rocks. At Bromma, near Stockholm, G. de Geer (1932) found a 56 m long and 0.4-0.7 m thick till-raft of red boulder clay containing Silurian limestones.

Also worth mentioning are Hyyppä's investigations, quoted by Donner (1965). Hyyppä (1963) found evidence that the Viipuri (Viborg) rapakivi boulders occurring in southwest Finland, west of Helsinki, were transported by icebergs along the then submerged coast in a different direction from that taken by the inland ice.

### *Aberrant striae*

Ice-rafting being a plausible transport mechanism, we must consider the aberrant striae in south Scania, Öland, Gotland, and Bornholm and on Rön and Malö (see p. 51).

According to Flint (1971) one should proceed with caution in interpreting striae that diverge from a paramount ice stream direction, because crossed striations are frequently due to shifts in ice motion along the margins of a glacier during a phase of deglaciation. This means that discordant trends are not indications of distinctly different glacial invasions. Flint remarks that: 'Evidence of a long lapse of time is prerequisite to the interpretation of crossed striations as the product of successive glacial invasions'. Besides striations made by ice streams, Flint (1971) mentioned those made by snow avalanches, landslides, freeze and thaw flowage, and floating ice. McLellan (1971) argued that striations below the water level, either in the past or at present, could have been formed by boulders pushed shorewards by lake- or sea-ice. Such striations are indistinguishable from glacial striations and therefore 'do not provide unequivocal evidence for the direction of movement of continental ice sheets'.

Hence, the former water level at these sites is of primary importance for forming an opinion on the origin of the divergent striae. Examination of the Late Glacial maps of southern Sweden published by G. de Geer (1910) shows that the aberrant striae occur mainly along the coasts and on the coastal plains. Since these areas were submerged during one or more stages in the development of the Baltic Sea, they lay below and at the water level in the past. This makes a glacial origin of these discordant striae doubtful and floating ice must be seriously considered as a possible agent.

The divergent striations studied by Hillefors (1967, 1968), Mattsson (1960), and Vortisch (1972) were shallow or absent in hollows between rock projections — even when these hollows were only a fraction of a millimetre deep — and they were distributed irregularly in different directions. According to Charlesworth (1957) and Flint (1971), these are generally the features of floating-ice striations. Vortisch (1972) might object that the crescentic cracks he observed point to a glacial origin, but McLellan (1971) has shown that even chatter marks can be formed along lake shores by ice-pushed boulders.

Another condition to be considered here is the time element. The concept of the Baltic ice stream is limited to restricted periods: immediately prior to and after the advance and retreat of the inland ice. On the other hand, since floating ice is an active agent along the Baltic coasts even at present, the intervals in which non-glacial striae may be formed must be much longer. Therefore, to ascribe aberrant striae to one of the Baltic ice streams, it is a necessary condition that the time of their formation coincides with the interval pertaining to the ice stream in question. Thus, certainty that a set of striae was made after the NE ice retreated, is insufficient to assign such a group of scratches to the Young Baltic ice stream. In this respect, delimitation of their time of formation to the Daniglacial is essential, but in most cases — especially for the coastal areas — only the rough conclusion that one group of striae is younger or older than another, is possible.

To return to Öland, Gotland, and Bornholm, most of Öland and Gotland are thought to have been submerged during the Baltic ice lake and the *Yoldia* Sea stages in the evolution of the Baltic Sea, and the lowlands of Bornholm also lay below the water level. If this is true, although some investigators doubt it (Lundqvist, 1965), serious consideration should be given to the action of floating ice in explaining the aberrant striae which, as comparison of the outline map of G. de Geer (1910) with topographic charts shows, are found chiefly on the lower parts of these islands.

The shallow aberrant SSE striae occurring on a score of the outermost islets of Bohuslän and Halland on the Swedish west coast could have been formed by coast ice under influence of a climate-dependent rise and fall of the water level and by floating ice. Hillefors (1968) attributed these striae to the hypothetical Kattegat ice stream flowing between Jutland and the Swedish west coast, i.e. from NNW to SSE, but he too is a supporter of iceberg transport to explain the occurrence of Cretaceous flints and Oslo erratics on the Swedish west coast.

Hillefors put the lower time-limit of the Kattegat ice stream at 11 000 years B.P.. This limit coincides with the Ra Substage which ranges from 11 000 to 10 200 years B.P. (Andersen, 1965; Feyling-Hanssen, 1972). Since the south Norwegian Ra moraines, which correspond with the central Swedish and Finnish Salpausselkä moraines, were deposited in the sea, the Skagerrak must be abandoned as a possible region of alimentation of the Kattegat ice stream. A much more northerly open sea is consistent with the attribution of these aberrant striations to the action of floating ice. In 1974, Hillefors reconsidered the SSE striae. He questioned their meaning and gave preference to main NE-SW ice movements from the Göta river valley into the Kattegat.

### *The Young Baltic moraine in southern Scania*

The main direction of ice movement in Scania was from NE to SW. On top of the moraine of this so-called NE ice, but often separated by intermorainic glaciofluvial sediments, lies the Young Baltic moraine. What is its horizontal extent? Fig. 22 shows that the Young Baltic deposits are found in a 15 km wide strip running roughly parallel to the coast. Topographically, the Young Baltic moraine is restricted to the coastal plains, or, as stated by G. de Geer in 1885, the Baltic ice was only able to transgress the lowest and flattest parts of Scania.

The thickness of the upper Baltic moraine ranges from 2 to 6 m. In contrast to the moraine of the NE ice, which is generally deficient in clay, the Young Baltic is clayey. According to Vortisch (1972) the Baltic clay bears a resemblance to water-laid sediments. Carbonates are virtually absent in the moraines of the NE ice, but the lime content of the Baltic deposits is high. The Baltic moraines are characterized by indicators from the Baltic, in the form of boulders from the Åland islands and red and brown Baltic porphyries, which is in agreement with the porphyry counts made by Grey (1932), who found that these Baltic indicators predominate in a narrow coastal strip (15-25 km wide) in western and southern Scania.

Unlike the NE ice stream, the Young Baltic in Scania must have been weak.

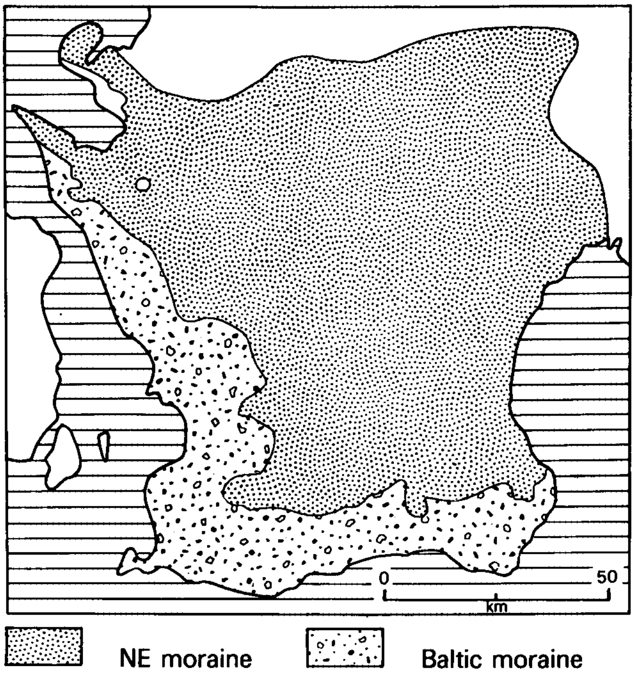

Fig. 22. Horizontal extension of the Young Baltic moraine in Scania, after Vortisch (1972).

On this point the investigations of Gustafsson & Stjernkvist (1966), who studied a moraine section occurring in the northern part of the province of Lund, are of interest. In their opinion, the intermorainic sands of this section were deposited on beaches of lakes, and when the water became deeper clay covered the sand. Later, the Baltic ice entered the area but the intermorainic sediments were not affected by ice pressure. These authors thought it quite possible that the ice advanced into a lake.

The age of the Young Baltic is still uncertain. The clay-varve method of G. de Geer, pollen-analysis correlations done by Nilsson, and radiocarbon datings have yielded an absolute chronology reaching back to 12 000 years B.P. (Håkansson, 1971). On this basis, the oldest reliably dated recession line in Sweden lies roughly on the northern boundaries of Scania and Blekinge. Owing to absence of varved Late Glacial sediments in most of the area south of this line, it has not been possible to perform a continuous line of varve measurements further southward.

In central Denmark the absolute time scale covers the Holocene. No $^{14}C$ dates are yet available for the main stationary line in Jutland or the ice-border stages (C-H) in eastern Denmark, so that here too the absolute age of the Young Baltic is unknown. We know from the review by Hansen (1965) that the Young Baltic penetrated the Little Belt, the Great Belt, and the Öresund. The Öresund glacier, which also covered Scania, is thought to have been the final phase of the Young Baltic ice stream.

Relatively, the Young Baltic in Scania is younger than the NE ice stream, because the Baltic Upper moraine lies on top of the NE moraine. The intermorainic sediments and the Baltic moraine covering the osar of the NE ice stream, as observed by G. de Geer (1885), means that there must have been an ice-free region before the final advance of the Baltic.

The assumption of the existence of a Young Baltic ice stream in the interpretation of the field data leads to the following unharmonious picture. One ice stream retreating to the north during a general improvement of the climate, was trailed by another ice stream — now coming from the south — despite the same improved climatic condition. The advancing ice stream even invaded the partially submerged deglaciated area from which the receding ice stream had withdrawn. This contradictory picture lies at the root of the differences of opinion about the age relations between the NE and the Baltic ice defined by Lundqvist (1965), Vortisch (1972), and Mohrén (1973).

But another approach, based on the gradually contracting ring of marginal glacier lakes and the receding Scandinavian ice sheet as integral parts of a whole, leads to a more regular development of retreat. In this view, the circum-Baltic zone of the Urstromtäler swelled to a cohesive body of water in the Baltic depression and tailed off into a valance of separate lakes and lacustrines against the upgrading grounds of Sweden. Thus, during the climatic amelioration the margin of the ice sheet in the Baltic depression bordered on a ice lake under arctic conditions. In this light the restriction of the Baltic moraine to the coastal plains of Scania, its clay resembling water-laid sediments, and the weakness of the presumed ice stream, seem to point to a para-till, as Harland, Herod, and Krinsley (1966) defined deposits formed by ice-rafting. In this context it is worth noting that Spjeldnoes (1973) suggested the possibility that 'a number of tills which have been described as bottom moraines — especially in the marginal part of a glaciated area — were really ice-rafted'.

### *The glacial morphology of the Weichselian in Denmark*

The features of the Quaternary landscape in Denmark are well illustrated by Hansen and Milthers. Their survey map, published by Hansen in 1965, is repro-

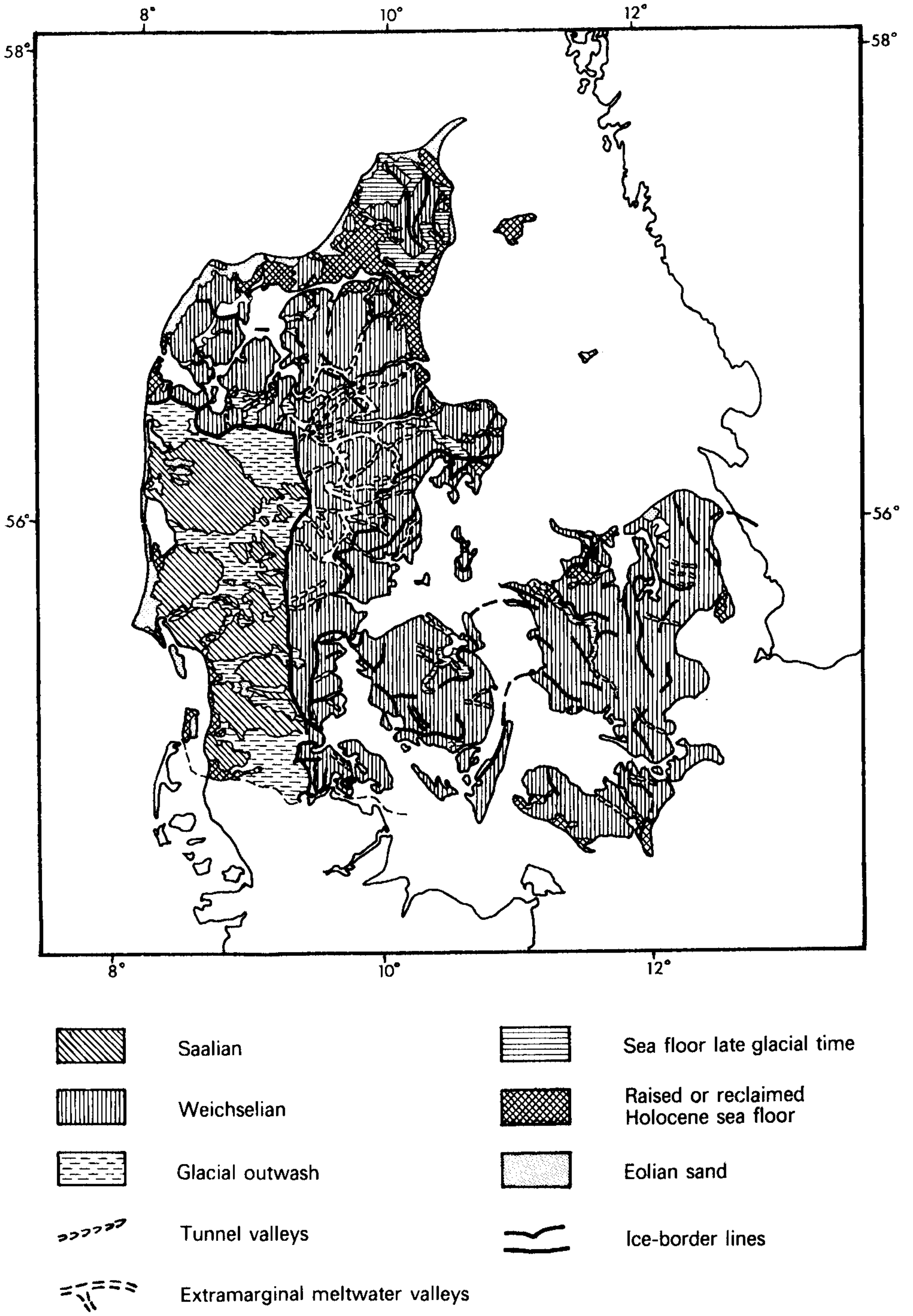

Fig. 23. The Quaternary landscape in Denmark, after Hansen (1965).

duced in Fig. 23. From this map it is evident that the glacial morphology of the Weichselian in Jutland, i.e. the greater part of Denmark, is clearly discernible. On the Danish archipelago, however, this structure is less pronounced. The glacial pattern is even obscure, and it is hardly surprising that the interpretation of these incoherent field data (in contrast with those in Jutland) led to the many question marks that Hansen and Nielsen (1960) had to put on their map of the glacial morphology in southern Denmark.

There is no consensus among the Danish geologists on the 'significance of the different ice borders and recession lines in southern and eastern Denmark and the stratigraphic models accordingly', as Berthelsen (1973) stated. More recently, Binzer (1974) questioned whether the glacial advances from different directions really took place in Denmark. The difficulty underlying the conflicting views is that the islands do not form a related whole. Glacio-morphologically, the Danish archipelago looks like a jig-saw puzzle with some of the parts missing. This complicates attempts at correlation, the more so because of the lack of palaeontological evidence.

Another reason for the indistinct glacio-morphological pattern of southern Denmark are the glacial features that intersect the trend of the NE ice stream. These features are ascribed to the 'Younger Baltic' or the 'south-east ice' which is thought to have followed the NNW-SSE-running depressions between Jutland, Fyn, Sjaelland, and Scania. The Little and the Great Belt glaciers only touched the coastal parts of W, S, and E Fyn (Hansen & Nielsen, 1960), but crossed the coastal plains of southern Jutland and of western Sjaelland. Even so, the intersecting features may be seen in another way, and we will return to that point in the section on the Weichselian recession in Denmark.

## The consistent distribution unit

### FURTHER ANALYSIS AND ELABORATION OF THE FLOWLINE PATTERN

#### *Flowline pattern, eskers, moraines, and recession lines*

After taking stock of the indicator distribution in the marginal belts of the Weichselian and Saalian ice sheets, we found that the flowline pattern in Fennoscandia satisfies a consistent distribution. Conformity between the distribution and the flowline pattern means that the glacial directions refer to the advance.

The trends of most eskers, as indicated by Flint (1971), parallel in a general sense the directions of ice flow during deglaciation. These features of retreat have been mapped on a regional scale in Fennoscandia, and shown in combination with the directions of movement in Fig. 24, from which it is obvious how well the patterns of flowlines and the system of Fennoscandinavian eskers blend. Consequently, the pattern of ice flow is consistent with the retreat as well.

Just as a set of stained rings on the inside of an emptied bowl bears witness to the changing form of the liquid it contained, the recession lines at intervals of a thousand years — shown schematically by E. H. de Geer (1954) — throw light on the transformation of the last Scandinavian ice sheet during its retreat. These lines, which are shown here in Fig. 25, are intersected perpendicularly by the

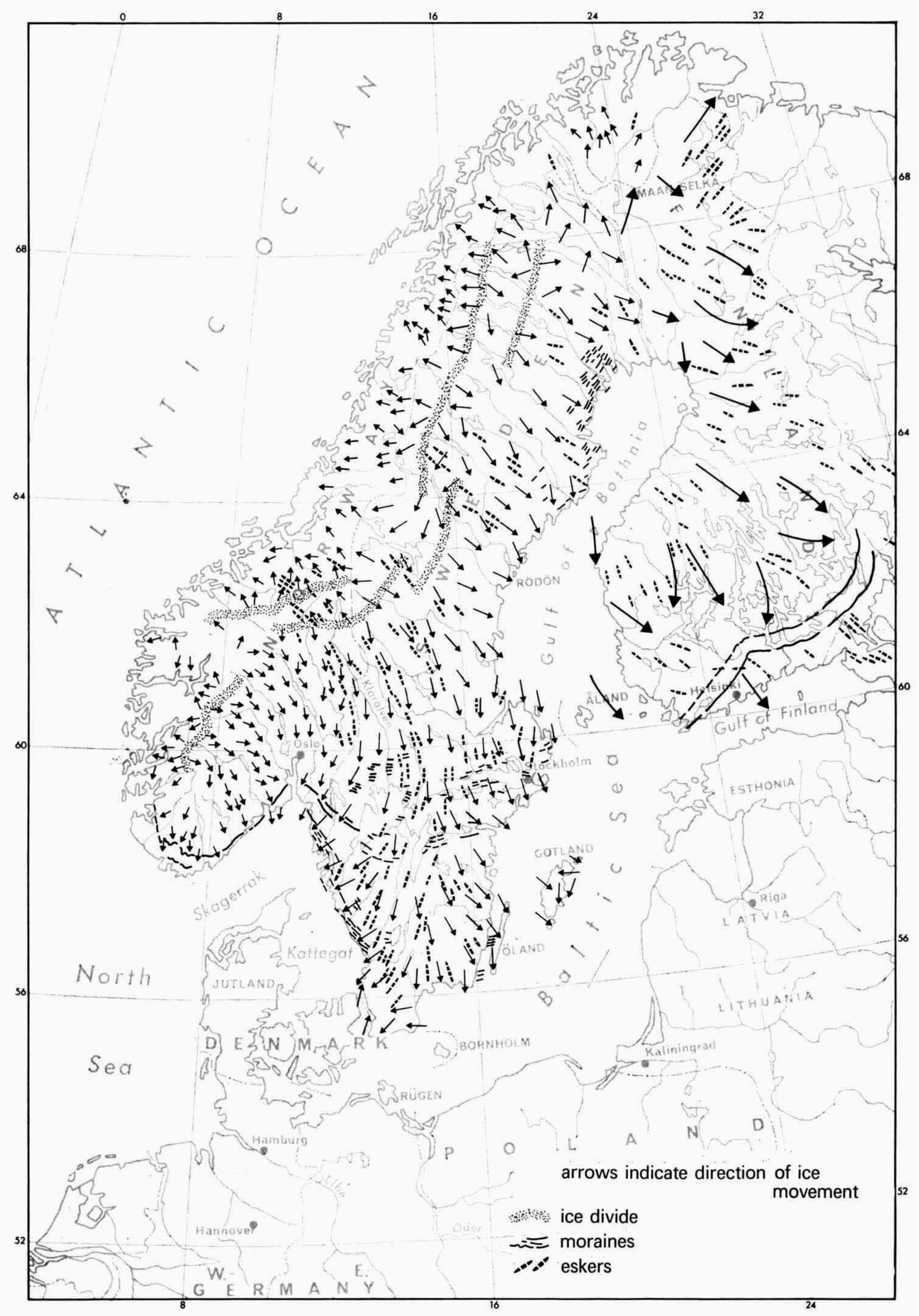

Fig. 24. Pattern of eskers in relation to ice movement.

Swedish and Finnish eskers. Because eskers parallel the directions of flow during deglaciation and the main directions of ice movement must in general have been transverse to the ice margin, the esker pattern agrees with that of the streamlines of the Weichselian ice sheet during its retreat. The recession lines together with the limits of the Weichsel (We) and Saale (S) glaciations, the Saalian ice front phases a, b, c, d, and e, after ter Wee (1962), and the terminal moraine of the Warthe (Wa) Substage, all seem to form part of the same concentric pattern. If this is actually the case and since the maximum extents indicate the extremes of the growth of the ice sheets, an advance of the north European ice mantle along the same course as the retreat seems likely here too.

This may also have been the case in Canada. Flint (1971) discusses the close association of the streamline features of a large part of this country with end moraines and esker systems in particular, both of which he takes as features of deglaciation. This flowline pattern also conforms, however, to that of the maximal ice sheet obtained by analogy simulation with a field plotter. As a result, Flint was uncertain as to whether these glacial directions were related to the advance or to the retreat of the ice sheet. This uncertainty itself might be an indicator that in the broad sense the general pattern of movement was similar in the advance and the retreat.

The re-expansion effect occurring during the general shrinkage of a glacier suggests the same thing. As reported by Flint (1971), radiocarbon investigations of end

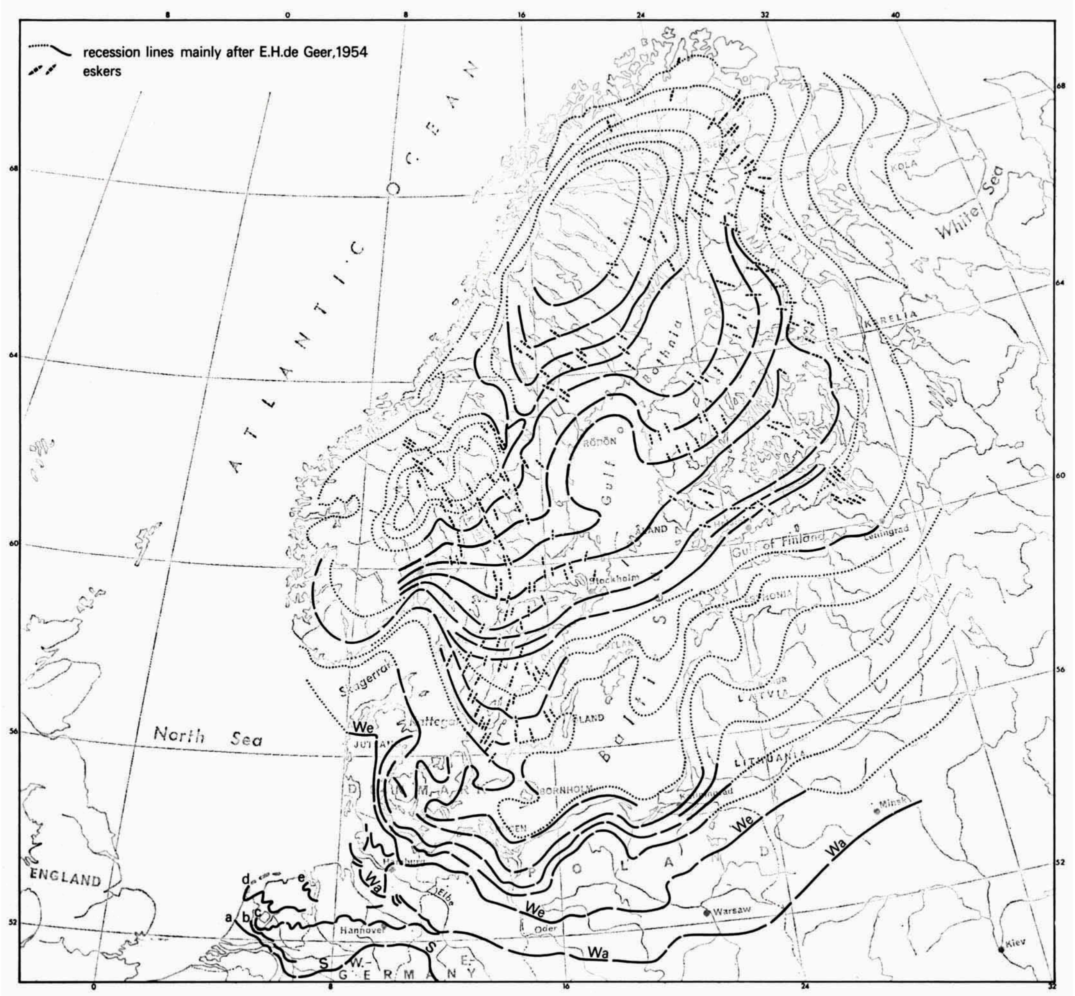

Fig. 25. Recession lines and maximum extension of ice sheets in relation to esker pattern. For further explanation, see text.

moraines from the last 10 000 years give the impression that on the whole these forms are the result not of pauses in the course of general shrinkage of a glacier, but of culminations of re-expansion during the period of retreat. Small advances occurring while the ice was retreating indicate that the ice was still flowing at least by fits and starts. Thus, on the whole, the moraines left by the retreating ice may after all promote information about the advance as well.

The Fennoscandian recession lines are shown in Fig. 25 together with some limits of various glaciations and the flowline pattern. The two systems intersect roughly perpendicularly, which suggests that they contribute to a whole. The flowline pattern is in agreement with the esker system but also with the consistent distribution of indicators; the recession lines are features of shrinkage but the lines of maximum extent belong to a growing ice sheet. Thus, there are features which belong to both advance and retreat. Thus far, in a tentative way we obtained a general picture of a possible flow pattern and outlines of the last Scandinavian ice sheet. The further investigation, completion, and elaboration of this integrated structure will be discussed in the following subsections.

### *Approximation of the outlines and flow pattern of the ice sheets by a set of confocal ellipses and hyperbolas*

As shown in Fig. 26, the recession lines may be regarded as rough ellipses lying concentrically around common foci. Particularly in the southeastern direction they waver around means of nearly true elliptical contour, but south of Oslo, in southwest Sweden, in the Danish archipelago, and in Jutland, a clear indentation in these series of concurrent ovals attracts the attention. Deviations from the true elliptical contour should of course be expected. Ice of moderate thickness tends to follow the depressions, but with greater thickness the ice movement is more independent of the subglacial relief. It is interesting to note that elliptical outlines reappear in the reconstruction of the Scandinavian ice sheets made by Aseev (1968), by Aseev et al. (1973), and in the isobases of the domelike upwarping in Fennoscandia.

If the last ice sheet in northwest Europe maintained a roughly elliptical shape while it shrank, the theoretical direction of ice movement would be perpendicular to the circumference of each ellipse, and this raises the question of the extent to which the trends of ice movement found in Fennoscandinavia coincide with the theoretical directions pertaining to the concentrical ellipses.

The normal curves being perpendicular to the greatest diameter of the central ellipses, this diameter should intersect the equivalent sections of the flow pattern at right angles too. The strong curvation in Dalarna, as well as the perpendicularity of the directional trends north of Maan Selkä to those in central Sweden, offer prima facie an indication of the rough lie of the greatest median. To approximate the true position, the assumed median should be adjusted to intersect the trends of movement in central Sweden at right angles. Fig. 27 shows the result to be a remarkable fit, the normal curves of the concentrical ellipses running parallel to the Fennoscandinavian flow pattern. There is a deviation in the extreme southwestern part of Sweden, but a glance at Fig. 26 shows that for south Sweden the deviation concerns the divergence of the recession lines from true ellipses.

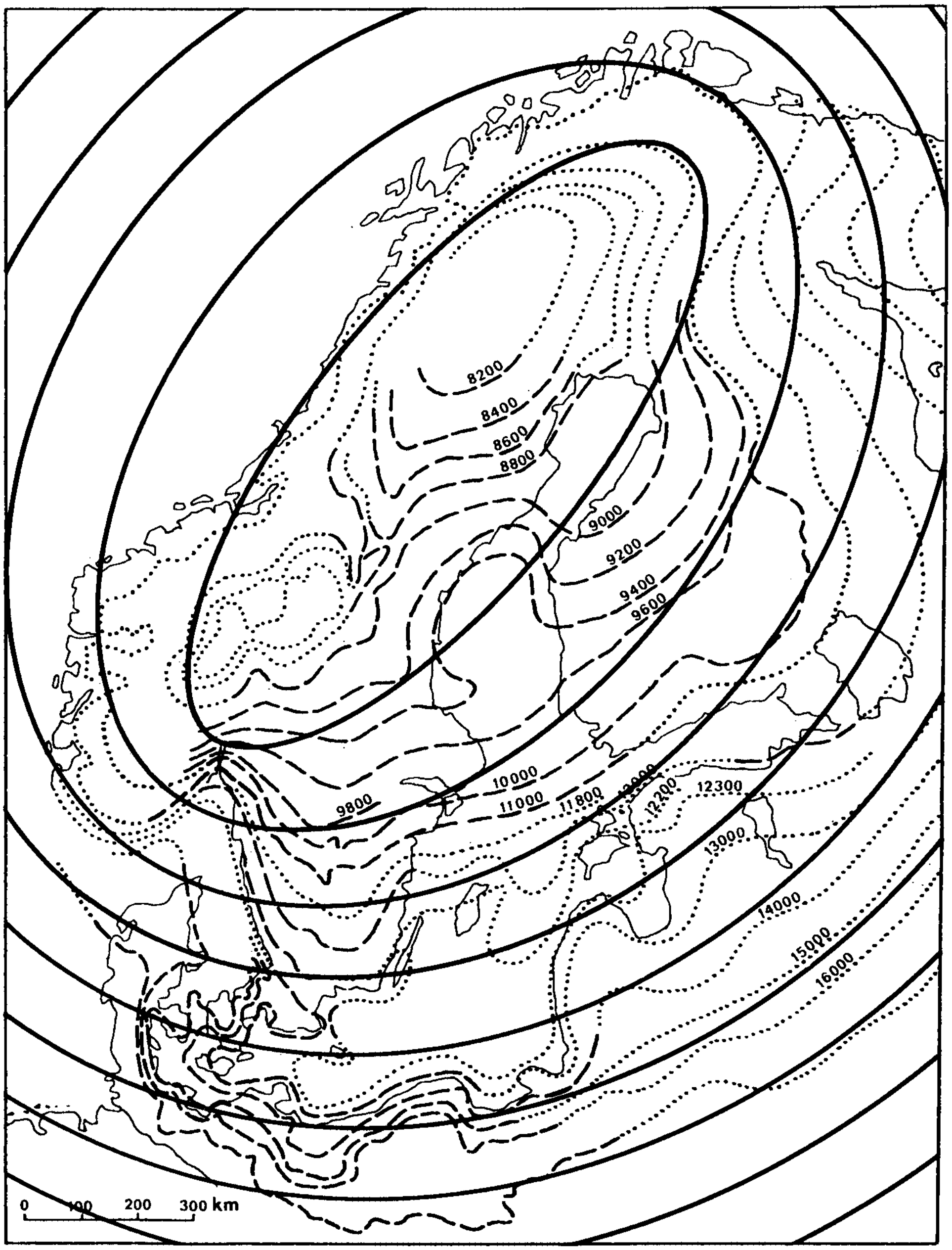

Fig. 26. Recession lines after E. H. de Geer (1954) in relation to confocal ellipses. The approximate dates are given in years B.P. Heavy lines: ellipses; dotted and dashed lines: recession lines.

### *Location and form of the main ice divide*

Curves normal to confocal ellipses are hyperbolas, and the major axis of the ellipses, which is also the median of the set of confocal hyperbolas in Fig. 27, may be considered a theoretical ice divide.

East of this median, the directions of arrows and lines match fairly well. On

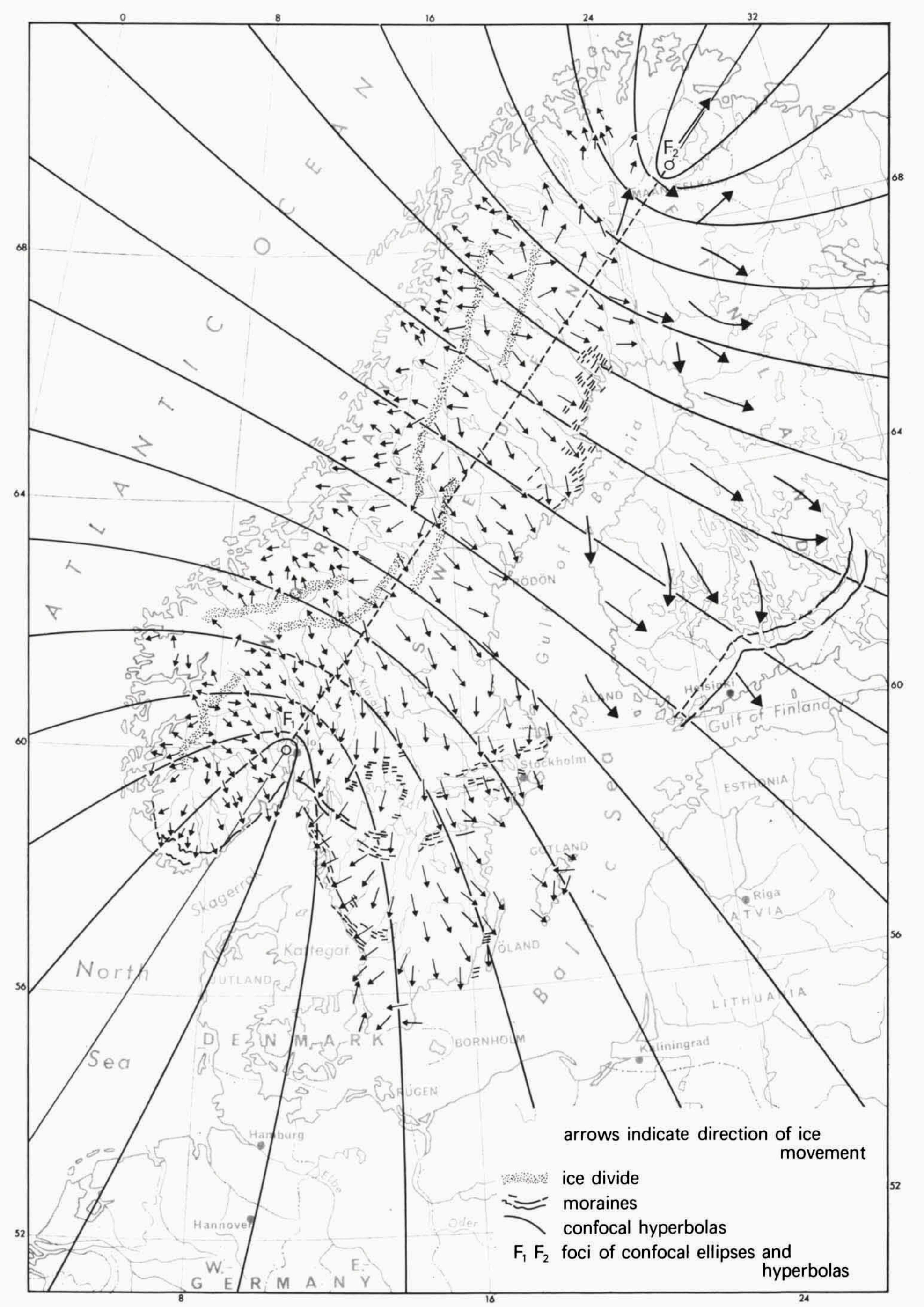

Fig. 27. The trends of curves normal to the confocal ellipses in relation to directions of ice movement.

the west side, however, there is some disagreement in the axial zone. This discongruity may have been brought about by the westward movement of the ice divide at the end of the last glacial, the shifting ice mass disturbing and obscuring

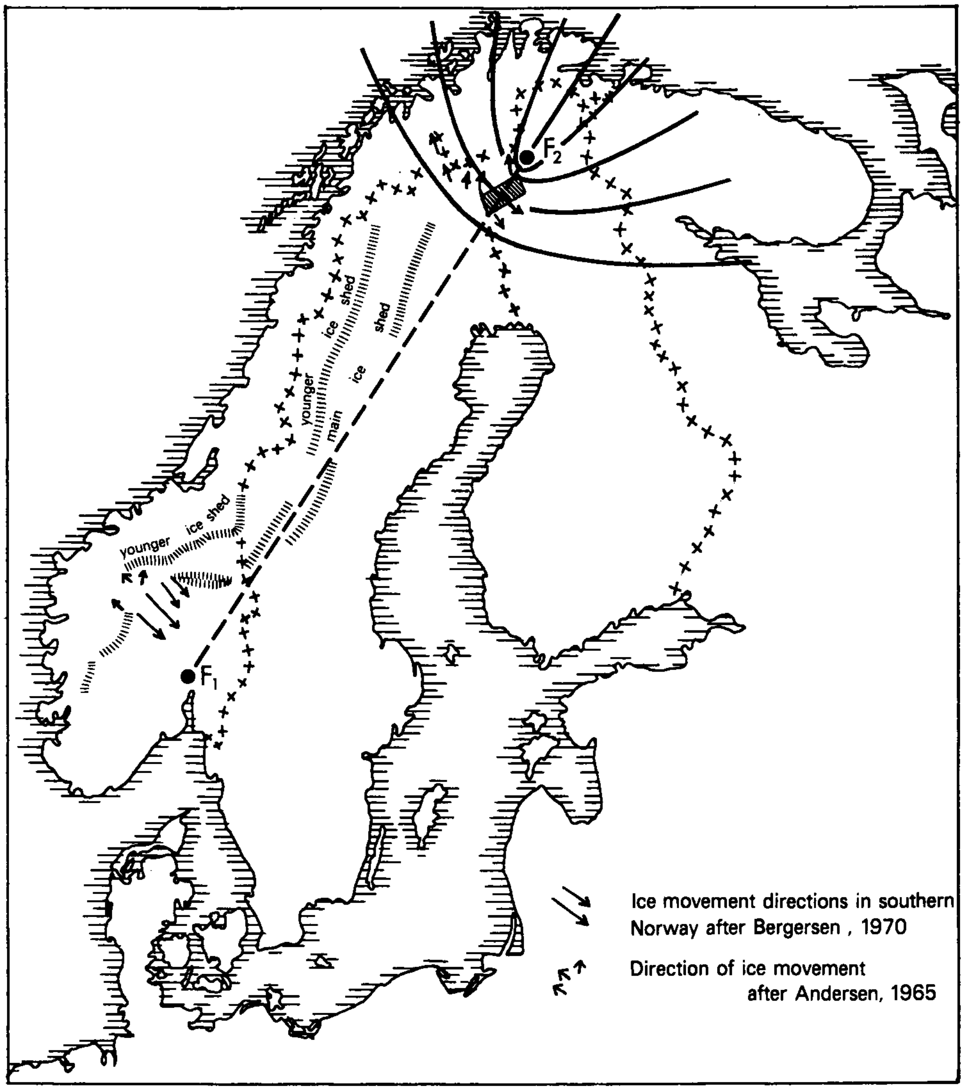

Fig. 28. The Weichselian ice sheds (Andersen, 1956; Lundqvist, 1956) and the median $F_1F_2$ of the confocal hyperbolas. The ruled parallelogram in Finnish Lappland is a zone of the ice divide, and the arrows show trends of the ice movement of the Weichselian main glaciation (Kujansuu, 1967). The trends of ice movement can be compared with the directions of some hyperbolas in this area.

the features of the main glaciation. At some distance from the median, east of the Swedish-Norwegian border and in Norway, the trend of ice movements and hyperbolas run more or less parallel again, except for the southern part of Norway, to which we will return below.

Although the divide of the ice sheet presented by Aseev et al. (1973) lies further to the east, since their construction is also based on the isostatic subsidence, the difference in position might be explained by the structure of earth crust and substratum in this area. The easternmost ice divide proposed by Lundqvist (1974) approximates the Swedish component of our median. To the north, however, the divide of Lundqvist continues eastward across northern Finland and follows the longitudinal axis of the Kola peninsula. The directions of ice flow consistent with this deviation to the east, should be approximately northward and southward. But the observed directions, which are from northwest to southeast, do not support Lundqvist's hypothesis.

Our view of the topographical location of the median of the confocal hyperbolas is supported by the general agreement between the directions of ice movement and those of the hyperbolas. The principal axis separates the concordant trends of ice movement to the east from the deviating trends to the west. Furthermore, the ice divide zone of the Weichselian main glaciation in the western part of Finnish Lappland, which Kujansuu (1967) defined after careful glacio-geological investigations, is consistent with the hypothetical zone, the trends of the main glaciation lying parallel to the northern hyperbolic directions of ice movement (see Fig. 28). Apart from the conformity between the hyperbolic trends and both the directions of movement and the distribution pattern of the indicators in northwest Europe, the criteria mentioned above imply that the main ice shed would roughly coincide with the median in question. On this basis, the westward deviation of the northern end of the main ice divide, as represented in Fig. 28, seems to be part of one of the younger ice sheds.

The southern end of the Weichselian ice shed also diverges from the theoretical median. The aberrant component, running roughly parallel to the Norwegian coast (like the greater part of the median), and the opposite ice movement directions on both sides of the deviation, confirm the impression that this southern feature represents a bend of the main ice divide. If this is the case, the bend should manifest itself in the streamline pattern.

### *The zigzag bend in the south end of the divide; resulting flowline pattern and morainic contours*

Figure 29 depicts the re-entrant and salient angle of a bend with straight streamlines perpendicular to the sides. These lines diverge in the larger angle and converge in the smaller angle. Since the theoretical streamlines are not straight but hyperbolic, the straight lines are replaced by hyperbolas in Fig. 30. Divergent streamlines give rise to a convex ice front, convergent streamlines to a concave ice front; in other words, re-entrant and salient angles are reflected by the shape of their respective ice fronts.

Armed with this knowledge, we return to the flowline pattern in Fig. 31. The divergent streamline system in southeast Sweden, with its apex adjoining the re-entrant angle of the ice divide, confirms the postulated bend in the main ice shed. Since the convex south-Swedish recession lines and moraines represent the re-entrant angle of the bend in the ice divide, the concave Ra moraines of the Oslo district could reflect a salient angle in the divide. The Ra-Gothiglacial Substage moraines form a kind of Z bend that also shows up in the main stationary line in Denmark and matches the crooked Norwegian ice divide as well (see Fig. 31).

It seems as though the shape of the bend in the ice divide is expressed in the outline of the southwestern moraines and as though a rotation of the ice front took place. Figure 32 shows that a common centre of circles describing the rotation can be determined.

Because these circles run parallel to the esker system in southwest Sweden and to the dividing lines between the area with prevailing rhomb-, Dalarna, and Baltic porphyries in Denmark, they are represented in Fig. 33 next to the diverging bundle of hyperbolic lines at the southern end of the divide to permit comparison

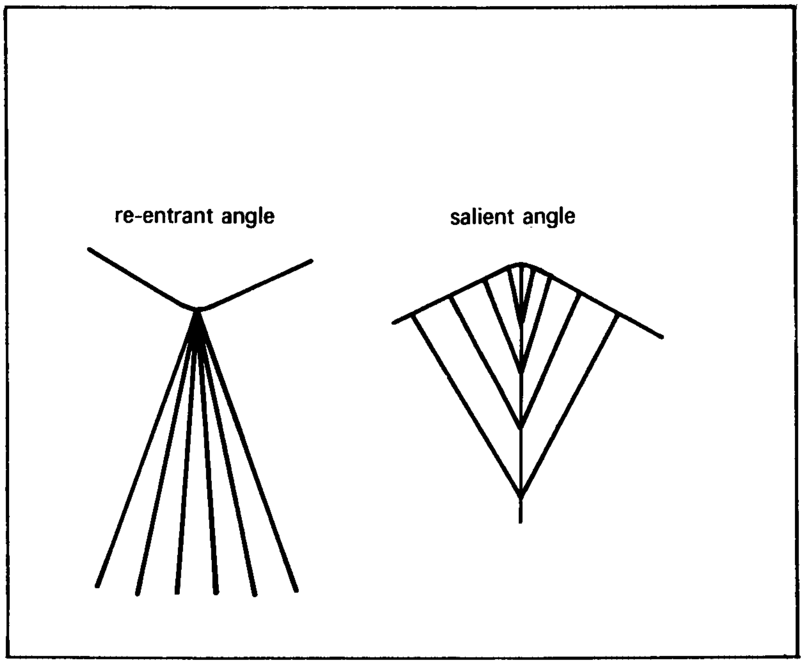

Fig. 29. Straight streamlines in re-entrant and salient angles.

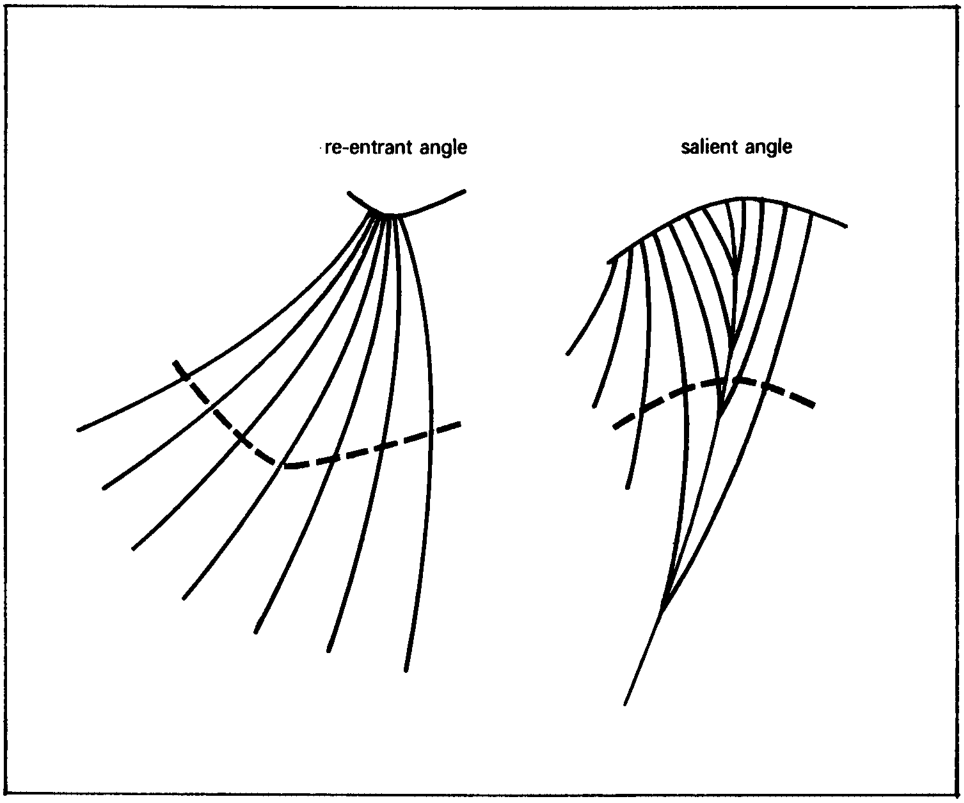

Fig. 30. Hyperbolic streamlines in same angles as in Fig. 29. Dashed lines: resulting ice fronts.

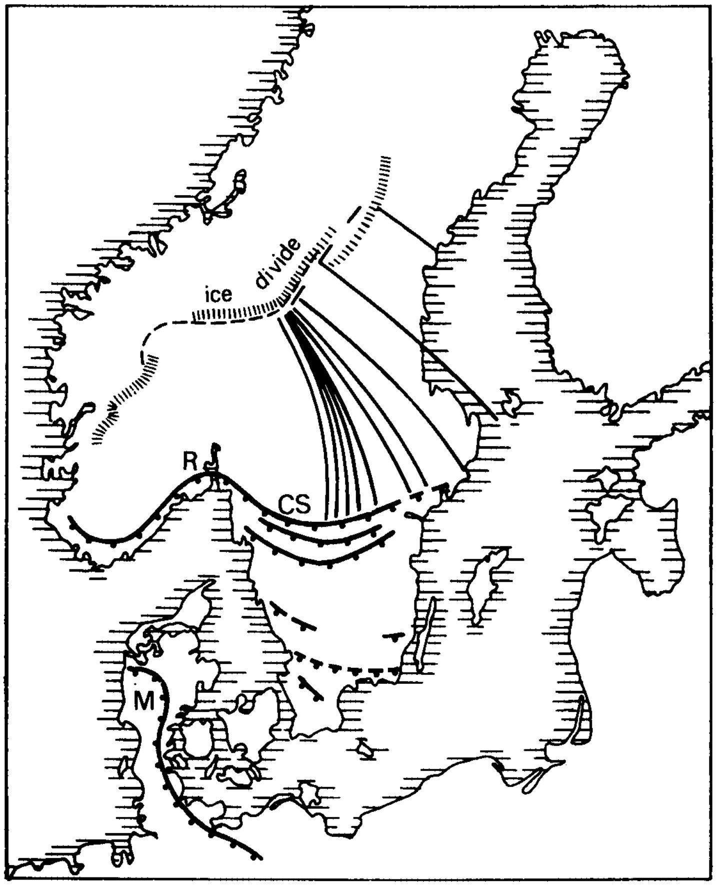

Fig. 31. The zigzag bend in the ice divide, in the Ra Central Swedish moraines (RCS), and in the main stationary line (M) in Denmark.

with the main directions of ice movement. The constructed directions match those of the ice movement fairly well. This supports the idea of an ice flow across the Skagerrak (Holtedahl & Bjerkli, 1975). Nevertheless, there are traces of ice movement in southwest Sweden that deviate. Because in general the esker and stream patterns correspond rather well with the circular lineature (see Fig. 32 and 33), the deviations might be explained by topographic control during deglaciation.

The general outline of this flow pattern related to the zigzag bend in the ice divide is correlated with the dispersal of some major groups of indicators (see Fig. 33). On its east side, the Oslo district is encircled by circular lines of ice flow. The westernmost circle runs west of the Oslo fjord and touches the northwest coast of Denmark. This configuration confines the glacial dispersal of the Oslo indicators to a relatively narrow circular zone that corresponds with the presence of these indicators in north Jutland, which lies in this zone, and the absence of these indicators in The Netherlands, which lies well outside this zone.

The immense dispersal area of the Dalarna indicators, reaching from Denmark and The Netherlands up to Lithuania, follows from the position and shape of the divergent system, whose apex lies at the Swedish-Norwegian border in Dalarna and whose westernmost streamline follows the easternmost circular line.

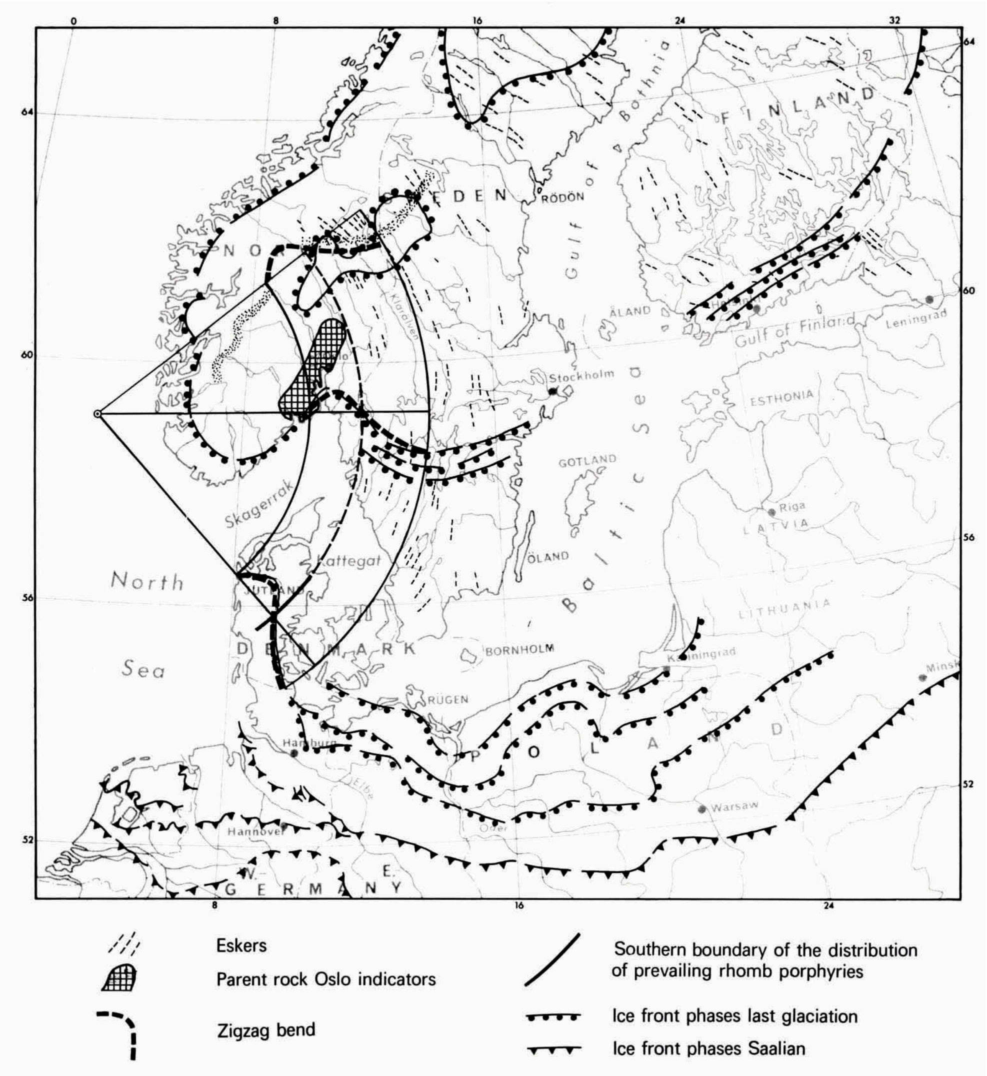

Fig. 32. The circular pattern.

## THE INFERRED STRUCTURE OF FLOWLINES IN RELATION TO THE DISPERSAL OF INDICATORS

The analysis of the linear trend of the flowline pattern resulted in a generalized descriptive picture with three geometric components: a set of confocal hyperbolas, a divergent system, and a zone of concentric circles. This picture not only visualizes the outline and interrelationships of the flowline pattern, but also permits interpolation or extension of the initial delineation. As indicated above, the dividing lines of the indicator distribution were lengthened toward the flowline pattern in Fig. 20; now, in Fig. 33, the extension starts from the flowline pattern.

This new approach again shows the close relationship between distribution and flowline pattern. It also enables us to fill in the interspaces between the few connection lines of our first attempt, which means that a fresh and a more detailed appraisal of the interrelationships between the inferred lines of ice flow and consistent distribution is feasible.

Thus, the rest of this section concerns the dispersal of several species of indicators, with emphasis on the corresponding tracts of the flowline pattern. Most of these indicators have already been taken into consideration, but there are others that require attention.

### *The tract of flowlines toward The Netherlands*

The key position of The Netherlands with respect to Pleistocene stratigraphy — according to Brouwer (1963) and elaborated by de Jong (1967) — also holds glacialogically, because the southwesternmost continental traces of the Saalian ice sheet lie within the Dutch borders. In addition, since the mean ice movement in the southwestern sector of the ice mantle that covered The Netherlands, Denmark, and southern Sweden was roughly NE-SW (see Fig. 33), the corresponding actual paths of ice movement are accessible in this area, because at present they lie almost entirely overland. This amounts to an ideal situation for a reconnaissance of the route of consistent transport in the southwestern sector of the Scandinavian ice sheets.

There is one drawback, however. The flowline pattern is indistinct here and not yet understood. On the other hand, thanks to the investigations of Maarleveld (1953), ter Wee (1962), and Zagwijn (1974), the locations of various ice front phases of the Saalian are known. Starting at the southernmost location, flowline directions are drawn normal to the general regional trend of these phases. This procedure is permissible because of the correspondence between the directions of ice movement in the Saalian and Weichselian and the similarity between the general patterns of ice flow of the expanding and the shrinking ice sheets.

Figure 34 shows this retraced tract, which with its southern end in northeastward direction turns to the east. It is interesting to note that this course parallels the valleys of the Saalian ground moraine in the northern part of The Netherlands and northwestern Germany (Edelman & Maarleveld, 1958). Maarleveld thought it likely that the prevailing direction of these valleys reflects the direction of movement of the Saalian ice sheet. Further to the north, the route perpendicularly intersecting the moraine of the Warthe Substage proves to be normal to the general trend of the end moraines of the Last Glacial as well, and, then turning through east northeast in northwest Germany and the Danish archipelago, the tract goes straight north in southwest Sweden, and even takes a northwest direction beyond Lake Vänern. The excellent maps published by G. de Geer in 1910 make it possible to compare the south-Swedish part of this path of retreat with the directions of åsar and thrust striae; the results show a close resemblance in general trend.

If the transport of erratics, with The Netherlands as ultimate destination, took place along the roughly Z shaped route starting in the Dalarna area, an appreciable percentage of Dalarna indicators would be expected in the Dutch boulder clay. This is confirmed by the findings of van Calker (1912) and de Waard (1949). The latter made a special study of the erratic associations in the boulder clay of the Noord Oost Polder, which was once part of the Zuiderzee. Other investigators (van der Kley & de Vries, 1941) have also reported that Dalarna

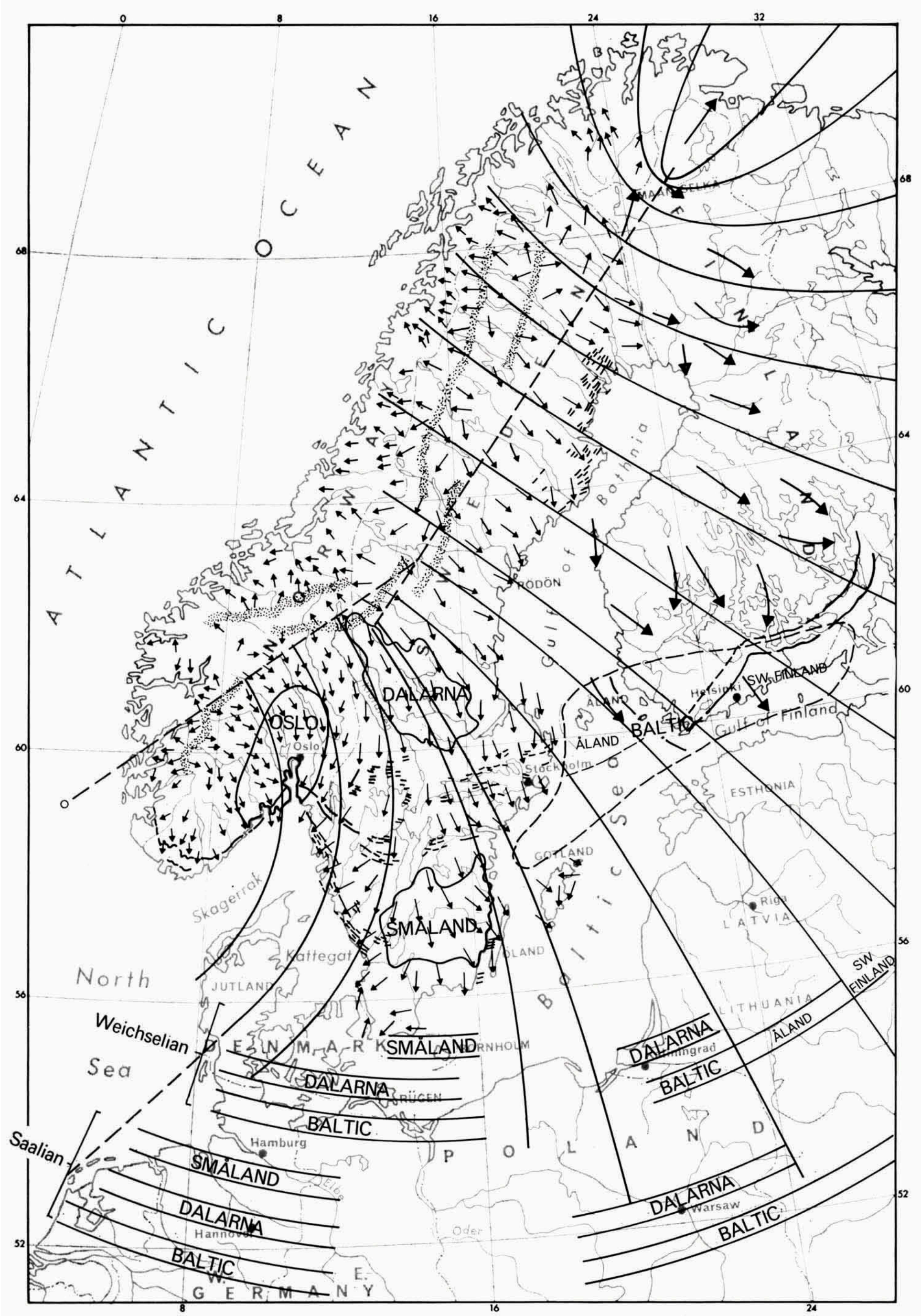

Fig. 33. Inferred flowline pattern (heavy lines) of the ice sheet in relation to directions of ice movements (arrows) and the distribution of indicators (See also Fig. 4, p. 16).

porphyries, Dala sandstones, and diabases from Dalarna occur generally in The Netherlands.

Although several authors ascribed the provenance of the numerous flints found in most of the Dutch glacial sediments to the Cretaceous outcrops in Jutland, the Danish archipelago, southern Sweden, or northern Germany, Veenstra (1963) traced these flints back to the Danish archipelago and southern Sweden. His studies concerned, for instance, the Bryozoa enclosed in the boulder clay. The locality of this provenance argues strongly for a transport of the flints along the southern part of the Z shaped course. This would explain the exceedingly high percentages of flint of the coarse fraction of erratics in the Weichselian glacial deposits on the

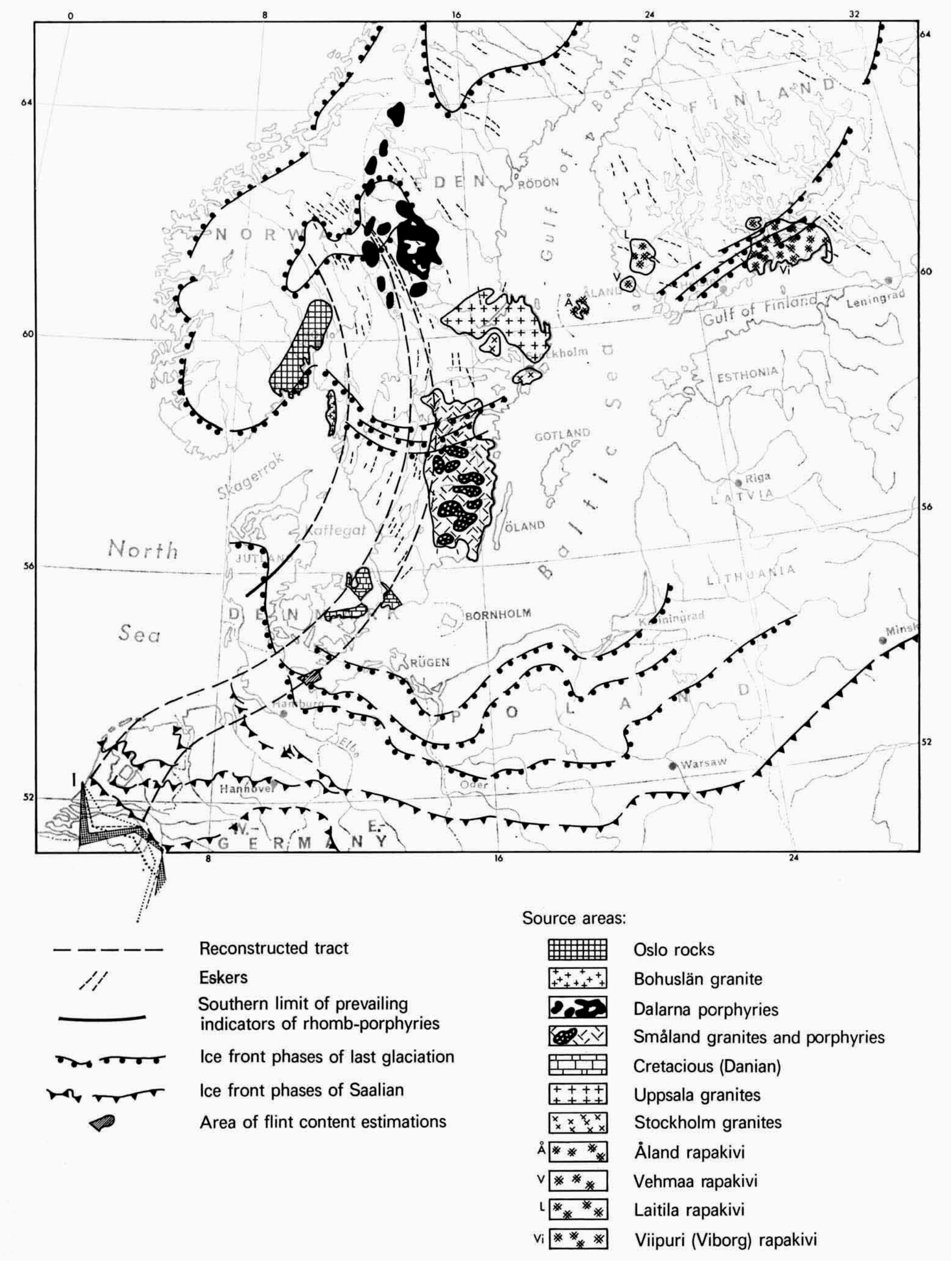

Fig. 34. Reconstructed tract of flowline pattern through The Netherlands. I: topographically incorporated indicator diagrams (Fig. 15). The key also applies to Figs. 35-37, 50-53.

east side of Schleswig Holstein, where there are no Cretaceous outcrops. During an excursion conducted by A. C. Koenderink and P. Schuddebeurs in July, 1968, the present author made the following rough estimates (see Table 10) in a number of exposures situated in the hatched area in Fig. 34.

Table 10. Approximate flint percentages of the coarse fraction of erratics on the east side of Schleswig Holstein.

| Locality | Kind of deposit | Percentage of flint |
|---|---|---|
| Stendorf am Bungsberg | fluvioglacial | 70 to 80 |
| Kasseedorf south | fluvioglacial | 10 to 20 |
| Kasseedorf north | fluvioglacial | 30 to 40 |
| Kassau | fluvioglacial | 25 |
| Kreuzfeld 1 | fluvioglacial | 20 to 30 |
| Kreuzfeld 2 | fluvioglacial | 30 to 40 |
| Luschendorf | fluvioglacial | 30 |
| Malente south | fluvioglacial | 30 |
| Sieversdorf 1 | fluvioglacial | 70 |
| Sieversdorf 2 | fluvioglacial | 70 |
| Weissenhaus | fluvioglacial | 30 |
| Övelgönne (Süsel) | fluvioglacial | 70 |
| Retin (Neustadt) | boulder clay (coastal cliff) | 50 to 60 |

Finally, the puzzling scarcity of Oslo indicators and Bohuslän granites in The Netherlands tallies with a route of transport bypassing their provenances.

Are the ratios of the indicators in The Netherlands also consistent with this transport route? Returning to Table 6, we learn that — excluding the Hondsrug and the lenses of red boulder clay on account of their large quantities of Baltic material — the added percentages of the Scania, Småland, and Dalarna groups amount to more than 30%. At the same time, in cases other than the Utrecht ridge, where the Bornholm indicators amount to 11%, the shares of the Oslo-Swedish west coast and the Bornholm-Blekinge unit do not exceed 4%.

Thus, the predominance of the combined percentages of indicators from Dalarna, Småland, and Scania over those from the adjacent areas also supports a Netherlands-bound transport route starting from Dalarna and proceeding roughly through the median part of southern Sweden, bypassing the Oslo area and the Swedish west coast to the west, and to the east, the province of Blekinge and the island of Bornholm. If the flints from Scania and the Danish archipelago had been included in the Hesemann counts the results would have been much more pronounced, since the flint content of the recognizable indicator association in the normal grey boulder clay in The Netherlands amounts to at least 28%. Thus, for a better understanding of the directions of ice flow, there is much to be said for not restricting counts to the crystalline or sedimentary erratics only, as has been done because of the two widely divergent specialities. Nevertheless, for the present study the Dutch Hesemann counts were not altered in this respect, leaving them suitable for comparison with crystalline counts made in other areas.

In concluding the discussion of the route of indicator transport toward The Netherlands, reference should be made to the danger involved in inferring spatial relations of ice movements from the Hesemann numbers with the reserve that Hesemann numbers lent themselves above all to stratigraphic ends. Ter Wee (1962) directed attention to an interesting relationship between the Hesemann numbers and the Saalian ice front phases in The Netherlands. From the maximum extension of the ice northward, the indicators from southern Sweden (Hesemann area III) decrease and the north Baltic elements (Hesemann area I) increase, which ter Wee attributed to a west-to-east shifting of the ice stream directions upstream. Despite the rational conclusion ter Wee drew from the Hesemann numbers, the frequency curves in Fig. 15 do not account for a west-to-east shift of the source areas in the successive recessional Saalian ice front phases in The Netherlands. On the contrary, as illustrated by the incorporated indicator diagrams, the curves of Fig. 34 pertaining to the three westerly oblong source units show an almost perfect symmetry, which supports a fixed path of the Netherlands-bound inland ice.

The lines of motion of the Saalian ice movement represented by Münnich (1936) are also based on Hesemann numbers. His flowlines from Dalarna toward The Netherlands — showing a convex curve to the northwest — pass through Bohuslän, the west coast of Sweden, and Jutland, instead of curving to the southeast and transversing the Danish archipelago and Schleswig Holstein as indicated by the dispersal of indicators in The Netherlands.

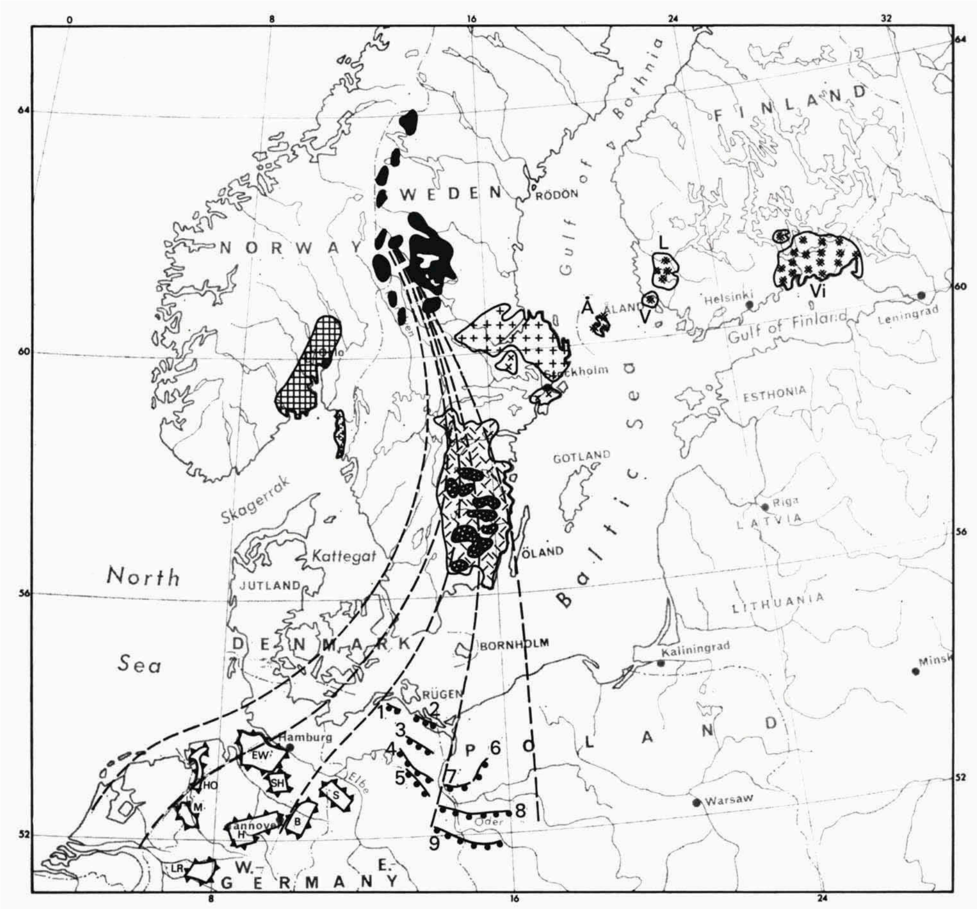

Fig. 35. The consistent distribution of the areas between the Rhine and the Elbe and on both sides of the Oder. For key, see Fig. 34. The capital letters refer to Table 8 (p. 41), the numbers to Tables 3 (p. 23) and 4 (p. 27).

### *The consistent distribution east of The Netherlands to the Oder and beyond*

Compared with the route of indicator transport toward The Netherlands, a section of the reconstructed flowline pattern covering most of the area between the Rhine and the Elbe, includes more of the source area of the Småland granites and lies further from Oslo (Fig. 35). This conforms to a higher amount of Småland granites and a greater scarcity of Oslo indicators in the Saalian indicator association of Western Germany.

The route of the indicator transport toward the region west of the Oder is still further away from the Oslo district and the Swedish west coast, which might account for the absence of indicators from these sources on the west side of the Oder. In accordance with the transport route running through Dalarna, Småland, Scania, and Bornholm, indicators from these provenances are here abundantly represented. Except for the Baltic association, their combined percentages range from 93 to 99, as is apparent from Table 3A.

When the percentages in Table 4 for the Weichselian on the east side of the Oder are considered, the deficiency of the Bornholm indicators is manifest, as could be expected with a course of ice flow that bypassed this island.

### *The gap in the distribution pattern*

Although the gap in the distribution pattern is due to the lack of counts, Ladwig (1938) did some 80 Hesemann counts for the Weichselian of eastern Pomerania in an area west of Gdansk denoted by EP in Fig. 36. Unfortunately, he gave only the Hesemann numbers, which means that his results cannot be regrouped. Besides making these counts, however, he investigated the frequency of occurrence of a number of sedimentary erratics and found that the Neksö sandstones cropping out on the island of Bornholm were scarce in eastern Pomerania, as distinct from the indicators of *Paradoxides tessini* Sandstone, whose source is in the southern part of Öland. The highest density of the distribution pattern of this sandstone in the central part of the area investigated by Ladwig declines to the east and west, which tallies with the flow pattern, since the reconstructed streamlines cutting across the southern part of Öland run virtually through the centre of this region. The streamlines traversing Bornholm, which pass well to the west of the site in question, agree with the observed scarcity of the Neksö sandstone.

In analogy with this, the major dispersal of the 'Beyrichien Kalk' in Poland (Reuter, 1885) and its main source area southeast of Gotland (Hucke, 1967), both of which lie west of the flowline through Kaliningrad (see Fig. 36), is consistent with the inferred directions of ice flow.

### *Comparison of the Saalian in Poland and White Russia with the Weichselian in Lithuania*

As shown in Fig. 36, the segment of the inferred flow pattern covering the regions investigated by Milthers & Milthers in Poland and White Russia is made up of two parts. One contains the main source areas of the Dalarna porphyries together with regions I, II and III, and the other the Åland islands with regions IV and V. Thus, the inferred tracks toward regions I, II and III have their seat in the provenance of the Dalarna indicators, which is consistent with the fair amount of Dalarna porphyries in the Saalian indicator associations of these regions.

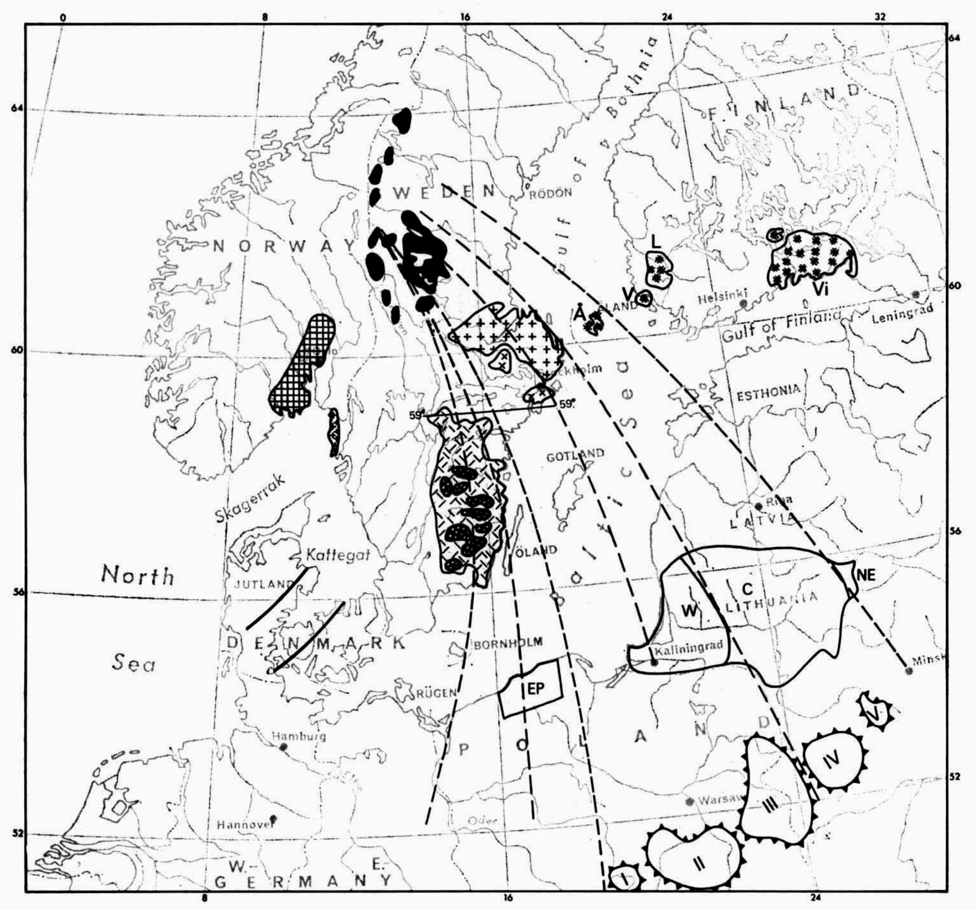

Fig. 36. The Weichselian in Lithuania in relation to the Saalian in Poland and White Russia. EP: area west of Gdansk (in the gap in the distribution pattern). Source areas as in Fig. 34, I-V, regions where Milthers & Milthers performed their counts. W: west, C: central and NE: northeast Lithuania after Tarvydas (1960). Solid-line segments: dividing lines between areas with predominant porphyries in Denmark. Dashed lines: inferred flowline pattern.

Apparently, the Dalarna porphyries were transported along a corresponding route in the Weichselian, because G. de Geer (1885) concluded from the presence of Älvdal porphyries on Gotland and their absence in the Uppsala region, that they passed west of Uppsala and reached Gotland from the NW. Königsson and Svantesson (1975), however, questioned the genuineness of the Älvdal porphyries. They refer to Hedström, who pointed out in 1894 that the porphyries on Gotland originated from the bottom of the Baltic north of the island. This may be partly true, but the high percentages of Jotnian sandstones in the gravel deposits imply that, likewise, porphyries from Dalarna are bound to occur on Gotland. The decline of the Dalarna porphyries from west to east in the investigated area in Poland also agrees with the position of the tracks under study, since the distal parts of those toward regions IV and V lie outside the source areas, and such that the farther they lie to the east, the greater the distance to the outcrops. Although the main provenance of the Dalarna indicators is not covered by the routes to regions IV and V, low percentages of Dalarna porphyries are still found in these parts of White Russia. If, however, the distal sides of the routes to IV and V are extended northwestward, they come to lie over outcrops of Dalarna, or more precisely Bredvad, porphyries along the Swedish-Norwegian boundary in Jämtland. The locations of these porphyries, it is true, lay on the wrong side of the main ice shed for their boulders to be carried in glacial transport toward the southeast. Even so, since the outcrops are situated on the east side of the main watershed, boulders of the Bredvad porphyries must have been carried to the east by river transport in the pre- and interglacials in order to have been picked up in the glacials by the southeastward-moving ice stream. This might explain the presence of part of the Bredvad porphyries in regions IV and V. On the other hand, in view of the opinion of Eskola (1933) it is conceivable that outcrops of porphyries similar to the Dalarna types occur on the sea-bed of the Baltic or the Gulf of Bothnia.

The areas of the theoretical flow pattern that connect the Åland islands with regions IV and V in White Russia cover the central part of Lithuania, where, as already mentioned, indicators from Åland predominate. Thus, in analogy with the conveyance of the Dalarna porphyries, the route by which the Åland indicators were conducted to regions IV and V in the Saalian seems to coincide with the transport route of these indicators in the Weichselian as well, but with central Lithuania as the destination. Viewed in this light, the predominance of the Åland indicators in central Lithuania as compared with the 89 and 88% of such indicators in the White Russian regions is explained. A noteworthy point is the parallelism of the dividing lines separating Tarvydas' meridional zone with the theoretical lines of ice movement.

As can be seen from Fig. 36, the hypothetical route of ice movement close to the southwestern tip of the Finnish mainland and over the adjoining archipelago connects up with the area of NE Lithuania where indicators from southwest and south Finland predominate. It is true that Viborg and the neighbouring regions of Karelia lie outside this track, but Eskola (1933) pointed out that rock varieties from these areas also crop out on the sea-bottom and the archipelago southwest of Finland. This is the case, for instance, for the Viipuri or Viborg rapakivi. Therefore, there is little or no point in distinguishing between indicators from southeast and southwest Finland. On the other hand, east Finnish indicators could have been shifted westward by floes and icebergs before the advance of the ice. According to Hyyppä (Donner, 1965), such transport took place in the Finnish Gulf during the last retreat of the inland ice.

The introduction of south Finnish indicators into the lower moraine horizons of the Eopleistocene and Mesopleistocene in SE Lithuania could just equally well have been promoted by partially waterborne transport. However, Gaigales (1963, 1965), who called attention to these lower horizons, suggested an ice movement from north to south to explain the presence of the south-Finnish material, and held a NW-SE ice stream responsible for the indicators from northern Sweden and the Baltic, which are encountered in the upper horizons of the moraines of the Eopleistocene and Mesopleistocene and the moraines of the Neopleistocene in southeastern Lithuania.

Gaigales and Gudelis (1965) specified percentages of the various groups of indicators in the Brandenburgian, Frankfurtian, and Pomeranian substages in SE Lithuania, a region which ranges under central Lithuania, as designated by Tarvydas (1960) in his tripartite regional distribution of the Pomeranian Substage. The indicators of the Åland islands, which fluctuate between 51 and 54% predominate not only in the Pomeranian but in the two older substages as well. Besides the Åland group, there are those of the Baltic sea-floor and of Sweden, with average percentages of 16 to 20 for the three substages. The indicators from southwestern Finland are in the minority, their percentages ranging between 5.4 and 13. The distribution of the association's percentages in each substage agrees with a NNW-SSE drift over the Åland islands toward SE Lithuania. This also holds for the Pomeranian Substage, despite the N-S ice stream proposed by Gaigales & Gudelis in 1965, because the 5.2% difference between the south Finnish associations of the Brandenburgian and Pomeranian substages is not sufficient to make an exceptional case of the direction of the Pomeranian glacier movement. On closer analysis of the erratic association of the last glacial, Tarvydas (1967) too arrived at the conclusion that in both the Brandenburgian and the Pomeranian the direction of the ice flow toward Lithuania was more or less the same, i.e. roughly NNW-SSE.

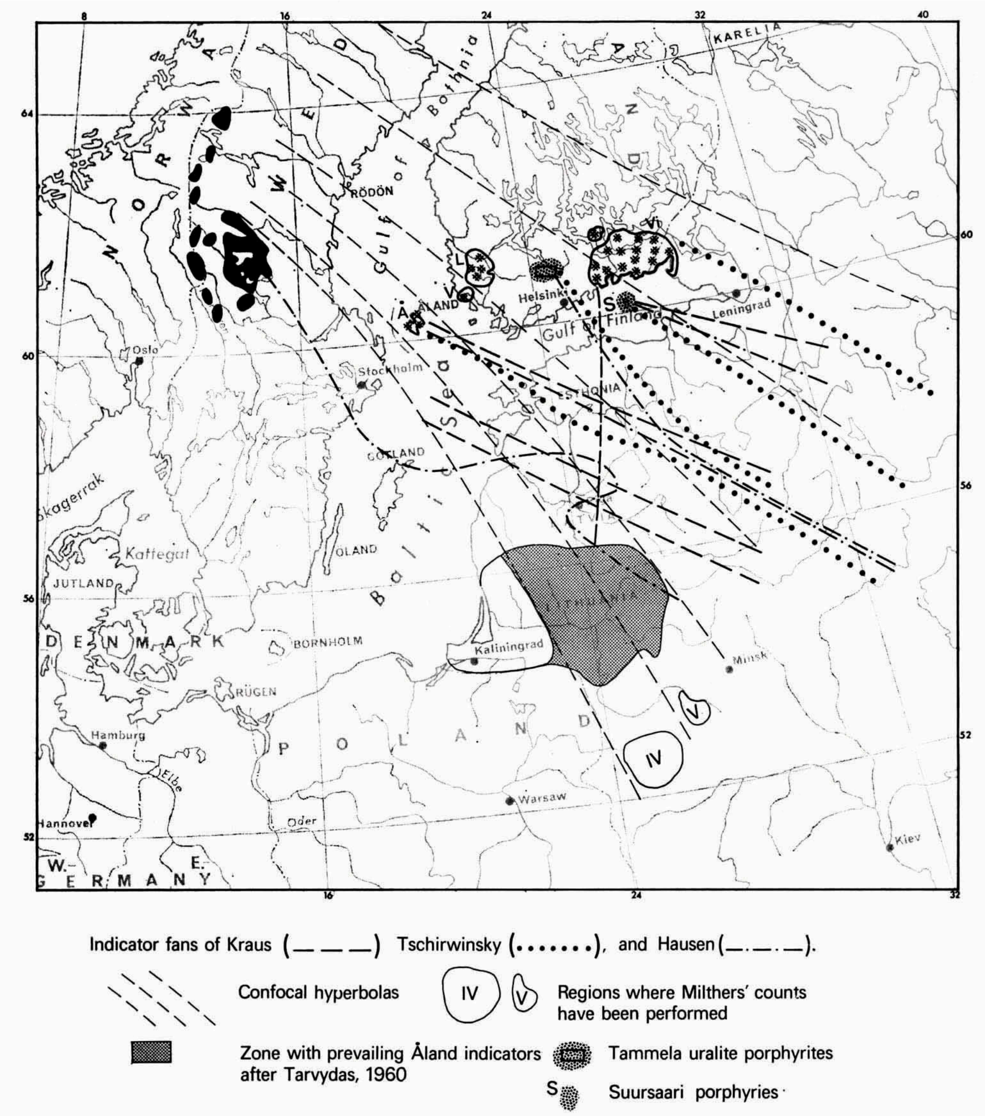

Fig. 37. The indicator fans of Kraus, Tschirwinsky and Hausen in relation to directions of the confocal hyperbolas. See also key to Fig. 34.

Further inland, southeast of Lithuania and Latvia, lie White Russia and Wolhynia. To what extent do the indicator associations of these regions fit into the dispersal pattern of the Baltic coastal areas? Tschirwinsky (1926) found that the indicators from Åland predominate in Grodno, a region lying between central Lithuania and Milthers' region IV in White Russia (see Fig. 36 and enclosure map). These indicators also predominate in the western part of Wolhynia, where, according to Gagel & Korn (1918) there is also a small amount of Dalarna porphyries.

In the eastern part of Wolhynia (the Kiev and Tschernigov districts), and the eastern part of White Russia (southeast of Minsk and the Mogilev districts) Tschirwinsky (1926) found neither Dalarna nor Baltic porphyries and only a few Åland indicators, but indicators from southern and southwestern Finland were in evidence. Since these areas lie north of the line of ice flow (see Fig. 36 and folding map), which all but coincides with the dividing line separating the central part of Lithuania from the northeast corner of that country, where indicators from Finland predominate, the indicator dispersal pattern of the eastern coastal areas of the Baltic continues further inland to the southeast, in accordance with the inferred lines of ice movement.

### *Indicator fans in the eastern circum-Baltic*

Kraus (1934) is one of the investigators who worked on the reconstruction of indicator fans. Some of his fans, whose eastern limits are shown in Fig. 37, were subjected to further investigation in the present study. Because, as Eskola (1933) pointed out, the provenance of the Viipuri rapakivi is not restricted to its type locality, the western lateral limit of this indicator fan as shown by Kraus cannot be maintained. Since rapakivi granites related to the Viipuri type also occur in the rapakivi areas on the west coast of Finland, the initial point of the western lateral limit of this fan would have been west of the Finnish west coast and not on the west side of the Viipuri massif. Accordingly, the shifted limit trends roughly NW to SE instead of N by E to S by W, as in Kraus' representations.

The easterly lateral limits of the indicator fans represented by Kraus (1934) run more or less parallel from NW by W to SE by E and intersect the hyperbolas at an angle of 20-30°. It should be pointed out that the eastern limits of the indicator fans, whose apices lie north of the Baltic and the Finnish Gulf, are more reliable for determination of the consistent directions of ice movement than the western lateral limits in this area. There are two main reasons for this. Firstly, the westward extension of the provenances of some of the important indicator types cannot be directly observed, e.g. outcrops of the Viipuri rapakivi and the Suursaari (Hogland) porphyries are theoretically present under the Baltic. Secondly, for the western limits lying mainly in the Baltic, i.e. the territory of the Baltic ice stream, these limits are more closely related to the inconsistent than to the consistent ice movement. This means that the eastern limits of the indicator fans are indicated to learn us more about the directions of movement of the inland ice in this area.

As represented by Kraus (1934), these limits intersect the inferred lines of ice movement at an angle of 20 to 30°. Figure 37 shows that the eastern limits defined by Tschirwinsky (1926) and Hausen (1912) correspond much better with the trends of the hyperbolas especially those of the Viipuri granites, the Suursaari (Hogland) porphyries, and the Tammela uralite-porphyrites. The eastern limit of the Åland indicator fan deviates distinctly from the direction of the hyperbolas,

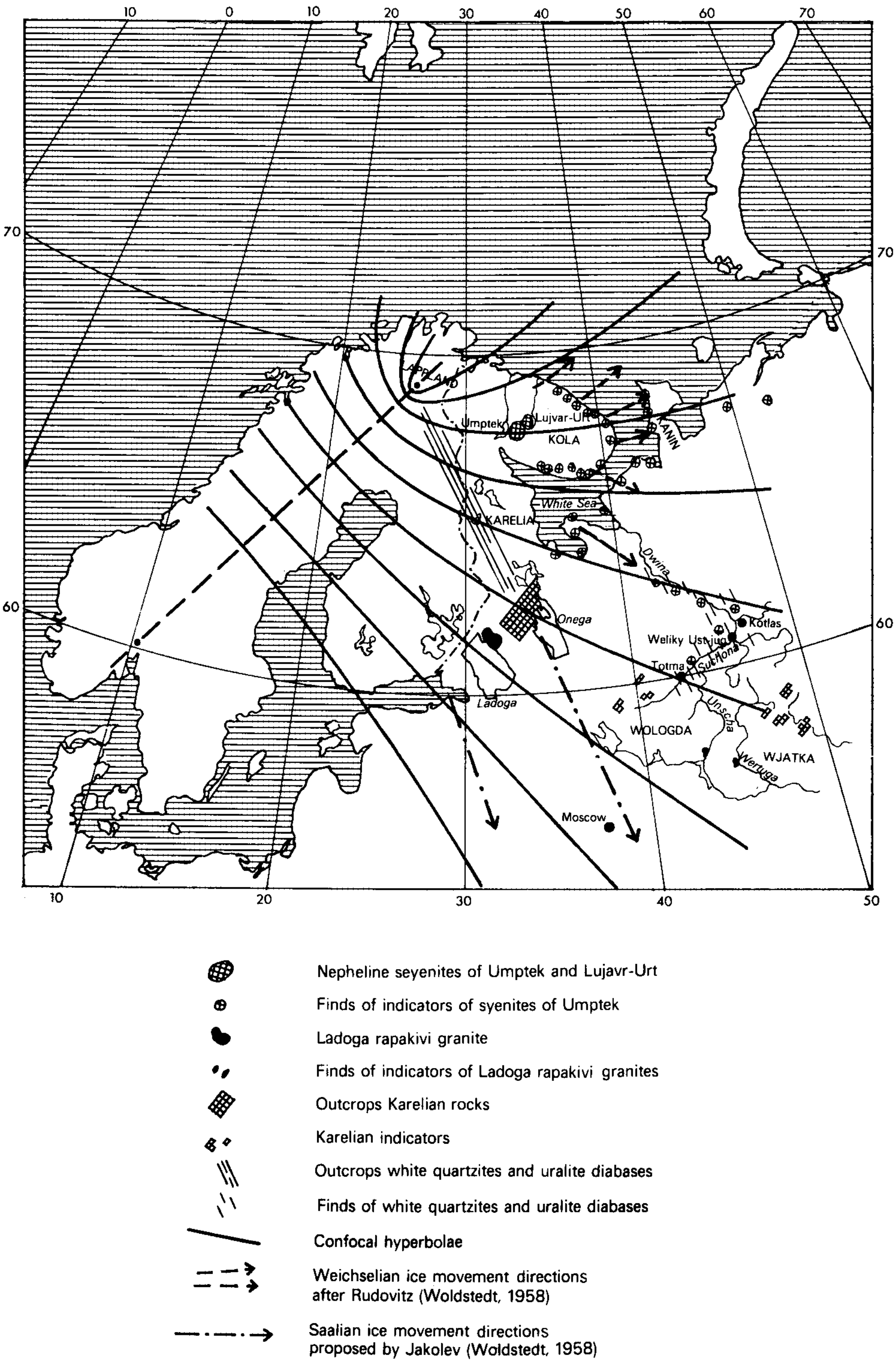

Fig. 38. Dispersal of indicators in northwestern Russia as described by Ramsay & Hackman.

which might be due to the lack of information about the exact submarine extension of the Åland rapakivi massif.

These three investigators are in complete agreement about the shape and position of the eastern limit of the Dalarna porphyries, the latter is indicated in Fig. 37 by the symbol used for Hausen's view. The Swedish continental part of this limit coincides rather well with the inferred direction, but on the Baltic coast both the limit and the direction diverge widely, the inferred trend continuing toward Grodno, the eastern limit crossing the northern tip of Gotland and zigzagging through Estonia. As we have seen (p. 79), this deviation could be due to the outcrops of Bredvad porphyries in Jämtland and/or possible submarine occurrences of Dalarna porphyries in the Baltic, but there might be another reason.

As the dates of the quoted publications show, the fans under consideration were defined at a time when the quantitative method was rarely or not yet used for the study of indicators. It can be inferred from these publications that in the mapping of indicator-fans, localities with only a few or even only one indicator were used. Therefore, deviations from the main ice movements during glacial and non-glacial transport are apt to manifest themselves in such representations, especially along the lateral limits. Thus, the main ice movements may be obscured by a deceptive background effect. Conceivably, this effect could be suppressed by estimating the pro rata contributions of every recognizable indicator group in each locality, and excluding those groups whose percentages lie below a certain minimum threshold. The height of the threshold for each separate indicator category could be determined by trial and error. This might yield lateral limits of indicator fans giving a better approximation of the main flow directions of the inland ice than those of the initial fans.

Although appropriate handling, including the making and analysis of supplementary counts, is required to carry the proposed method into effect, a possible case in point is of interest here. The afore mentioned eastern limits of the Åland indicator fans were based on occurrences of Åland indicators, which were in the minority. In contrast, they predominate in the central zone of Tarvydas's tripartite division (Fig. 37) of the Pomeranian Stage in Lithuania. His investigations show that the indicators of the Åland indicator fan are not evenly distributed and are distinctly predominant in the central Lithuanian zone. This zone with its parallel boundaries trending NNW to SSE is directed toward the Åland islands. It need hardly be said that this density zone is more likely to indicate the direction of the main ice flow over the Åland islands than is the eastern lateral limit of this indicator fan.

### *The distribution of indicators observed by Ramsay and Hackman in northwestern Russia*

Ramsay and Hackman (1894) were of the opinion that during the main extension of the ice sheet the glacial flow over the Kola peninsula was from west to east, the ice stream having transported boulders from north Finland toward this area. Because the glacial drift in Fennoscandia formed during the last glaciation (drift older than the Weichselian is exceptional here), the glacial deposits of the main extension in Kola are likely to be considered Weichselian too, the more so because according to Ramsay subsequent the nunatak phase developed, around the time of ice halt at the Salpausselkä. In 1912, however, Ramsay reconsidered his view in that the ice stream direction from west to east followed the main phase, in which the glacial flow direction over the Kola peninsula was to the SE. He did so because he had found that the extension of the dispersal area of the nepheline-syenite from Umptek and Lujavr-Urt was much larger than he had initially thought. While sailing down the rivers Suchona and Dwina (Fig. 38) he saw the first nepheline-syenite in the pavements of Totma. Further downstream, syenite indicators occurred among the river boulders, but the first embodied in moraine were found in Weliky Ust-Jug and Kotlas. The syenite finds along the Suchona and the Dwina form part of a small fraction representing only one per cent of the whole body of crystalline erratics. The syenite indicator density is greater on Kanin peninsula, where it amounts to about one per cent of the total number of crystalline erratics, which seems to suggest that the main ice flow over the Kola peninsula was after all from west to east.

This direction is supported by additional information obtained by Ramsay (1912) about the dispersal of some other indicator groups. Typical Karelian rocks that crop out north and northwest of Lake Onega are found in the Wologda area

Fig. 39. The circular zone round $F_3$ further to the south. $F_1$, $F_2$: foci confocal ellipses. $F_3D$: base of circular pattern. $NF_3$ is normal to $F_3D$. M: main stationary line, W: moraines of the Warthe glaciation. a, b, c, d, e: Saalian ice front phases. $F_n$: centre of circular configuration in The Netherlands.

and in the Wjatka district. As shown in Fig. 38, this dispersal points to a consistent transport direction. The same holds for some indicators belonging to the Ladoga rapakivi that were found in the rivers Unscha and Wertuga. White quartzites and uralite-diabases, whose provenances lie in a zone running from Lake Ladoga and Lake Onega into Lappland, occur generally along the rivers Suchona and Dwina.

Since the dispersal of the additional indicators fits reasonably well into the framework of hyperbolas and the higher density of the nepheline-syenites on Kanin also fits into the theoretical streamline pattern, there is after all good support for a west-to-east ice flow over the Kola peninsula during the main extension of the ice sheet. The main ice movement directions indicated by Rudovitz over Kola peninsula are also shown in Fig. 38. They hardly deviate from the inferred streamlines. This is not the case for the Saalian main ice flow directions toward Moscow represented by Jakowlev on a map of the Russian Quaternary, reproduced in Woldstedt (1958).

The evaluation in this chapter of the consistent indicator distribution on the basis of the inferred flowline pattern, has led to the following results. It not only confirmed the conclusions arrived at thus far, but also contributed to a better understanding of the relationships between the source, the route of transport, and the consistent distributions in The Netherlands and in Germany as far as the east side of the Oder. It partially filled the gap in the distribution pattern in which no Hesemann or Milthers counts had been performed. It furnished detailed evidence confirming the corresponding stream directions in the Weichselian and in the Saalian, in this case toward Lithuania and toward Poland and White Russia. The eastern limits of indicator fans and the dispersal of a number of species of indicators in Russia proved to coincide passably with the inferred pattern of ice flow.

Crude as the results may be, they justify a further elaboration of the flowline pattern, which might be useful in considering the changing shapes of the Fennoscandinavian ice sheets. Accordingly, an attempt to work out the inferred flow structure will be discussed in next section.

## GEOMETRICAL ASPECTS

### *The circular zone further southward*

We have shown above that the pattern of ice flow and successive outlines of the Fennoscandinavian ice sheets may be compared to a set of confocal hyperbolas and ellipses adapted in the southwestern sector to a zigzag bend in the ice divide. As expounded on p. 39, the flowlines between the ice divide and the main stationary line in Denmark resemble arcs of a set of concentric circles. In Fig. 39, $F_1$ and $F_2$, the coequal foci of the ellipses and hyperbolas, are indicated by circlets. $F_3$ is the focus of the circular pattern. This pattern returns in the general tendency of the river courses in this particular zone of former ice movement.

We have followed the circular feature as far as the main stationary line in Denmark, but how will this pattern continue in the southward direction? In central Jutland the stationary line strikes north, but farther to the south the moraines strike east-to-west. The direction of ice flow being normal to the moraines, a shift in the orientation of the moraines means a shift in the trends of flowlines. Accordingly, the encircling structure flattens out toward The Netherlands and even turns to the southwest.

For a better understanding of this zigzag tract we may turn to The Netherlands, where diverse glaciation phases of the Saalian have been studied by, among others, Brouwer (1948, 1950), Maarleveld (1958, 1960), and ter Wee (1962). A detailed review has been given by de Jong (1967) and Jelgersma & Breeuwer

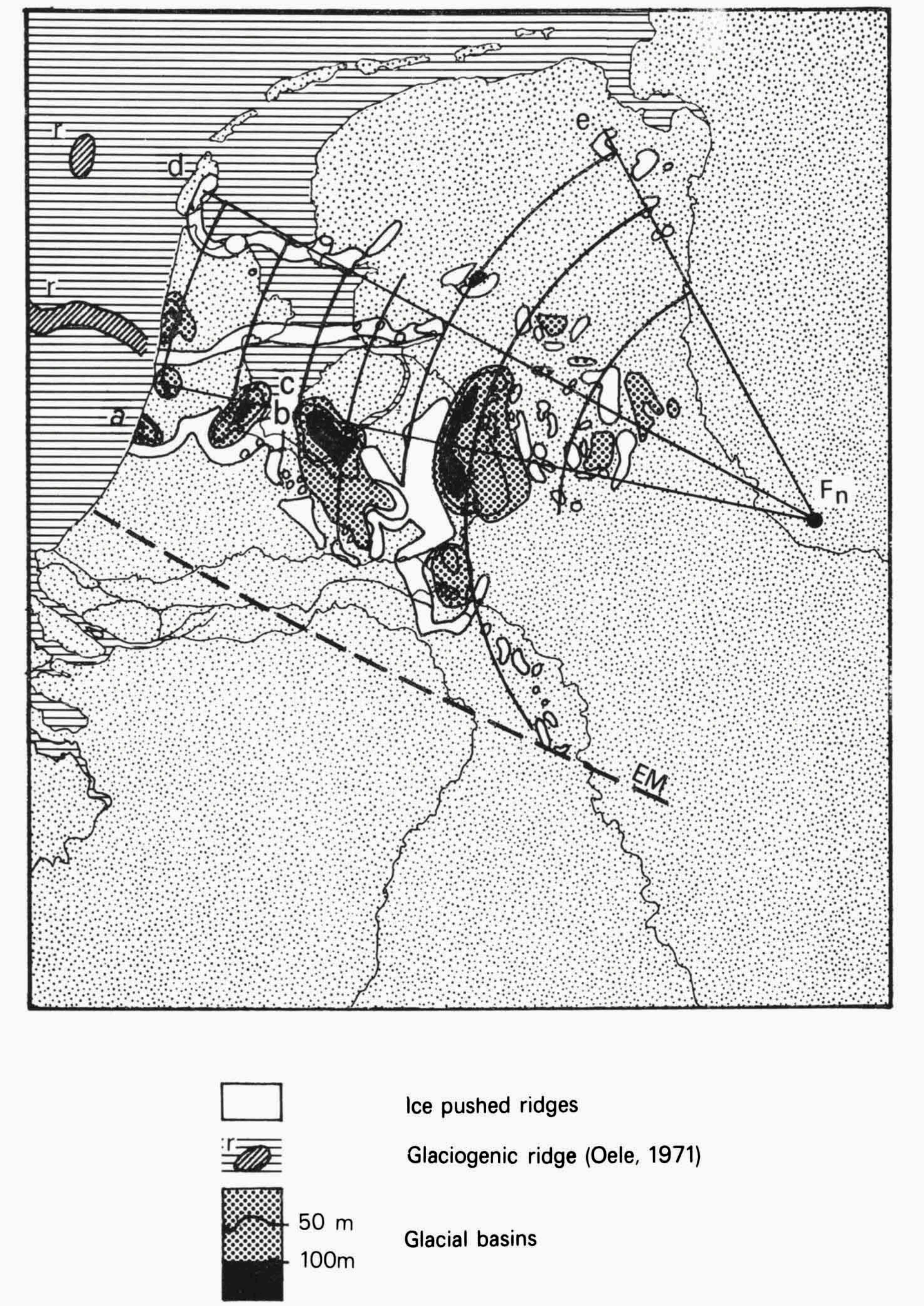

Fig. 40. The pattern of the Saalian morphology in The Netherlands in relation to circular tracts about $F_n$. Saalian after retreat of inland ice from Zagwijn (1974). a, b, c, d, e: Saalian ice front phases according to Maarleveld (1958, 1960) and ter Wee (1962). EM: part of the confocal ellipse to which the maximum of the Saalian in The Netherlands approaches.

(1975). Fig. 39 shows the phases of the Saalian compiled by ter Wee (1962). It would appear from the diverging trends of ice front phases that a wheeling movement of the ice margin took place, but there is other evidence to be considered.

Zonneveld (1975) pointed out that many of the ice-pushed ridges show 'drumlinized' forms. Those of phase d, being parallel to each other and striking NE to SW, argue – according to Zonneveld – for an inherent ice stream from the NE. The drumlins of phase e, on the other hand, strike N60°E to S60°W. Thus, as compared with phase d, a change of directions as one should expect with a wheeling movement. In both cases the directions of ice flow agree with the trends of the glacial ridges they belong to.

Since not only the main stationary line and the moraines of the Warthe glacial but also phase e in Groningen are collateral, the ice flow directions pertaining to these phases must have been much alike, which would virtually restrict the change in direction to The Netherlands. Therefore, the centre of rotation of the wheeling movement should be sought nearby, and a centre of revolution was indeed found, by trial and error, just east of the Ems. Figure 40 presents a set of confocal circles drawn by means of this centre ($F_n$), and shows how the circular structure and the pattern of the glacial landscape interlock. This circular pattern of movement also answers the question as to why, despite the different directions of ice flow in different parts of The Netherlands, the consistent indicator distribution of the diverse glacial phases remained the same.

How is $F_n$ related to the flowline pattern geometrically? In Fig. 39 the distance between the centre, $F_n$, and the focus, $F_3$, equals the distance between $F_3$ and D. Since $F_3D$ coincides with the ice divide in the circular zone, it may be looked upon as a base or a line of symmetry of the circular pattern.

Although the measured distances are equal, the neglect of the curvature of the earth surface with respect to the scale and projection of the map in use might lead to inaccuracies that are not negligible.

To evaluate this point, I applied the formula $\cos X = \sin M \sin M_1 + \cos M \cos M_1 \cos (L-L_1)$ from spherical trigonometry (Donnay, 1945) to the coordinates M, L (68°36′N, 25°50′E) of $F_2$ and $M_1$, $L_1$ (52°18′N, 7°36′E) of $F_n$, and obtained a spherical distance x of 18°15′. If 6377.36 km is taken as the radius of the mean curvature of the earth's surface, the actual distance is 2049.875 km, which on a scale of 1 : 12 070 000 (the original scale of Fig. 39) amounts to 16.98 cm. Measured on this scale, thanks to the type of map projection used, $F_2$ and $F_n$ are 16.99 cm apart. Thus, the difference between the spherical and measured distance is within the magnitude of the error of measurement, which permits direct measurements from maps of the same size or smaller. No greater accuracy will be achieved by the application of spherical trigonometry.

In Figure 39, angle $F_3DF_1$ measures 20°. $NF_3$ is perpendicular to $F_3D$, and angle $NF_3F_n$ measures 20° too. The recurrence of the angle of 20° and the equality of $F_3F_n$ and $F_3D$ may indicate that $F_n$ is a natural component of the geometrical framework. This could mean, in effect, that $F_n$ is an inevitable result of the unhampered development of the ice flow pattern.

On the other hand, $F_n$ may have been induced not by internal but by external forces, i.e. a trigger effect from the resistance offered by the Harz, the Teutoburger Wald, and the interjacent range of mountains to the advancing ice. This 300-400 m high massif which rises 200 to 300 m from the north-German plains, was the largest obstacle the ice encountered on its way southwestward. A spur of this obstacle, the Teutoburger Wald, must have been overridden, while the rest of the Harz massif created a reentrant ice margin in the maximum extent of the Saalian glaciation.

Such an obstacle slackens an ice flow, and in this case must have slowed down the advance on the east flank of the ice stream to the southwest, a stream whose width may be put at 300 km. The impediment to movement on the east side of the ice in combination with a free passage to the west may account for the wheeling effect of the ice front in The Netherlands. An obstruction interfering with the natural development of the growing ice sheet, as in this case, can lead to stresses which may build up until they trigger off glacial surges. This fits into the view of Zagwijn (1974), who proposed sudden, torrential ice flows as the active agents in the formation of the ice-thrust ridges or lobes at the southernmost extension of the ice sheet in the central part of The Netherlands.

In sum, it appears that the circular pattern round $F_3$ of the Weichselian continues from the main stationary line in Denmark as far as the Saalian phase e in The Netherlnds, where it seemingly changes over into another circular unit with its centre in $F_n$.

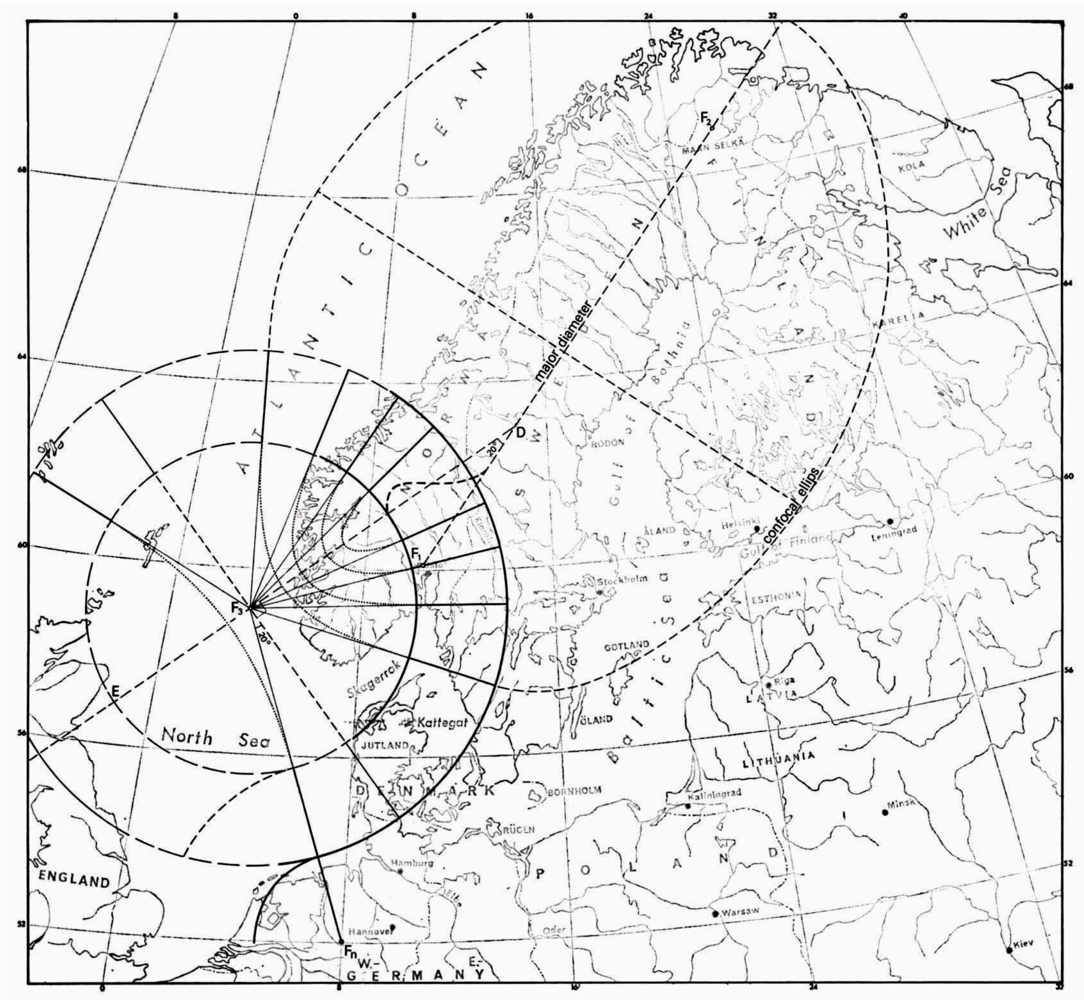

Fig. 41. Morainic contours on the inside of the circular zone, constructed by symmetry operations. For explanation, see text.

### *Provisional flowline and ice margin pattern in the North Sea*

In the foregoing, a flowline pattern was analysed and developed as far as the maximum extension of the Saalian ice sheet. Traced on land, this alignment is very clear in Fennoscandia. It disappears into the Gulf of Bothnia and the Baltic, to reappear, partially blurred, in the circumjacent area south of the Baltic. The perceptible pattern has several elements of symmetry, such as the median of the set of confocal ellipses and hyperbolas, $F_1F_2$, the diameter of the concentric circles which coincides with $F_3D$, and the centres of rotation $F_3$ and $F_n$. Symmetry elements mean symmetry operations, and this led to the question of whether, on the basis of our flowline pattern and with the help of these elements, a flowline structure could be obtained in the North Sea, and Atlantic. The following discussion attempts to answer this question.

The broad sinuous zone toward The Netherlands gives some clues about the position of the former ice borders. It provides a correlation of end moraines and recession lines in The Netherlands, Denmark, southern Sweden and Norway, with plausible elliptical counterparts to the east. Before this feature can be used as a kind of gauge, however, further elaboration of the pattern is necessary.

In the circular zone with $F_3$ as centre, the morainic contours hardly underwent any change, as appears from the persistance of shape of the zigzag bends (Fig. 39). To simplify matters, the Z bends are represented as straight segments of lines through $F_3$ in Fig. 41. The diameter coinciding with $F_3D$ is the most plausible axis of symmetry for the circular pattern. Equivalent straight-line segments of the circular zone on either side of $F_3D$ are connected by thin lines to the focus $F_3$, and are coupled together by symmetrical arched curves. The arches, still narrow at the beginning of the movement, become wider and wider the more the ice sheet grows, and even become rectilinear when the straight segments of the circular zone are in line with each other. This right-line meets $DF_3$ perpendicular at $F_3$ the centre of rotation of the circular pattern. That is to say, at an angle of rotation of 90° a straight stretch appears in the contour of the corresponding moraine. In this tentative approach, the moraines at the inside of the circular zone are initially convex. The moraine through $F_3$ is rectilinear, and between $F_3$ and E the moraines are concave.

The angle between the straight line through $F_3$ and the line denoted by $F_nF_3$ is 20°. Figure 41 shows the concave contour that coincides with $F_nF_3$. A concave margin which, at least on its southern branch, forms the limit of the movement that can be reconstructed by means of $F_3$.

This descriptive appraisal of possible relationships between several elements of the movement pattern provides the following features with which a provisional flowline and outline pattern of the Scandinavian ice sheets can be constructed (Fig. 41):

1) The most essential element is the sinuous zone, the combination of two circular units. The major, northern part round $F_3$ trails off in a smaller, southern part round $F_n$. As a result, a rough correlation of assumed or subsistent ice margins in this zone with counterparts on either side is possible. Since the foci and the location of the transition of the circular zones are known, the circular lines of flow are easy to reconstruct. The result is a winding course which may be seen as a dial to correlate ice fronts on both sides.

2) Any stretch of end moraine in the sinuous zone can be linked up with an appropriate member of the set of confocal ellipses. This gives a rough idea of the

extension of the ice sheet in question on the east side of our dial.
3) On the west side of the sinuous zone, the assumed configuration of ice front phases on the inside of the circular unit around $F_3$ offers a useful basis for an attempt at a theoretical reconstruction of Fennoscandinavian ice sheet margins.

Let us try, with these tools, to determine a maximum Weichselian extension of the Scandinavian ice mantle in the North Sea and Atlantic. In Fig. 42 the sinuous-shaped zone, a combination of the circular units about $F_3$ and $F_n$, contains three Z bends that refer to the ice divide, the Ra central Swedish moraines (RCS), and the main stationary line in Denmark (M). According to the method specified in Fig. 41, a convex ice margin that links up with the west side of the Ra moraine has been drawn in as a dotted line in the inner circle. The actual terrestrial equivalent (solid line), however, curves further outward. It appears from the direction of the glacial striae represented by Andersen (1965) that the north-to-south-striking mountain spur in southwestern Norway held a local ice divide. Consequently, the terrestrial moraines in the southernmost part of Norway extend further southward with respect to their theoretical position. North of $F_3D$ the theoretical ice border skirts the west coast of southern Norway and continues into

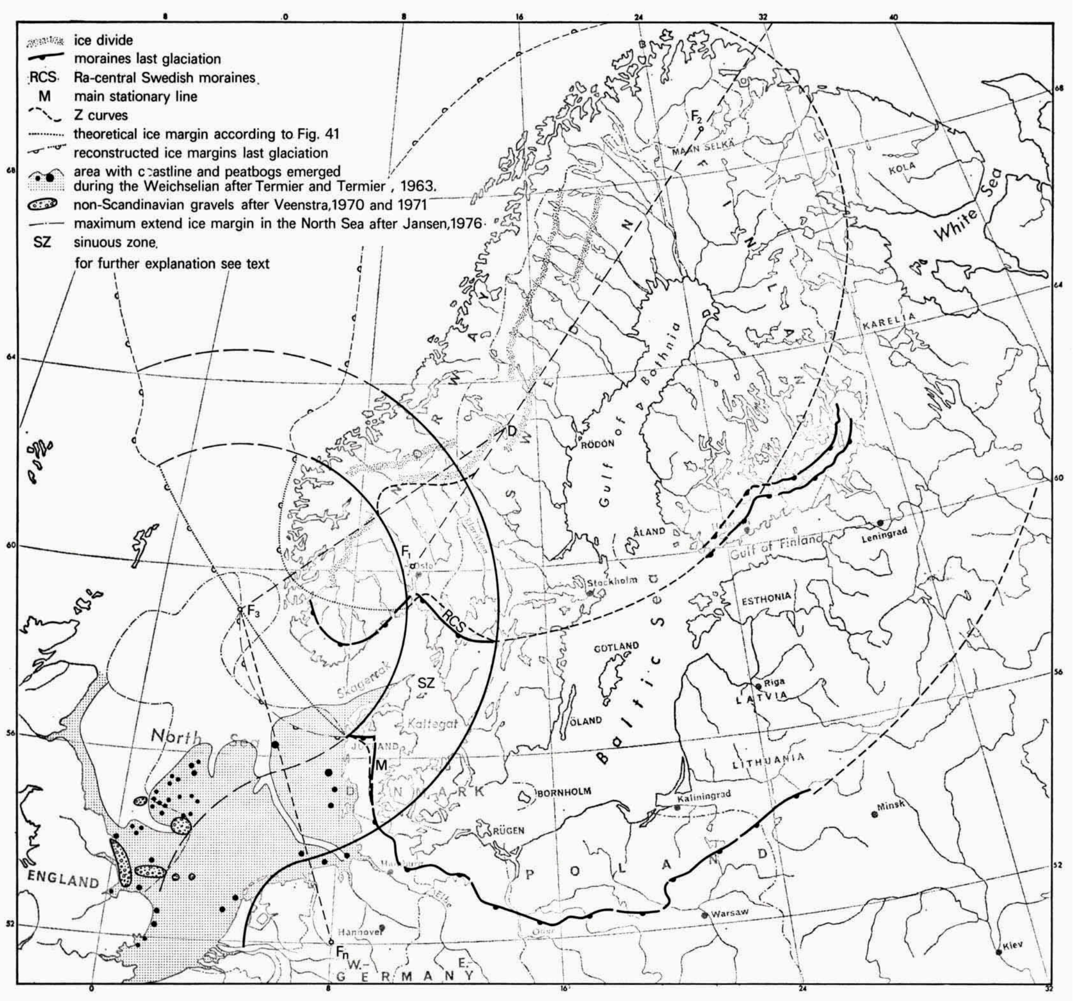

Fig. 42. A reconstruction of the maximum extension of the Weichselian ice sheet in the North Sea.

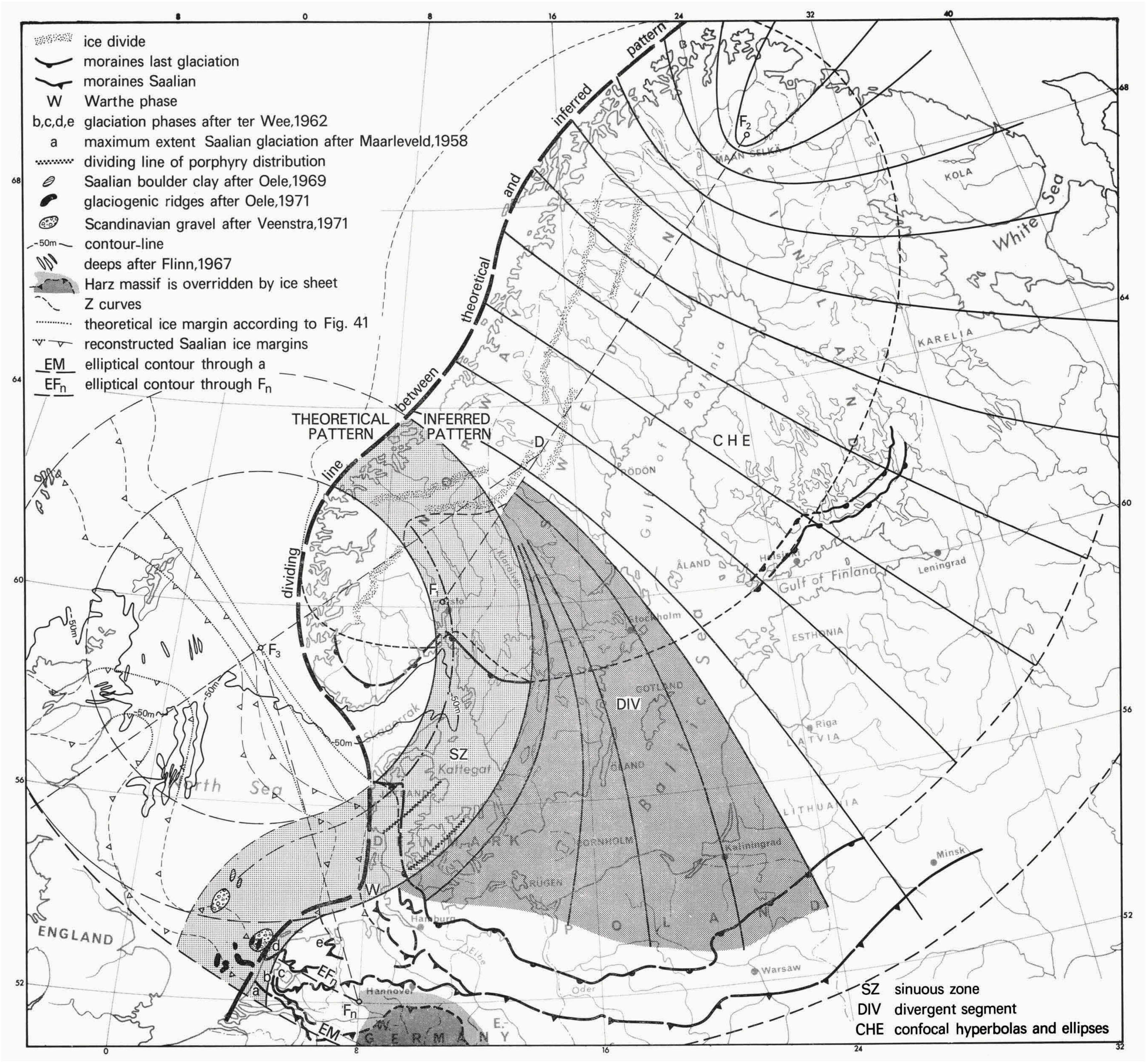

Fig. 43. Schematic representation of the flowline pattern and some ice margins of the Fennoscandinavian ice sheets, and a reconstruction of Saalian ice front phases in the North Sea.

the Atlantic. The southern end being normal to the adjoining fjords, it may approximate the corresponding former ice margin.

According to Fig. 41, the dotted line indicating the theoretical continuation of the main stationary line in the North Sea, as shown in Fig. 42, is only slightly convex owing to its nearness to $F_3$. But because of the difference between the theoretical and actual ice margins in southern Norway, this part of the hypothetical maximum Weichselian extension should protrude also. The dashed line in Fig. 42 gives an instance of this situation.

The development of the ice sheet, as expounded here, tends to have an elliptical outline, which means a symmetrical shape. Flint (1971) proposed, however, an asymmetric shape for the Scandinavian ice sheet, the southeastern expansion going beyond the extension on the northwestern side of the ice divide because the deep Atlantic water impeded expansion to the west. An asymmetric ice sheet determined by an underdeveloped northwest flank involves a possible smaller extension in the northern part of the North Sea and in the Atlantic than Fig. 42 indicates. Hence, apart from the bulging lobe between $F_3$ and the main stationary line, which could protrude differently, as suggested the Weichselian maximum north of $F_3$ as represented in Fig. 42 indicates an outer limit. Thus, according to these theoretical deductions, the Scandinavian ice sheet did not reach either the Faeroes and the Shetland islands or Scotland in the Weichselian.

Some authors are of the opinion, however, that in the Weichselian the Scandinavian ice sheet crossed the North Sea and linked up with its British counterpart. Figure 42 shows that one of the most recent views (Jansen, 1976) differs north of $F_3D$ from our reconstruction, but that south of this line the two are generally comparable. Likewise, the location of the Weichselian non-Scandinavian gravels between the Doggersbank and the English coast (Veenstra, 1970, 1971), conforms to a remote Scandinavian ice margin toward the north.

What are the implications of the preceding theoretical line of approach for the Saalian ice fronts in the North Sea area?

In Fig. 43 the Z bend is encircled farther to the south and joins with the Warthe Substage. Because the rotation passed through the 90° angle, the theoretical ice margin bridging the area of the inner circle of the circular zone must be concave (see Fig. 41). This ice front (dotted line) may bend outward again (dashed line) because of the disturbing effect of the local ice divide in southern Norway.

The ice front phase e of ter Wee (1962) lies in the neighbourhood of the transition zone of the encircling movement about $F_3$ to that around $F_n$. Its continuation in the North Sea is shown in Fig. 43.

South of ter Wee's phase e, the ice fronts wheel about the pivot $F_n$ to adjust themselves to the elliptical contours. Since $DF_3$ and its produced part form an axis of symmetry, a coexisting counterpart of this motion would have had its centre west of the Faeroes. No distinct traces of this movement have been found, however, in the Faeroes, the Shetlands, the Orkneys, or in Scotland, possibly because at the time of the Scandinavian ice approach these islands were covered by their own local glaciers, which were probably even merged with the Scottish Highland ice. This armour of ice may have protected the rock surface against the charge of the Scandinavian ice sheet. Another point to be considered is that the location of the focus west of the Faeroes coincides with a part of the Atlantic which at present is over 500 m deep. It is a question whether this focus lying on a buoyant member of the ice sheet would have had behaved in the same way as its terrestrial counterpart. On the other hand, since the wheeling movement about $F_n$ might also have been due to the resistance of the Harz massif, it could have been a solitary case sought in vain at the other side of $DF_3$.

Returning to The Netherlands, we note with interest that the wheeling movement bypassed the ellipse $EF_n$ through $F_n$. South of this ellipse, within a range of 150 km to the west of focus $F_n$, the ground is more heavily ploughed than on the north side. This zone between $EF_n$ and the ellipse EM, through the maximum extension of the Saalian ice sheet, is a zone where the hampering of the natural expansion of the ice sheet by the Harz massif must have set up stresses. The intense disturbance may have been a response to the release of these stresses, and the river valleys may have gauged the liberated forces. For Maarleveld (1960) found that the higher relief intensity of this glacial landscape had been promoted by the preglacial river valley topography in the central part of The Netherlands.

The Netherlands Geological Survey carried out extensive investigations in the Dutch part of the North Sea, which resulted in two maps. These detailed maps of the Quaternary geology were published by Oele in 1969 and 1971. Oele (1971) assumed that the southernmost ice-pushed ridges in the North Sea 'mark the location of the ice front during its maximum extension (phase a of Maarleveld, 1958 and ter Wee, 1962)'. The alignment of these ridges with the inland ice front phase a, supports Oele's assumption. Oele also considers the glaciogenic ridge west of Texel to be a continuation of the ice front phase d of ter Wee (1962). Again, both could belong to the same ice borderline. The Saalian boulder clay in the centre of the North Sea, which Oele denoted on his 1969 map, forms part of a moraine lying between ter Wee's phases d and e. It is interesting to note that the flowline through the Oslo fjord passes through this outcrop of the Saale glaciation.

During a bathymetric survey Flinn (1967) recognized an arcuate belt of deeps to the east of Scotland which he considered to have been formed at the front of an ice sheet. These trenches, as shown in Fig. 43 parallel the sides of the concave margins of the inner circle, on both the north and south sides of the median through D. Flinn argues that the area at the inside of the arcuate belt had been ice free. Since the geological age of the trenches is uncertain, however, we cannot attach very much value to the relative positions of the deeps and the theoretical pattern.

Veenstra (1971) describes a Scandinavian gravel consisting of porphyry, granite, and flint on the Cleaver bank situated southwest of the Saalian boulder clay just mentioned, and a gravel composed of quartzite, flint, and granite occurring on the west side of the island of Texel. Their locations fit into the general picture.

The southern elliptical contours running virtually parallel with the English coast throw new light on the Crag sequence in southeastern England. The flowline through the Oslo fjord pointing toward Norfolk and Suffolk coincides with the occurrence of Norwegian erratics in these areas.

The Fennoscandinavian flowline pattern and the trends of the areal distribution of indicators coincide in the consistent pattern. Before this pattern could be explored it had to be deciphered and distangled, but on the whole the search for this partially concealed alignment was descriptive in nature. The resulting inferred pattern is more or less substantiated, unlike the reconstruction in the North Sea, which represents an attempt to extend a known pattern into an unknown area. The result is a theoretical framework, which may be used for further thinking.

# Integration of consistent and inconsistent distribution processes

## THE WEICHSELIAN RECESSION IN DENMARK

### *An incorporation of the retreat in Jutland, the Kattegat and southern Sweden*

As expounded on page 39, the concave bends of the main stationary line in Jutland, of the combined Norwegian Ra and central Swedish moraines, and of the ice divide, are associated by circles with a common centre. The dividing lines of the porphyry distribution in Denmark form part of the same set of circles.

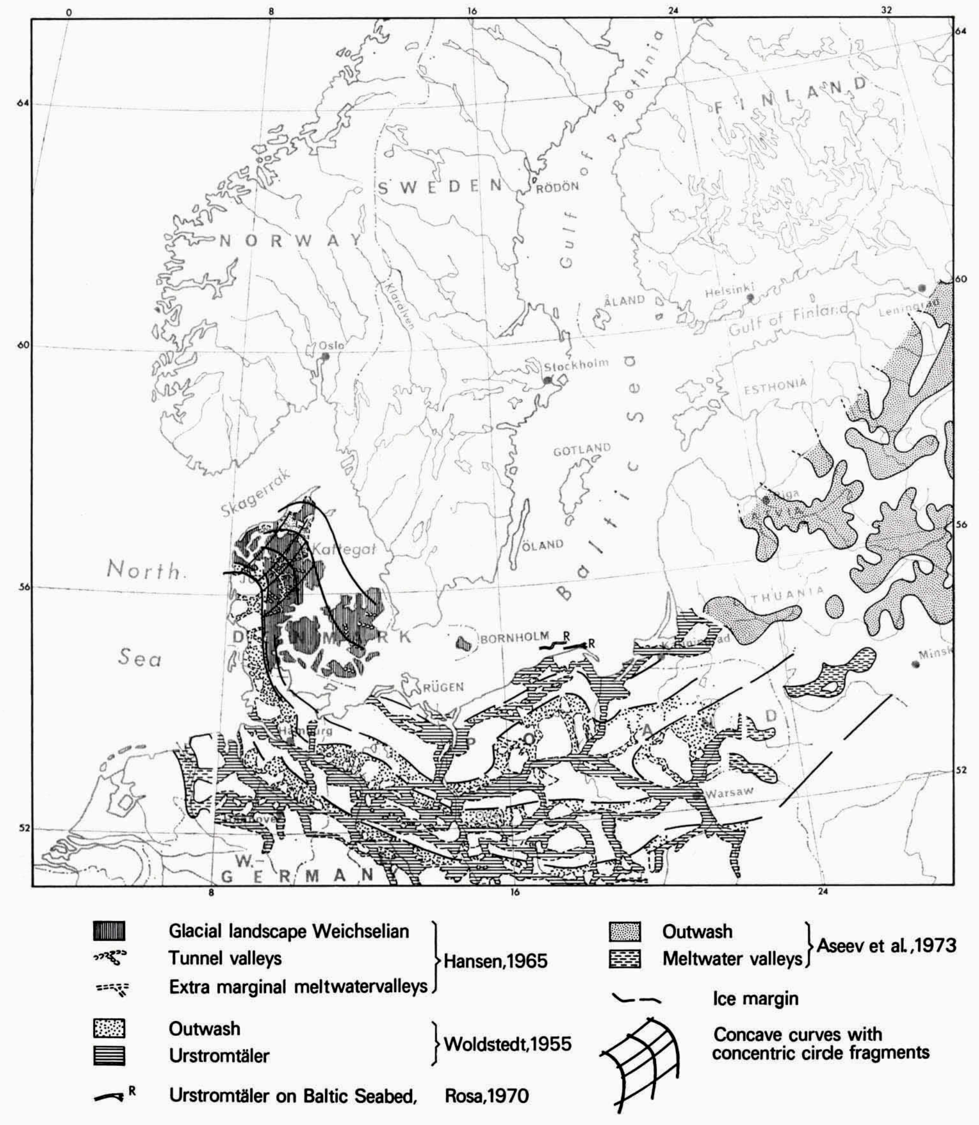

Fig. 44. An array of concave curves and concentric circle fragments set against the glacial landscape in northern Jutland and the ice-marginal channels and lakes of the circum-Baltic.

On the basis of the circular pattern, an array of matching concave curves and a few concentric circle fragments are superimposed on the northern part of Jutland in Fig. 44 for comparison with the glacial landscape. The result is clearly harmonious.

An additional check has been made possible by Mörner (1969), whose investigations threw new light on the Late Weichselian ice front phases in the Kattegat. He found no signs of a Kattegat ice stream toward the south, but saw a set of northwest-to-southeast-trending lines he interpreted as traces of margins of an ice sheet that receded toward the northeast. Not only the general trends of the individual lines in the central part of the Kattegat, but also the whole southeastward diverging bundles of lines on the corresponding part of Mörner's map agrees with the spreading Z curves which are radial parts of the circular pattern with a

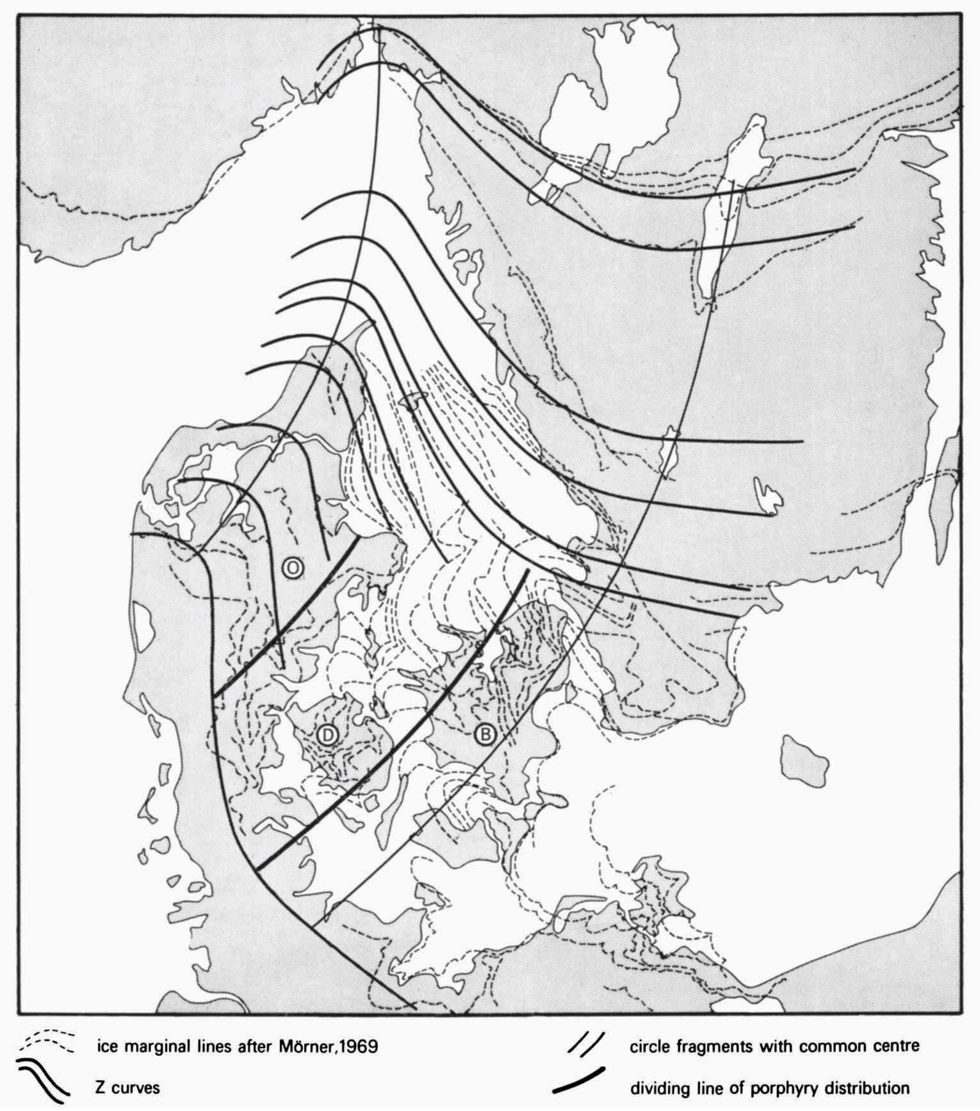

Fig. 45. Mörner's ice margins in the Kattegat in relation to the diverging Z curves in this area. O: predominating Oslo indicators; D: predominating Dalarna porphyries; B: predominating Baltic porphyries.

common centre in this area (see Fig. 45). The farther to the southeast, the greater the distance to the centre and the wider the equivalent arcs, not only in space but in time as well. Since these lines coincide with the recession lines in southern Sweden, it is clear that the deglaciation must have been more rapid on the east coast of that region as compared with the slower recession on the west coast, and no meteorological causes (Lundqvist, 1965) are needed to explain this structural effect.

Thus far, we have pieced together the glacial landscape of Jutland, the recession lines in the Kattegat, and those in southern Sweden. This unification is confirmed by the Danish investigations of the Younger *Yoldia* Clay in the northern part of Jutland. This Late Glacial marine deposit is interbedded between the Lower and Upper *Saxicava* Sands. As Hansen (1965) pointed out, the name *Yoldia* covers three different concepts. This term refers to: 1) the interglacial *Yoldia* Clay of Vendsyssel, 2) the clay now under discussion as the Younger *Yoldia* Clay, and 3) the Baltic *Yoldia* Sea which belongs to the Early Holocene or, more exactly, to the Finiglacial time (about 8000-7000 B.C.). To avoid confusion, it is proposed that the Younger *Yoldia* Clay occurring between the *Saxicava* Sands be designated the *Yoldia* Clay of the Daniglacial or, in short, the Dani-*Yoldia* Clay. The oldest radiocarbon age of this deposit in Vendsyssel being 12 330 B.C. (Knudsen, 1971; Krog & Tauber, 1974), and the Nunatak lakes at Romele-åsen in Scania being varve-clay dated around 12 900 and 12 600 B.C. (Nilsson, 1960), the ice recession in the northern part of Jutland and the southernmost part of Scania must have taken place almost simultaneously. In other words, the ice margin then lay in both the northern part of Jutland and southern Scania, just as do the inverted S lines which are crossing the northern part of Jutland (see Fig. 45).

Thus chronologically and structurally the Dani-*Yoldia* Clay is related to Scania, but environmentally this clay was deposited under the same conditions as existed during the Ra Substage in the Oslo fjord. According to the investigations of Knudsen (1971), the faunal diversity of the foraminiferal assemblages of the Dani-*Yoldia* Clay at Løkken (see enclosure map) is low. The species *Elphidium clavatum* and *Cassidulina crassa* predominate. The same holds for subzones $A_l$ and $A_u$, which according to Feyling-Hanssen (1971) were deposited in the Oslofjord region during a retreat to the Ra and to the Ås-ski moraines, respectively. In his opinion the sea water was then 'diluted by cold, fresh and turbid meltwater of low transparency. The foraminiferal assemblages were affected by these severe conditions, and it is characteristic that such assemblages are dominated by one or two species'.

Because the streamlines, but also the drainage system, converge in a concave bend of an ice margin, which results in a concentration of the drainage of the ice mantle at the rear, the abundant meltwater production along the glacio-marine contact in the concave bay of the ice sheet during the Ra Stage in the Oslo fjord region is explicable. The similarity of these environmental conditions in the Oslo fjord and in northern Jutland, confirms the localization of concave bends in the ice margin in northern Jutland.

As mentioned by Knudsen (1971), Jessen recognized two types of Dani-*Yoldia* Clay in Vendsyssel, one with a marine facies in the northern and eastern parts, and the other, deposited in brackish or even fresh water, in the southern and western parts. This could mean that when the concave ice margin had retreated just north of the broad southwestern parts of Vendsyssel, the sea could not yet exert a direct influence on this area. Hence, at that time the sea was still excluded

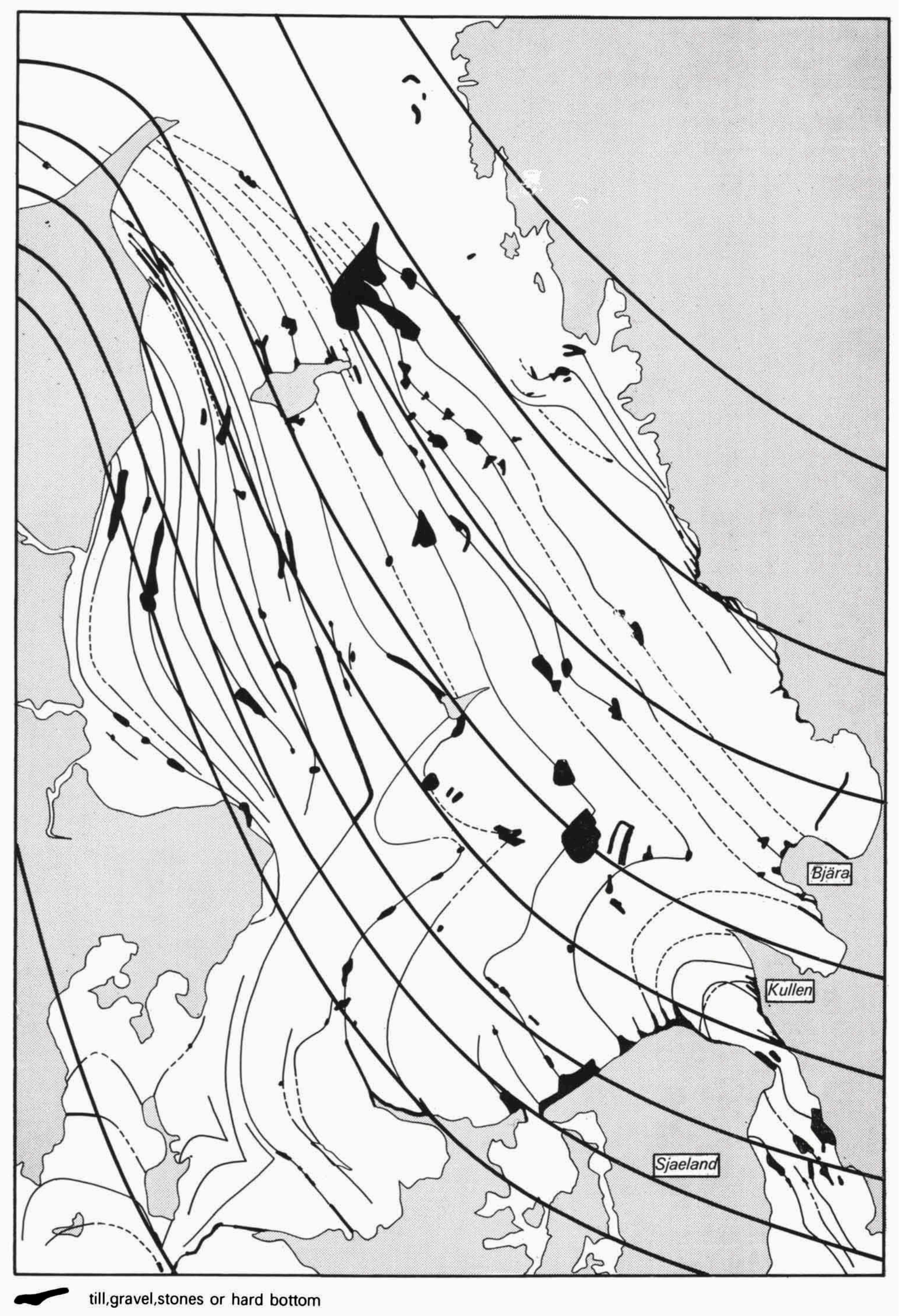

Fig. 46. The northwestward-extending till ridges of Sjaelland and the southwest-Swedish peninsulas approximately parallel to the Z curves (heavy lines). The seabed of the Kattegat and the ice marginal lines (thin, solid, and dashed line segments) after Mörner (1969).

from the inlets of the Baltic. When further retreat occurred, the ice-damming began to lose its effect, as shown by the first indications of the marine transgression at Løkken.

On the basis of the circular pattern it has been possible to delineate the southwestern section of the retreating ice mantle from the main stationary line in Jutland up to the Oslo district, including the major part of southern Sweden. To what extent can the remaining hiatus be filled?

Mörner (1969) correlated his marginal lines for the Kattegat with the ice-border lines proposed by Madsen and Milthers. If instead, however, the incomplete inverted S-shaped curves in the northern area of the Kattegat shown in Fig. 45 are extended southeastward, the segments of these curves passing from the Kattegat into Sjaelland are seen to run roughly parallel to the concurrent till ridges extending northwestward from the north coast of Sjaelland (see Fig. 46). The same holds for the ridges extending seaward from the south coast of Kullen and the Bjära peninsula in Sweden. These natural brackets, which (in the main) coincide with

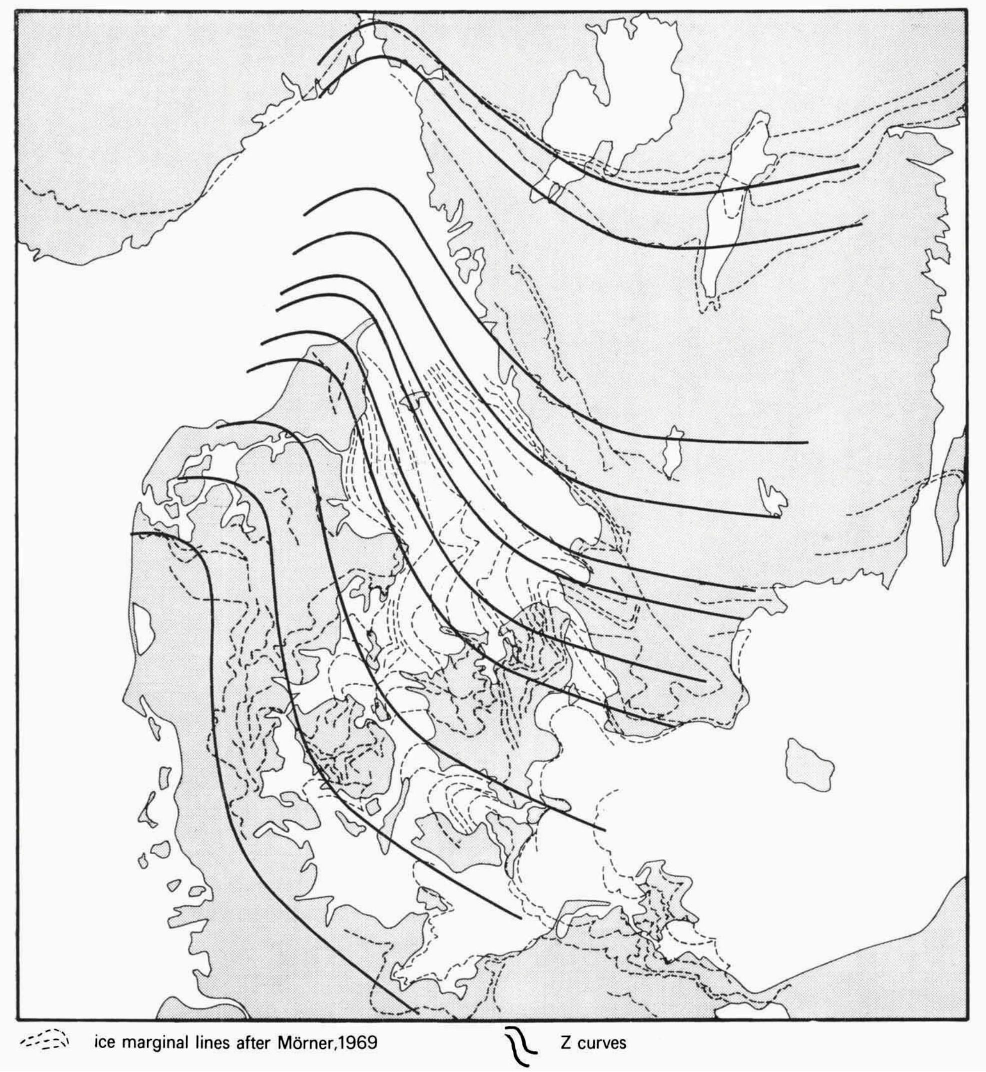

Fig. 47. Ice-marginal lines as represented by Mörner (1969) in relation to a suit of Z curves.

analogous marginal lines, show that an extension of the Z bends to the southeast would be feasible.

Although the pattern of the glacial morphology of the Danish archipelago is not yet understood, there are features that can be explained by the circular pattern. Some of the discontinuous, shifted, lateral moraines of the Little Belt and the Great Belt glaciers coincide with the theoretical ice edges. As is evident from Fig. 47, there are further relics of the glacial morphology which fit into the pattern in question but also others that do not. For all that, the question to be asked here concerns the extent to which ice-drift, ice-shove, and ice-push acted as geomorphological agents in the coastal lowlands of the Danish islands.

### *The development of the Baltic ice lake*

We shall first discuss the development of the Baltic waterbody in Denmark on the understanding that the ice mantle retreated according the pattern of the consistent unit.

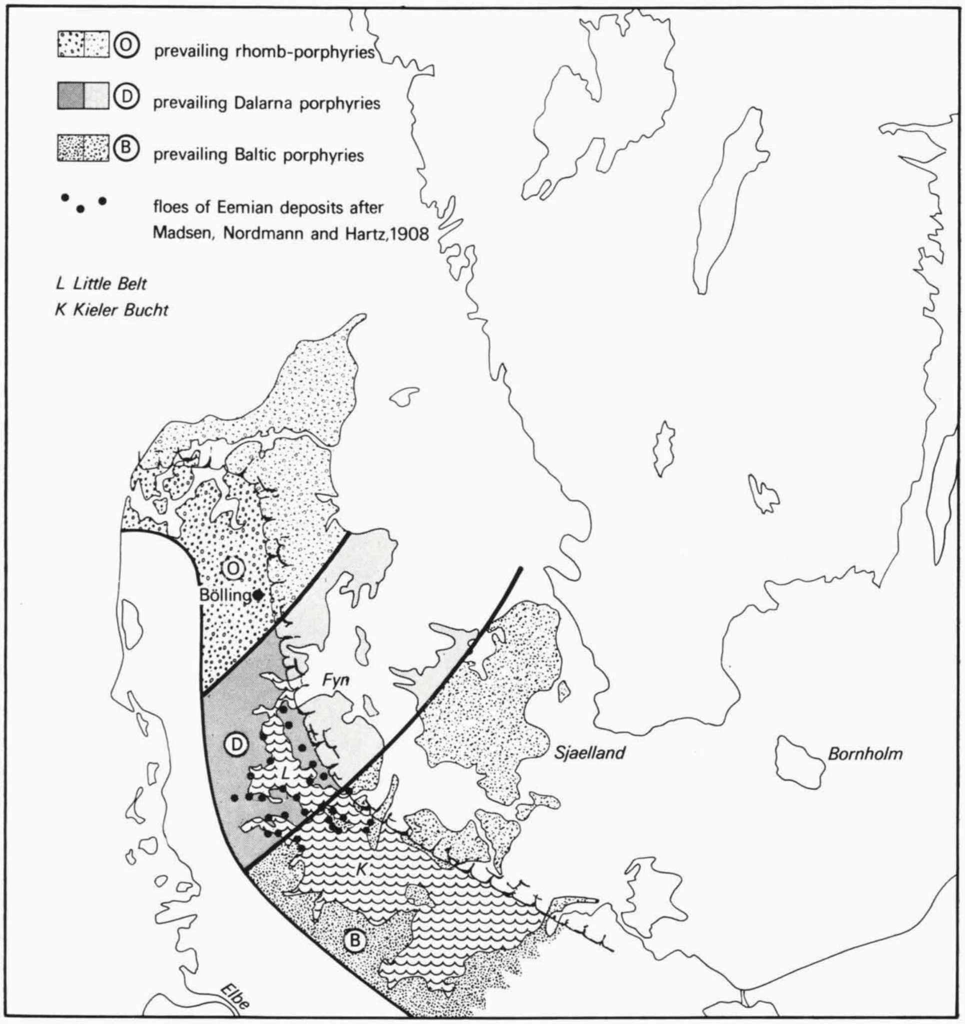

Fig. 48. Theoretical retreat, showing the Z shaped ice margin on the west side of the island of Fyn.

The Jutland unit of tunnel and extramarginal meltwater valleys is seen as part of the extensive reticular circum-Baltic meltwater valley system. One part of this fringe of valleys and lakes, which are features of a proglacial area with a ground surface sloping downward from the ice (Price, 1973), was fed by meltwater from the ice sheet, whereas another part where the ground surface was sloping upward from the ice was fed both by meltwater and by the roughly north-south running European rivers. Thus, during the maximum extension of the Weichselian ice sheet not only the glacial drainage, but also the water of the Weichsel and the Oder rivers was drained toward the west by the east-to-west trenches or Urstromtäler, as the German geologists call them. The discharge took its course via the Lower Elbe into the North Sea (see Fig. 44).

In the first phase of retreat, a disjunction probably took place between the drainage of meltwater and the river systems. While the large rivers continued to drain into the east-to-west-trending, main Weichselian Urstromtal, the glacial drainage underwent a radical change described by Gripp (1964). He discussed the reversal of drainage in Schleswig Holstein, which was initially directed toward the southwest, where it debouched into the Urstromtal of the Elbe, but later, during the retreat of the ice mantle, the drainage shifted northeastward toward the Baltic.

As far as we can deduce from the Pleistocene deposits of continental Europe, the formation of marginal lakes and valleys was a natural development, and there is no reason to assume that the crossing of the present coastline of the Baltic by the retreating ice front would have made any difference in that situation. Possibly, as soon as part of the Kieler Bucht and the Little Belt became ice free — which took place at almost the beginning of the Weichselian retreat because of the proximity of the maximum extension of the ice front to the coast and the great encircling ice movement in this area — marginal meltwater lakes must have developed in these released depressions. In the situation sketched in Fig. 48, the Baltic Sea as a physiographic unit did not exist, the greatest part of its present area being occupied by the ice sheet, which was then the dominating physiographic unit in this region. Consequently, the marginal lakes in the Kieler Bucht (K) and the Little Belt (L) must be seen apart from the long-held mental image of the Baltic. These marginal lakes, as integral parts of the ice mantle's circumferential fringe of lakes, did not have a direct communication with the ice-covered area which is now occupied by the present Baltic. Consequently, an introduction of Baltic indicators was prevented at that time.

Since, according the investigations of Gripp (1964) the connection with the Elbe Urstromtal was cut off, these lakes were mainly fed by meltwater, which means that the water supply was limited at first. However, with the continuing retreat of the concentrically shrinking ice body, the meltwater in its marginal lakes must have increased, and because the ice sheet blocked discharge of this rising water toward the northwest and northeast, these marginal lakes would have combined into one in course of time.

It is not known whether this happened before or after the break-through of the river Oder. This event had a drastic effect, not only because of the powerful increase of the water supply, but also because the water from the south was relatively warm as compared with the meltwater, due to the southward temperature increase shown by the isotherms of the last glaciation (Charlesworth, 1957). The resulting change in temperature must have accelerated the melting process, particularly where the water and the ice were in contact with each other.

To return to Fig. 48, the represented situation agrees with the view of Hansen

(1965) that while Bölling near Silkeborg in Jutland became ice free and the earliest Late Glacial sediments were deposited, normal glacial strata were still formed on Sjaelland and Bornholm. In the fresh-water lake developing at the edge of the ice, waterborne transport could occur and could have concentrated detached floes of Eemian deposits on the coasts bordering the Little Belt.

The receding ice border close to the east coast of Djursland is represented in Fig. 49. The fresh-water lake has grown, and the communication of the Belts with the Baltic are now open. By this time, drift ice of Baltic origin could have penetrated both straits from the southeast, which tallies with the opinion put forward by K. Milthers (1942) and Hansen (1965) that the invasion of Baltic porphyries into the Little Belt and the Great Belt took place almost simultaneously. According to Bahnson (1973), the distribution pattern of the Baltic porphyries is

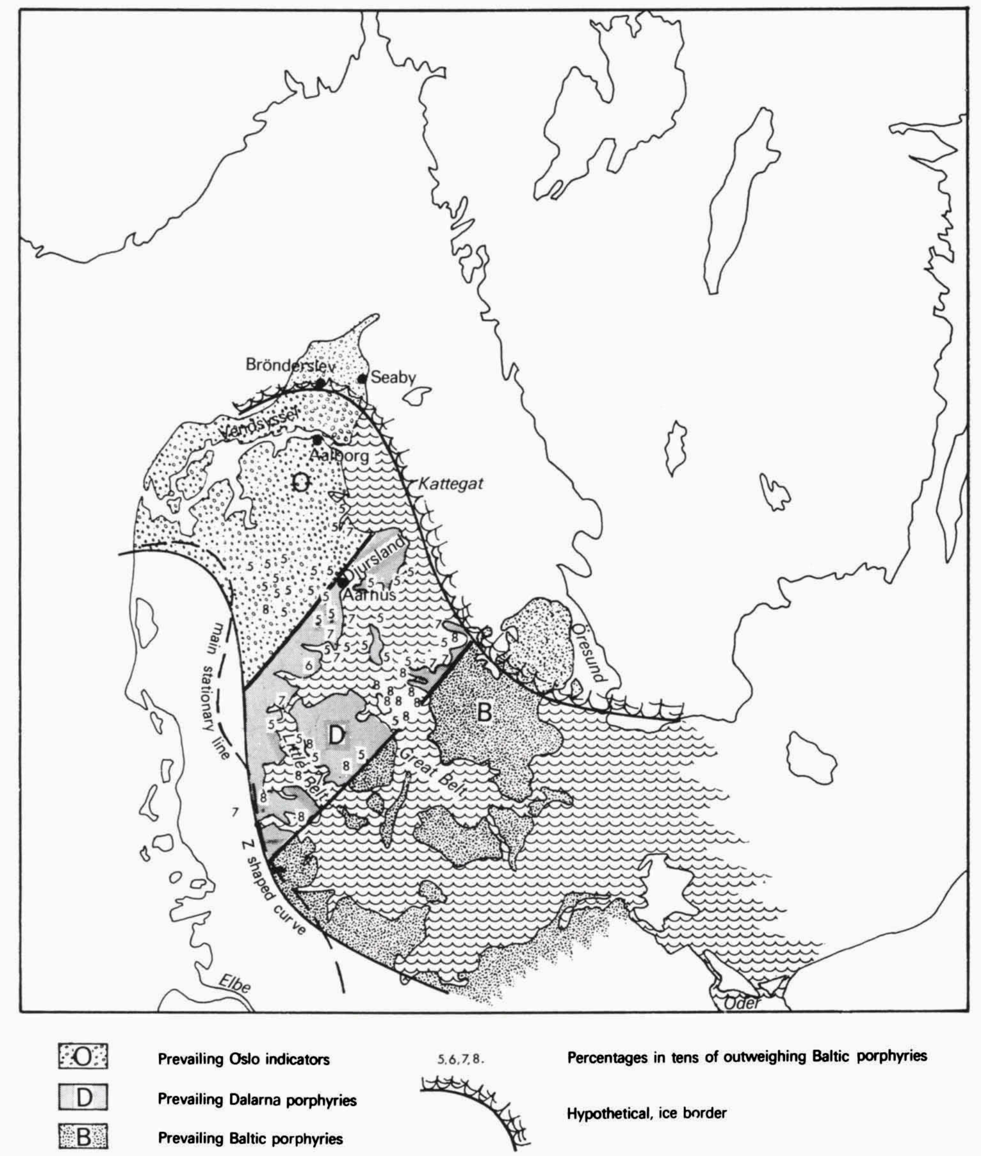

Fig. 49. Hypothetical Z shaped ice border close to Djursland.

consonant with the regional variation of the Palaeozoic limestone quotient in the uppermost boulder clay layer. The counts made by K. Milthers (1942) with outweighing Baltic porphyries, that occur as foreign elements in the zones of predominantly Dalarna and Oslo porphyries, are represented in situ in Fig. 49, where for convenience they are given in tens. The affinity of these foreign components to the coastal areas supports a waterborne transport.

Round about this phase of ice retreat, Late Glacial marine deposits were formed in northern Jutland. That is to say Upper *Saxicava* Sand, Dani-*Yoldia* Clay, and Lower *Saxicava* Sand.

Hansen (1965) gave an account of the sedimentation of the Dani-*Yoldia* Clay that is worth quoting. 'When the fossil free *Yoldia* clay was deposited in the Aalborg district, and W.N.W. from there the ice margin was located along the terminal moraines between Brönderslev and Saeby. From the Mid-Kattegat area large masses of meltwater were forced to move to the northwest past the Aalborg district through a wide, shallow bay where the sea level was the same as in the ocean, but where the influx of silt-laden meltwater succeeded in keeping the salt water and the marine mollusks away'. From this it follows that in the time under consideration, the meltwater had an outlet here toward the North Sea, which must have facilitated the transport of drift-ice through the Belts into the souhern Kattegat area. This also agrees with the view of Agrell (1976). In his opinion, the highest coastline along the western part of the Baltic was formed by the Baltic Ice Lake, which was probably continuously dammed above the sea level by the receding ice sheet. The outlet of this lake — before the final drainage of the Baltic Ice Lake at Mount Billingen — was situated south of the Danish islands or at the Öresund.

The presence of the Baltic porphyries NW of the Aarhus bight could be explained by the penetration of the rising melt- and river-water into the tunnel and meltwater valleys of this now ice free region. However, these porphyries could also have been brought in earlier by an advancing ice sheet that picked them up in the southern part of the Aalborg bight, where they had been accumulated by drift-ice.

After the Great Belt, the Öresund will have opened, in its turn admitting the Baltic indicators. Thus, this reconstruction of the final retreat yields the same sequence for the Late Glacial dispersal of the Baltic indicators as that deduced by the Danish geologists.

## ICE HALTS IN THE BALTIC WATER BASIN

As shown in Fig. 44, the marginal lakes and Urstromtäler surrounded the border of the Scandinavian ice sheet from Denmark as far as northwestern Russia. The marginal lakes in the northern part of Germany and Poland are described by Woldstedt (1955); those in Lithuania, Latvia, and Estonia are discussed by Vaitiekünas & Punning (1970); those southeast of Leningrad are treated by Kvasov, Bakanova & Davidova (1970); and those in the northwestern areas of the Russian plain are dealt with by Serebryanny, Raukas & Punning (1970). An overall picture of this lake and stream system is given by Aseev et al. (1973) as an essential part of their reconstruction of the Scandinavian ice sheets.

The circum-Baltic system of channels and lakes (see Fig. 44) was variform. It had three components: a network of true meltwater channels in Jutland; the Urstromtäler in Poland, Germany and The Netherlands; and a fringe of separate ice-marginal lakes in the Baltic States. The network of true meltwater channels in Jutland was fed solely by the ice sheet and was situated on a regional slope downgrading from the ice margin. The Urstromtäler are found where the ice extended against the regional slope, and they form a complex system combining the drainage of meltwater from the north with the discharge of the great rivers from the south. Heights which generally lay transverse to the ice margin disconnected the glacial and fluvial drainage in the Baltic States and adjacent parts of the USSR from the Urstromtäler. This resulted in large isolated lakes. Those on the southeast side of the general regional water divide were even drained southeastward.

This tight-fitting fringe of channels and lakes contracted or expanded in conjunction with the contracting or expanding elliptical contours of the ice mantle,

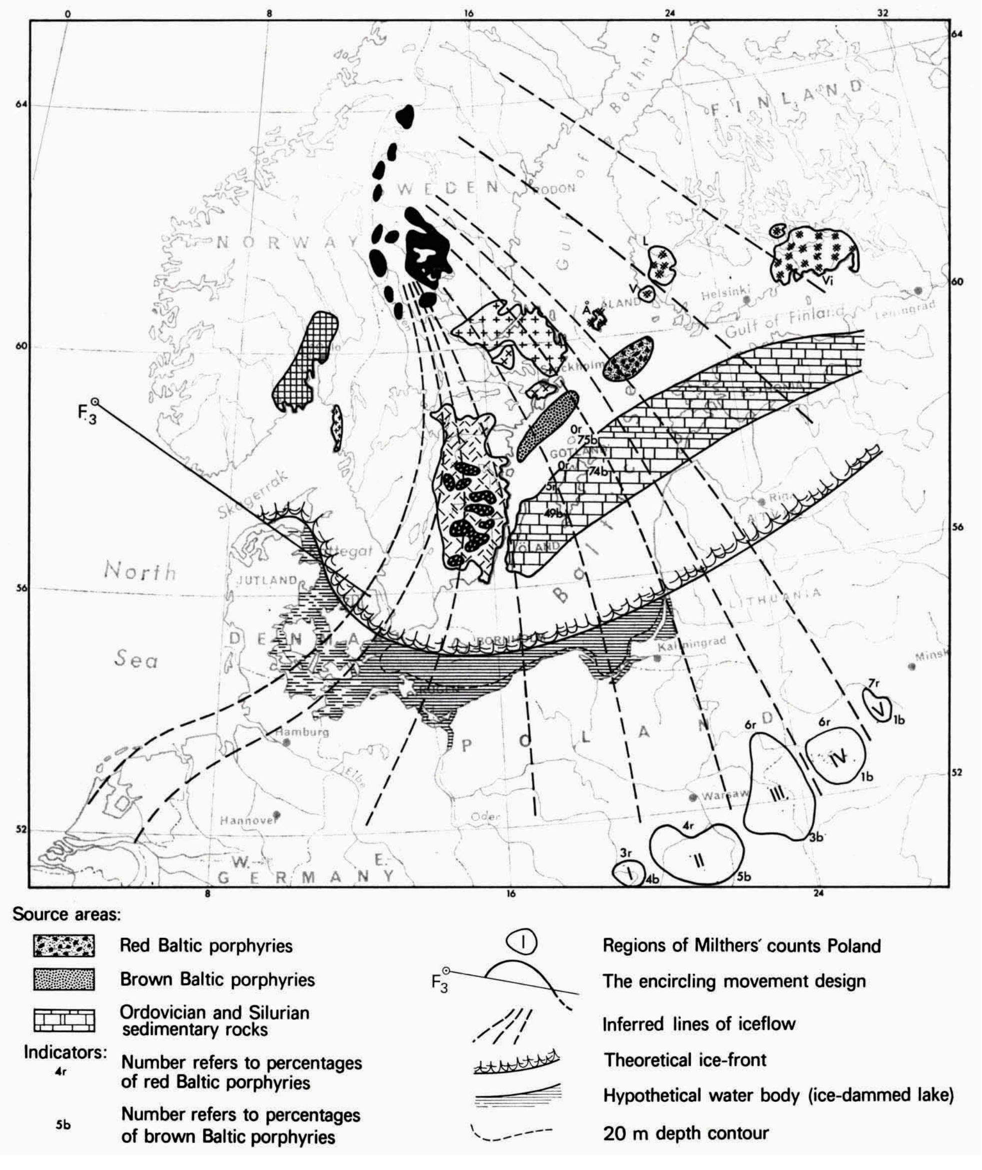

Fig. 50. Idealized sketch showing standstill phase with ice front bridging Sjaelland and Lithuania. See also key to Fig. 34.

the concomitant Urstromtäler discharging into lower areas when the latter were kept open by the retreating ice border. According to Rosa (1970), the drainage trenches also extended over the southern floor of the present Baltic. If so, they must have been formed before the conditions for the development of a true freshwater basin were fulfilled.

### *The distribution of the Baltic porphyries*

In Fig. 50, on the basis of the encircling movement the Danish Weichselian end moraine has been turned further northward, its southern part now lying just south of Scania. The ice border in the Baltic has been sketched in, along with the confocal ellipses. Tentatively, the 20 m depth contour of the present Baltic has been drawn to give an impression of the bottom relief of a hypothetical freshwater body in this stage.

Such a water basin would have affected the dispersal of indicators, and it is interesting to consider the possible consequences for the distribution of the Baltic porphyries. This is admittedly a somewhat dubious field of inquiry, because the provenances of the quartz porphyries are not yet definitely established. On the other hand, the circum-Baltic distribution of these porphyries has been carefully traced by the investigation of V. & K. Milthers. This distribution pattern, in combination with the hyperbolic lines of transport, enables us to evaluate the location of these provenances proposed by V. Milthers (1933) and adopted by Ludwig (1967) for his geological map (brought to my attention by Mr A. P. Schuddebeurs) of the pre-Quaternary rocks of the Gulf of Bothnia and the Baltic north of latitude 56°N.

The provenance of the brown Baltic porphyries is thought to lie between Gotland and the Åland islands. Therefore, the hyperbolic lines of ice movement passing through this area should be taken into consideration. These lines embrace regions III, IV and V of Milthers counts in White Russia (see p. 42). In regions IV and V the low percentage of brown porphyries — only one per cent — is striking. In the Polish regions to the west the percentages are 3, 5, and 4, respectively. In Gotska Sandön and the northern part of Gotland the percentages are 75 and 74. In the central part of Gotland brown porphyries account for 49% and some specimens have been found in Öland (V. Milthers, 1933). As compared with regions I, II, and III in Poland the percentages in Gotska Sandön and Gotland are high, which indicates that the provenance is not far from these islands. The drop in the percentage of brown porphyries from region III in Poland to regions IV and V in White Russia could mean that the hyperbolic line between regions III and IV delimits the eastern extension of the provenance. It is true that brown porphyries are still found farther east; according to Eskola (1933), this might be explained by a provenance on the bottom of the Gulf of Bothnia of brown porphyries that are indistinguishable from the Baltic ones.

In view of the relatively high percentages of brown porphyries in regions I, II, and III in Poland and the drop in the percentages east of the hyperbolic line separating regions III and IV, a case can be made for a location of the provenance of the Baltic brown porphyries west of the line separating regions III and IV and lying north of Gotland. It is self-evident that this provenance must lie outside the belt of Cambrian and Ordovician rocks that fringe the islands of Öland, Gotland, and Gotska Sandön to the north. Martinsson (1960), who analysed the general outline of the submarine distribution of these rocks, estimates the width of this belt to be roughly 60 km. On this basis, the provenance of the brown porphyries would be limited to the area NW of Gotland below the 120 m contour. This trough, which is rather broad west of Gotska Sandön, tapers toward the southwest.

If the outcrops of brown porphyries are evenly distributed over this trough, the wide stretch will contain more porphyries than the narrow stretch. Therefore, a higher percentage of brown porphyry indicators is to be expected on Gotska Sandön and the northern part of Gotland and smaller percentages to the south, which agrees with the actual distribution of brown porphyries in these islands indicated by the counts made by Milthers in 1933.

According to these arguments, there is much to be said for a location of the provenance of the brown porphyries between the mainland of Sweden and the islands of Gotland and Gotska Sandön, which is southwest of the area proposed by Milthers and shown by Ludwig on his 1967 map.

We may now return to the fresh-water basin assumed to have arisen when the southern Baltic became ice free (Fig. 50). At that time conditions for calving were favourable in the rather deep water north of the Gulf of Gdansk. Since this calving ice forming part of the segment of ice sheet that crossed the source area of the brown porphyries, some of these indicators could have become waterborne. For the red porphyries, however, the conditions for waterborne transport were not

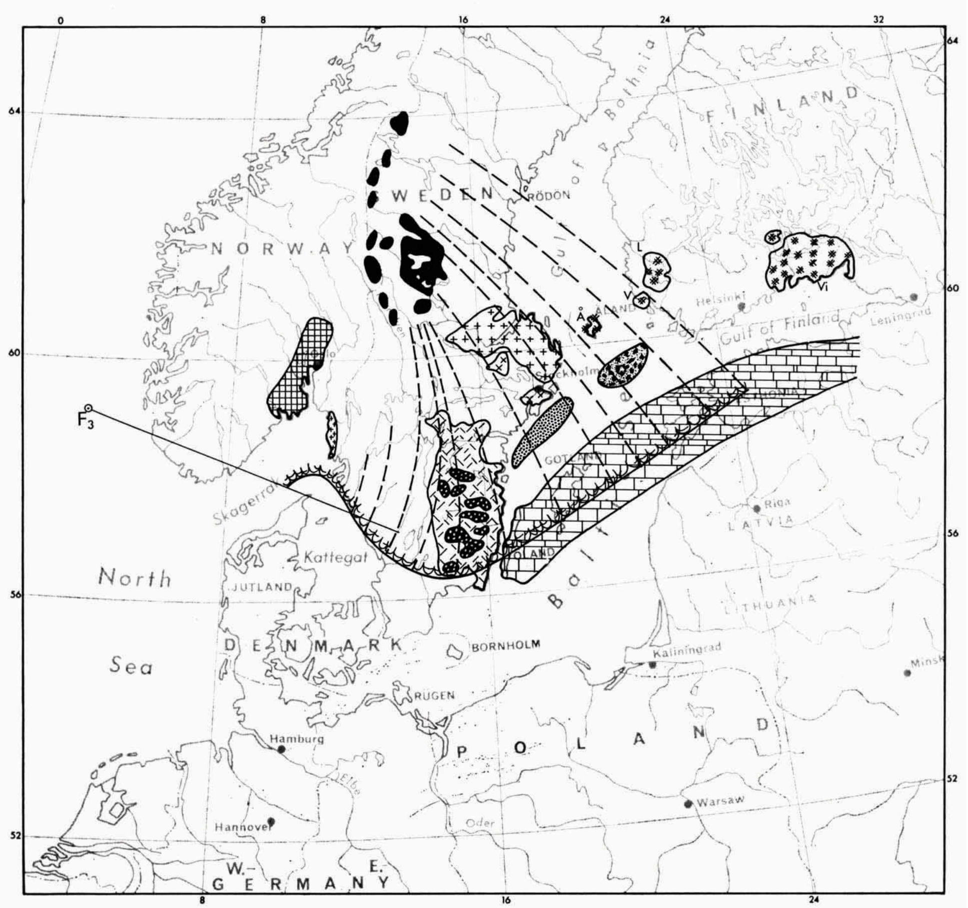

Fig. 51. Sketch of an ice halt in the broad trans-Baltic area where Silurian and Ordovician rocks crop out. For explanation, see Fig. 50 and the key to Fig. 34.

yet fulfilled at this stage. Consequently, the brown porphyries had the lead in the westward dispersion of the Baltic porphyries.

The drift to the west corresponded with the counterclockwise circulation and the easterly and northeasterly winds prevailing in the summer. A possible outlet for the rising waters of the marginal lake must be sought in Denmark. Even though the natural westward discharge of this lake was dammed by the ice sheet or lobes from the ice sheet in this area, the receding zigzag-shaped ice front, the eustatic and isostatic movements, and the continuous rise of the proglacial lake that was fed not only by meltwater but also by the Oder and the Weichsel, were weak points with respect to a hermetic sealing off of the lake water. Consequently, intermittent subglacial outflow and/or desultory overflow in areas of lowest relief are conceivable. On this basis, the waterborne brown porphyries — unlike the red ones — would have had the marginal lake themselves for some time in the course of the retreat or advance of the ice mantle. Therefore, higher percentages of brown porphyries than of red porphyries would be expected in associated indicator counts made in the southern circum-Baltic. This would explain why the counts of K. Milthers (1942) with twice as many browns as reds are restricted mainly to the coastal areas of the southeastern part of Denmark.

The described course of events offers an explanation of the predominance of brown porphyries in central Swedish indicator associations and the predominance of red prophyries in the assemblage of Åland and Finnish indicators in The Netherlands (Schuddebeurs, 1955, 1956) and northern Germany (Hesemann, 1936). We will go into this point further in the following.

### *Ice halts and indicator associations*

Figure 50 shows that the segment of the ice sheet overlying the source rock of the brown porphyries partially coincides with Uppland, Södermanland, Västmanland, and Dalarna. This explains the affinity of the brown porphyries to middle Swedish indicators in connatural glacial deposits.

In the same way, the source area of the red porphyries is related to the Åland islands and part of the south-Finnish archipelago by a common segment of the ice mantle. However, in the situation sketched in Fig. 50 waterborne transport of this association would be suspended until a further retreat of the ice front.

To turn back to the brown porphyries, it is evident that under the conditions shown in Fig. 50 the Småland granites, like the middle-Swedish indicators, had a chance of being transported by floating ice. Since the ice edge lay on the island of Bornholm, the indicators from this island could also have entered this association. With respect to the question as to whether equivalent glacial deposits are known, a publication by Schuddebeurs (1956) deserves attention. He evaluated the high percentages of brown porphyries as against the low percentages or even absence of red porphyries in the glacial deposits of the region of het Gooi, which forms part of the Utrecht ridge, as shown in Table 6 and Fig. 13. Zandstra (in Overweel & Zandstra, 1967) demonstrated that the Saalian till debris in this area contains a gravel association comparable to the rock compositions of decalcified lenses of red boulder clay. This resemblance to the red boulder clay may be an indication of waterborne transport, which is supported not only by the high percentages of Stockholm and Uppsala granites in these deposits of het Gooi, but also by the exceptionally large quantity of Bornholm indicators (see Table 6).

Thus, the area of the Utrecht ridge shows Saalian deposits with an indicator association that fits in with an ice halt in the Baltic as depicted in Fig. 50. But how must we account for the conveyance of the waterborne material to the Utrecht ridge? The halt of the ice front, as shown schematically in Fig. 50 also could have been a standstill phase of the advancing Saalian ice sheet. The standstill could have been induced by the relatively warmer water of the Weichsel and Oder rivers, which were discharging into the proglacial body of water. Where the ice front advanced further, ice shoals and drift ice could have been frozen in and later have been conveyed and partially deposited in the region of the Utrecht ridge by true glacial transport.

The formation of this association of indicators can, however, also be explained in another way. The line of the flowline pattern between region III and IV of Milthers' counts may be regarded as the line separating the circum-Baltic stretch of Urstromtäler from the fringe of isolated lakes. This would mean that the provenances west of this line were conjoined by the Urstromtäler. Thus, besides the standstill phase depicted in Fig. 50, these ice-marginal drainage channels too could have contributed to the origin of the indicator association under discussion.

Another hypothetical standstill phase is shown in Fig. 51. Here, the ice edge crosses the islands of Öland and Gotland and is located in the broad trans-Baltic stretch where the Silurian and Ordovician rocks crop out. In this stage indicators

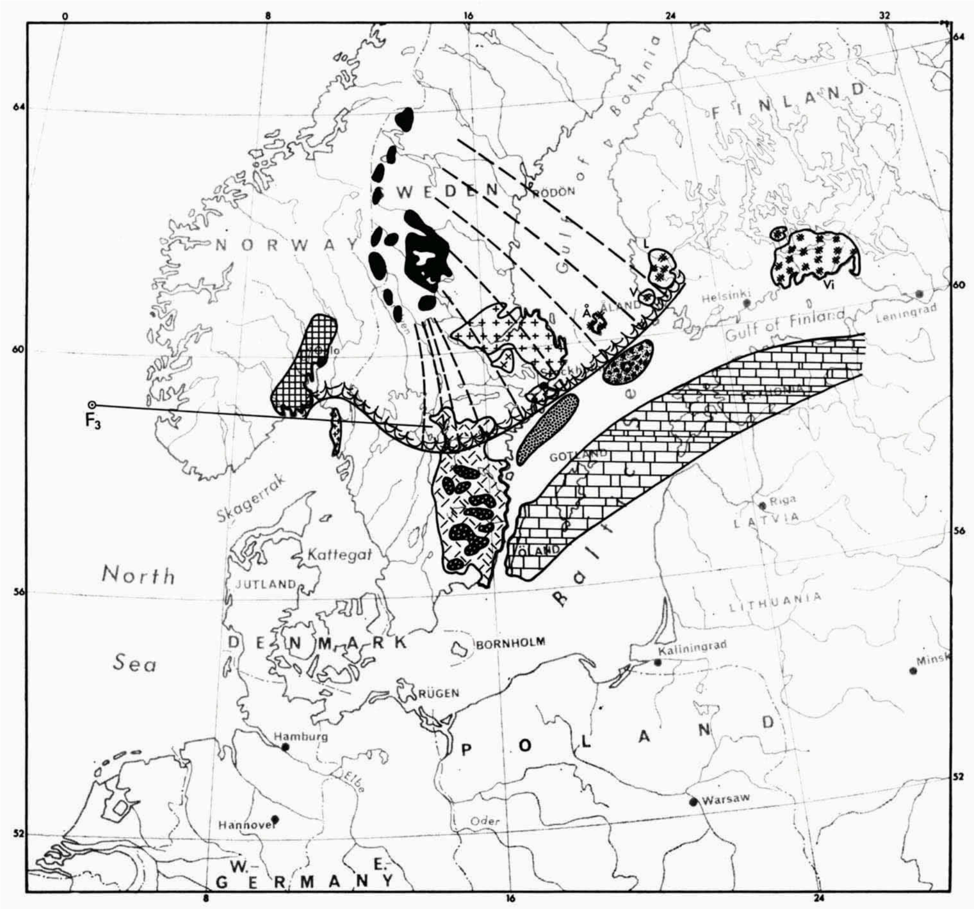

Fig. 52. Standstill phase of an ice front lying just north of the source rocks of red and brown Baltic porphyries. For explanation, see Figs. 50 and 34.

from Åland and the red porphyries also formed part of the indicator association. But the Bornholm indicators should be missing, because the ice edge was not in touch with their source area. In this circumstance, conditions would have been favourable for the formation of the waterborne lenses of red boulder clay. The ice edge rested on the Silurian limestones, which furnished the ground mass of these lenses. Along its edge, the ice mantle detached erratics and indicators which, intermingled by the westward drift, became imbedded as inclusions of the red clay on the threshold of the ice sheet.

In still another hypothetical standstill phase shown in Fig. 52, the ice edge lies north of the source areas of the brown and red porphyries. Hence, these porphyries no longer enter in and now the Åland, Stockholm, Uppland, and Dalarna indicators stand a chance of becoming waterborne.

As the last case in point, Figure 53 gives an impression of a stagnating ice front halfway along the Åland archipelago. Since the water-ice contact must have been favourable for quarrying, the waterborne Åland indicators would have had the Baltic pretty well to themselves then.

A tentative outline of indicator associations based on different halts of the ice front in the Baltic is given in Fig. 54. Here, the glacial deposits ascribed to waterborne transport, deserve notice first. Among these, the lenses of red boulder

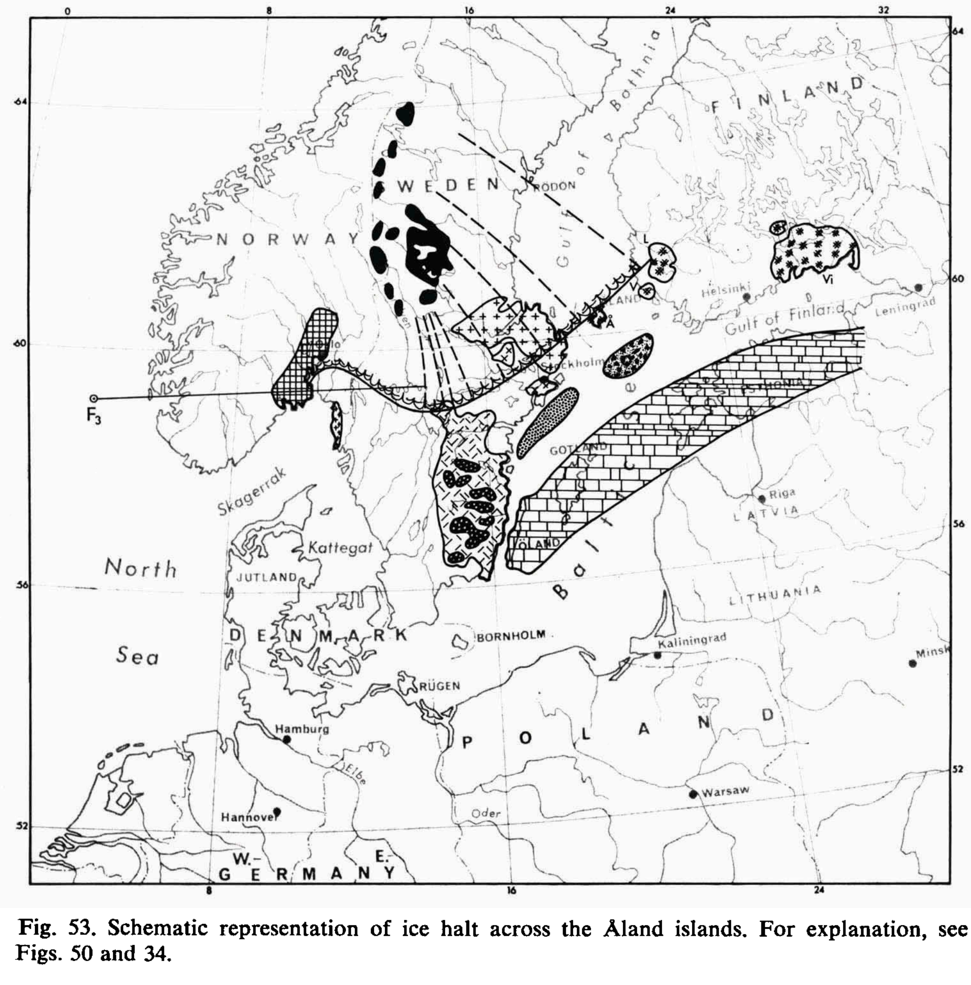

Fig. 53. Schematic representation of ice halt across the Åland islands. For explanation, see Figs. 50 and 34.

clay stand out. Those of the Saalian in The Netherlands contain an indicator association which agrees to some extent with that of an ice front situated in the area of Gotland and Öland. However, the Baltic porphyries are poorly represented in the lenses, in contrast with the Småland indicators. There are high percentages of Åland indicators, not only in the lenses and the red boulder clay of the Hondsrug but also in the average Saalian deposits in The Netherlands, which as a rule are intermixed with elements from waterborne transport. These high percentages may account for a prolonged halt of the ice front close to the Åland islands during its advance in the Saalian. But there is no denying that we should also take into consideration the glacial prior to the Saalian. For if another glacial should occur in the far future, the Fennoscandinavian and circum-Baltic deposits, upon which the Weichselian set its seal, will be redistributed. Consequently, the events deducible from the new sediments will refer not only to the added glacial but also to the Weichselian. In the same way, components of the Elsterian may have been recycled in the Saalian boulder clays.

Unlike the red lenses of boulder clay, the aforementioned Saalian deposits of the Utrecht ridge seem to offer an ideal example, due to their indicator association, which is completely consistent with that of an ice halt in Latvia, as set out in Fig. 54.

Notwithstanding the complications, it might be possible, along the lines expounded here, to remove a little of the veil that covers the standstill phases of the Scandinavian ice sheets in the Baltic, of substages that are even older than the Upper Pleniglacial, as defined by van der Hammen et al. in 1967.

In the last three of our hypothetical standstill phases of the ice edge across the Baltic the Kattegat was open, and this implies — depending on the height of the relative sea level — that ice-rafted Oslo indicators had a chance of slipping through to the Baltic proper via a possible tide-water glacier in the Skagerrak. Sauramo (1923), who compared the Salpausselkä ridges in Finland with the Ra end moraines in the Oslo area, pointed out that both slope away from the inland ice, which would have promoted calving.

In this connection two publications by Schuddebeurs (1959, 1967) are relevant. In The Netherlands, where Oslo indicators are scarce, he found a remarkable high percentage of Oslo pebbles (about 25) near Drachten in the province of Friesland. He related this occurrence to a count made by van der Lijn and Bos at Bergum, where Oslo indicators accounted for 20%. Furthermore, he came across such accumulations near Langefeld, Werpeloh, and Fresenburg in NW Germany, an area which may be compared with the northeastern part of The Netherlands. Although Schuddebeurs (1959) saw this situation as the result of a direct ice stream, waterborne transport is suggested by the occurrence of clusters of Oslo indicators in regions otherwise virtually without these erratics, their confinement to deposits underlying the boulder clay and the scattering of single Oslo boulders in a direction opposite to their natural southwest trend of distribution. Occasional finds of these Oslo indicators in the coastal belt of the southern Baltic as far east as Thorn in Poland (Casper, 1931; Charlesworth, 1957) are shown on the distribution maps by Schulz (1973).

In conclusion, it may be mentioned that as early as 1896, G. de Geer took drift ice into account (Charlesworth, 1957) as one of the possible mechanisms, to explain the presence of Norwegian erratics on the east coast of England.

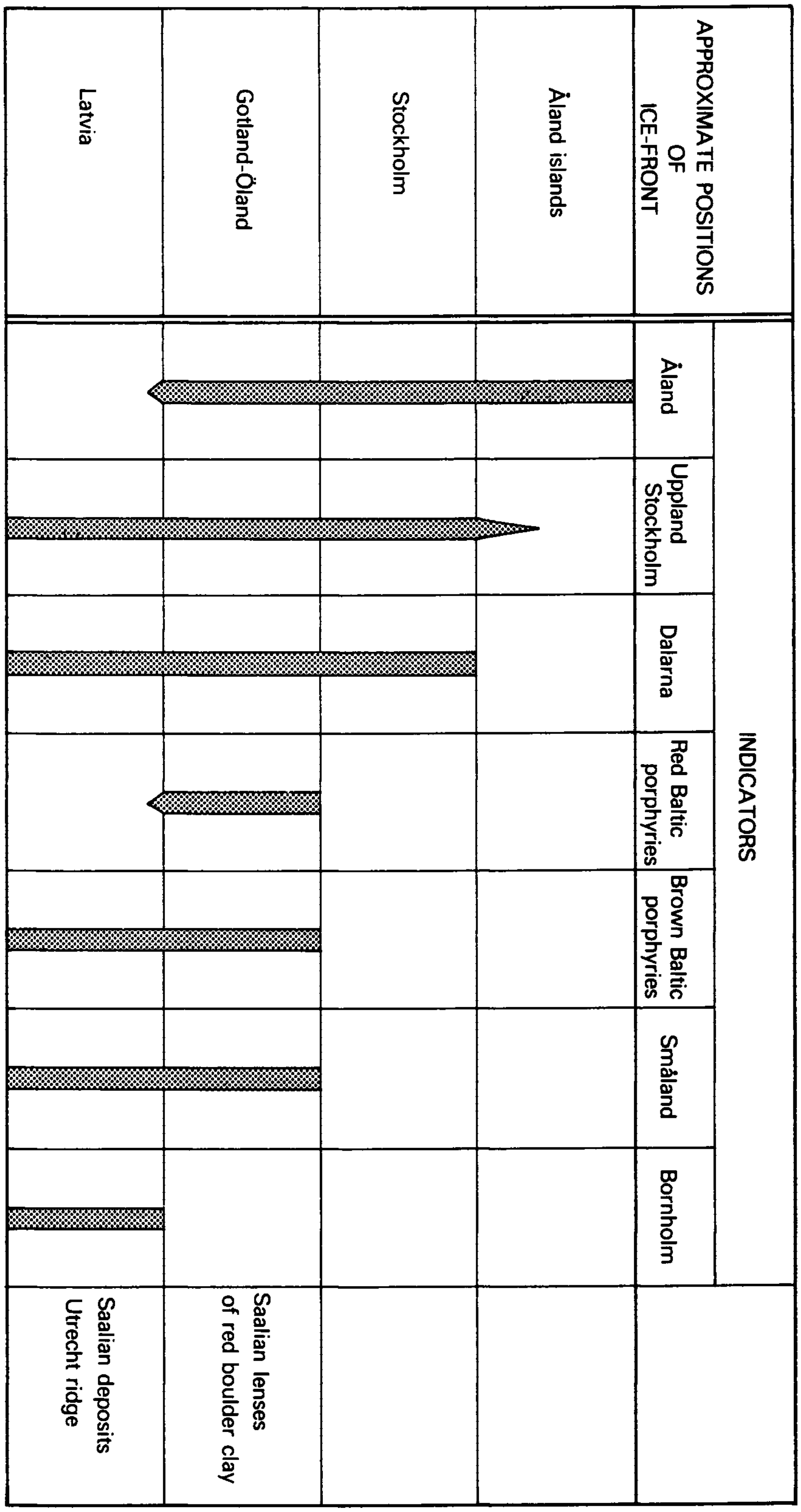

Fig. 54. Tentative outline of indicator associations according to different halts of the ice front in the Baltic.

## Conclusions

The approach to the re-evaluation of indicator counts on the basis of the general trend of the traces of ice movement in Fennoscandia has shown that the trends of these traces link up with the consistent distribution pattern of the circum-Baltic indicators. Because this holds not only for the Weichselian but also for the Saalian, the general directions of ice flow must have been similar in these two stages.

The interrelationship between the flowline and the consistent distribution pattern allowed an integration of these units, permitting a reconstruction of the Fennoscandinavian ice sheet. Other reconstructions have been made, for instance those of Aseev (1968) and Aseev et al. (1973). There are differences between those and our reconstruction such as variations of a structural or morphologic nature, for instance the location of the ice divide, but above all there is a difference of fundamental nature. The ice sheets defined by Aseev (1968) and Aseev et al. (1973) are static, representing standstill phases of the maximum extension of the Fennoscandinavian ice mantles in the Weichselian and the Saalian. The ice sheet proposed here, however, is dynamic. Dynamic in a functional way, because it is susceptible to expansion and reduction. With respect to indicator transport, the ice mantle should not be analysed independent of the peripheral water system. Whether receding or advancing, the ice sheet and its inseparable, closely following outer margin of water constituted a whole. It follows that without the alternating play of ice and water, which was taken into account in the chapter on the Integration of consistent and inconsistent distribution processes, the reconstruction would have appeared incomplete.

Since Lyell's drift theory was replaced by the idea of continental ice sheets, ice rafting has been neglected as a means of indicator transport. As a result, the share of ice rafting in the distribution of the Fennoscandinavian indicators has not been given the attention it deserves. To remedy this neglect, the role of the peripheral water system as a possible transporting medium for indicators has been stressed in this paper, and it was included in the discussion on the nature of the Baltic ice stream. Were the indicators of the inconsistent distribution conveyed by such an ice stream or by drift-ice in the peripheral water channels? In our reconstruction, the evidence favours waterborne transport.

In sum, the pattern inferred in this study revealed a relationship between indicator distribution and glacial and periglacial features. The flexibility of this pattern enabled us to simulate advance, retreat and standstill phases of the Fennoscandinavian ice sheets. Its application provided answers to some questions and again raised other questions. Whatever this reconstruction may be worth, it offers a new way of looking at old problems.

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Manuscript received 24 June 1977.

Overweel , Fennoscandinavian indicators, Scripta Geol. 43 (1977)

# KEY TO GEOGRAPHIC NAMES MENTIONED IN THE TEXT