Geologie en Mijnbouw **72**: 331–347, 1994.

Sediment-petrologic characteristics of Saalian and Weichselian deposits in the Hümmling region, NW Germany

L. Krook & J. Schwan
Faculty of Earth Sciences, Vrije Universiteit, De Boelelaan 1085, 1081 HV Amsterdam, the Netherlands

Received 11 March 1993; accepted in revised form 6 November 1993

Key words: Fractionated percentage-counts, heavy minerals, trace minerals, late Weichselian Pleniglacial

Abstract

In the lowlands of northwest Germany, Saalian (fluvio-)glacial plateaus and ice-pushed hills are surrounded by flat and low-lying terrain consisting of Weichselian fluvial to aeolian sands. The present work refers to the Ems-Hase fluvial basin and the adjacent part of the fluvioglacial Hümmling plateau. On the basis of heavy-mineral analyses and other data it was found that:

(i) The Weichselian deposits are significantly richer in garnet and alterite than the Saalian meltwater sands which flank and underlie them in the Ems-Hase fluvial basin. It is thought that Weichselian fluvial deposition was preceded by a period of erosion related to the low sea level of the last ice age. During that phase, the ancient riversystem extended its course in upstream direction and cut down into the headwater portion of its drainage basin. As a result, the subsequent infilling of the valleys was primarily by material derived from pre-Cenozoic rocks with the share of the Saalian substrate being subordinate only.

(ii) There is no significant difference in unstable-species content between fluvial and aeolian sands but for the occurrence of traces of glaucophane only in the second type. The latter feature suggests that, during the Late Weichselian Pleniglacial, deflation from the then dry part of the North Sea floor contributed to the deposition of the windborne coversands in the study area. Yet, the effect of the long-distance aeolian transport must have been slight only, and the buildup of the coversands resulted mainly from the local reworking by wind of the fluvial-sand substrate.

(iii) Mineralogically, there is a distinct contrast between the fluvial sands from the northern part and those from the southern part of the study area. The pertinent heavy-mineral spectra, supplemented with previously published analyses, reveal downstream trends in the composition of the Weichselian fluvial sand. These trends reflect changes in the sediment supply from Cretaceous and older rocks in the south to thick Cenozoic beds in the north. The northern strata include shallow marine deposits of Tertiary and Pleistocene (mainly Holsteinian) age and material laid down by the Late Tertiary to Elsterian north German riversystem.

Introduction

In the lowland of northwest Germany, Saalian glacigenic or glaciofluvial plateaus and ice-pushed hills (German: Geestplatten) are surrounded by flat and low-lying country (German: Niederungen). The latter type of landform represents a system of deep basins and valleys supposedly left behind by the Saalian ice and subsequently filled with thick piles of mostly sandy sediment (German: Talsande). Normally, the upper part of the valley fill consists of a Weichselian fluvial to aeolian sequence with or without a cover of Holocene peat.

This paper deals with the sediment-petrologic characteristics of the Weichselian fluvial to aeolian sands in the Ems-Hase drainage basin and the Saalian meltwater sands in the adjacent part of the Hümmling plateau.

Firstly, it attempts to account for the conspicuous difference in heavy-mineral composition between Weichselian fluvial sands and the Saalian meltwater

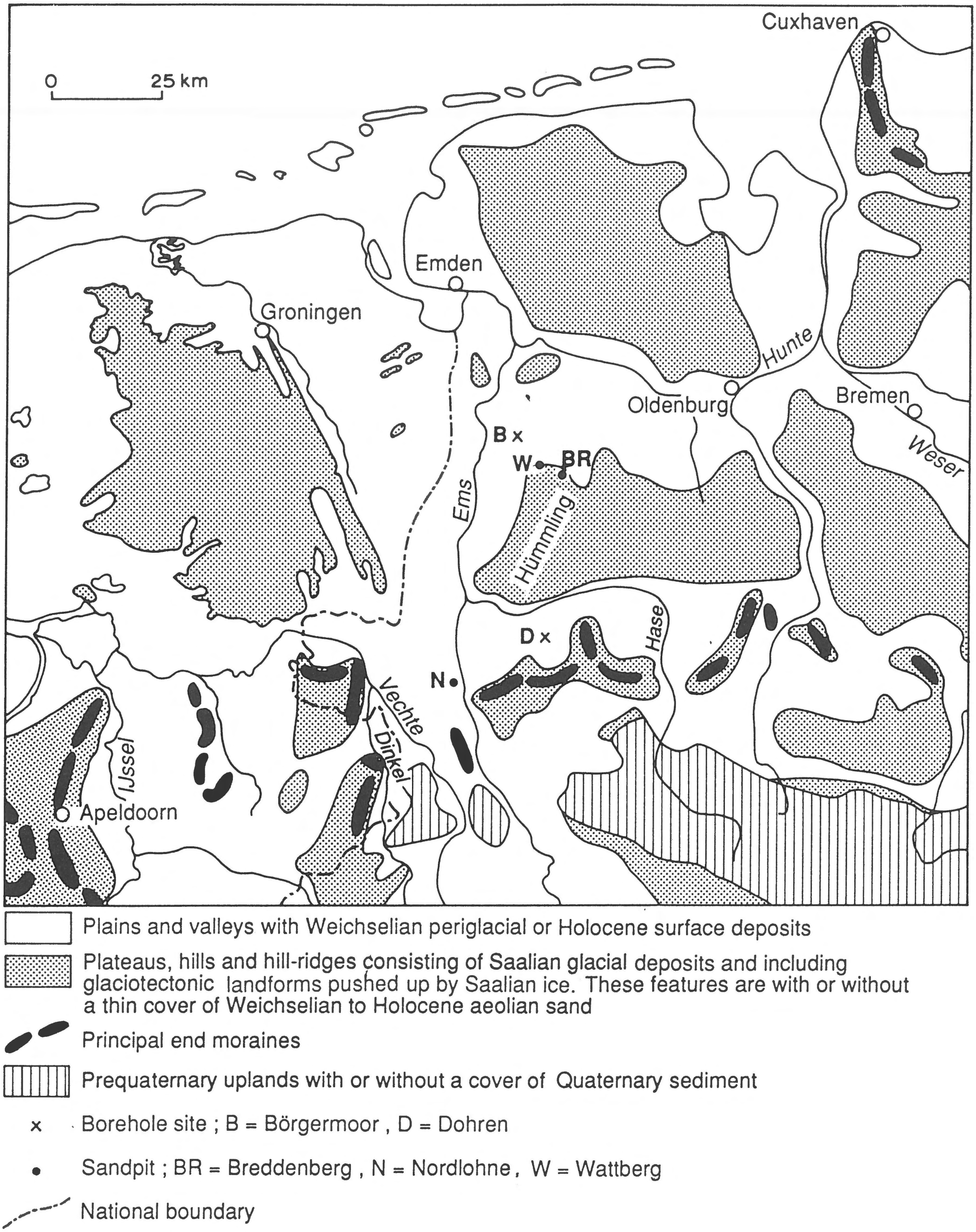

Fig. 1. Generalized geomorphology of northwest Germany and the northeastern Netherlands. Based on Liedtke (1973), Meyer (1983), Zagwijn et al. (1985) and Van den Berg & Beets (1987).

sands that flank and underlie them. Secondly, it discusses compositional modification of the Weichselian Talsand by aeolian reworking and the admixture of material from distant sources. In the third place, downstream change in heavy-mineral composition of the Weichselian fluvial sands across the subject drainage basin is analysed and tentatively related to provenance.

Geologic setting

Figure 1 shows the generalized geomorphology of the study area and the locations of the five observation sites. Figure 2 gives the stratigraphy of the terrain surrounding the observation sites. Below, the three lithostratigraphic units of Fig. 2 are discussed individually.

Unit 1 is believed to represent a huge outwash plain built up during the earliest phase of Saalian glaciation (the Main Drenthe Advance) and subsequently overridden by the expanding ice sheet (Schröder 1978). Much less clear is the origin of the deep and wide Talsand-filled basins that surround the Geestplateaus. Various German authors (quoted by Meyer 1983) suggested that at least part of them results from either glacial scouring or meltwater erosion when the ice sheet was retreating from the subject region. This interpretation seems plausible since it would account for (i) the fact that the flanks of the basins cross-cut the outwash beds, and (ii) the presence of Late Saalian glaciofluvial material in the basal part of the Talsand unit.

Unit 2 comprises (i) a generally thin layer of aeolian coversand that occurs on both plateaus and adjacent lowlands, and (ii) the Talsand that fills the basins. Essentially, the Talsand deposits in the area of concern consist of Late Saalian, Eemian and Weichselian fluvial beds having a capping of windborne sand. Within this sediment type, organogenic intercalations are fairly common. It has been suggested that both localized fluvio-periglacial activity as well as regional deposition by perennial or seasonal rivers contributed to the buildup of the subject unit (Boigk et al. 1960, Duphorn et al. 1973; Meyer 1983). In the next sections, the Weichselian upper part of unit 2 will be dealt with in greater detail.

Unit 3 consists of three subunits, viz. a podsolic soil marking the top of the Pleistocene plateau-sediments, a raised-bog peat that covers the Talsand north of the Geestplateau and, lastly, aeolian dunes that occur scattered in the study area.

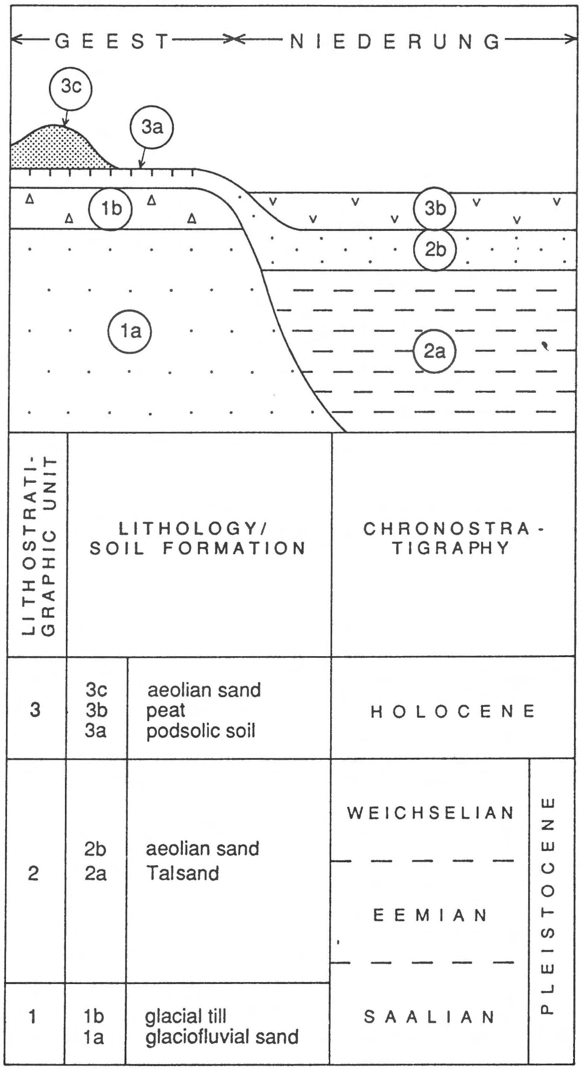

Fig. 2. Stratigraphy of the Hümmling study area.

Studied sections

Three sandpits and two borehole sections were studied (Fig. 1). The latitude, longitude and altitude above mean sea level of these sites are given below:

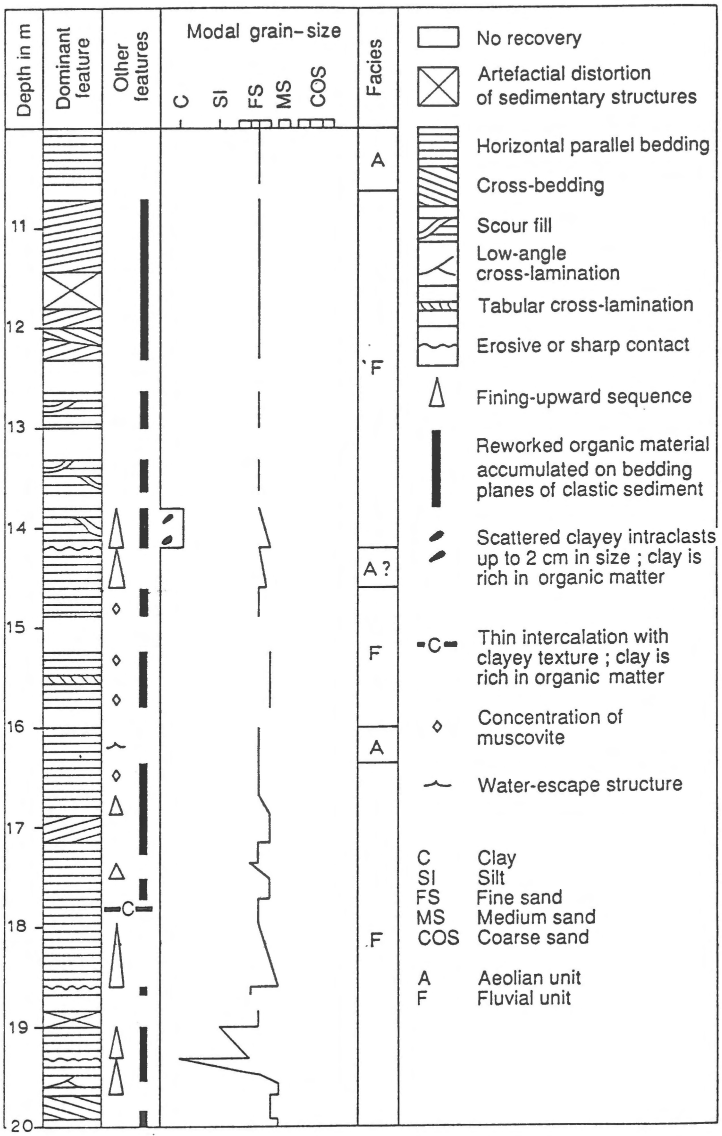

Fig. 3. Sedimentologic log of typical part of the Weichselian in borehole section Börgermoor.

Börgermoor	:	53°02′02″ N	;	
		07°26′46″ E	;	10 m
Breddenberg	:	52°57′00″ N	;	
		07°35′29″ E	;	20 m
Dohren	:	52°37′18″ N	;	
		07°33′23″ E	;	20 m
Nordlohne	:	52°31′29″ N	;	
		07°16′28″ E	;	25 m
Wattberg	:	52°58′12″ N	;	
		07°29′23″ E	;	30 m

Breddenberg and Wattberg

Sites Breddenberg and Wattberg are sandpits in Saalian glaciofluvial sands (Fig. 1). In both exposures, the top layer of till is discontinuous and thin only. Mostly, the glacigenic cover is represented merely by a residue of gravels left over from weathering and washing of an original boulderclay.

Börgermoor and Dohren

Sites Börgermoor and Dohren are boreholes made by means of a percussion coring device. The depth at site Börgermoor is 26.4 m and that at site Dohren 10.6 m. Both sections represent Weichselian fluvial to aeolian sequences in Talsand plus overlying coversand.

Information on the sedimentology, lithology, palynology and geochronology of site Börgermoor is given in Figs 3 and 4.

(i) Facies types: The gradational nature of the fluvial to aeolian sequence is evidenced by aeolian intercalations that occur in the fluvial zone before it gives way to the coversand top which is uniformly and unequivocally of windborne origin. This make-up is highly characteristic of Late Weichselian Pleniglacial environmental conditions (Schwan 1988; Schwan & Vandenberghe 1991).

(ii) Reworked pollen: As indicated in Fig. 4, the reworked organic matter in section Börgermoor does not derive from a vegetation that was penecontemporaneous with the depositional process. This applies in particular to pollenzone III, which suggests erosion of Tertiary beds by the ancient river.

(iii) Age: Reworked organic material is common in the fluvial part of the section. Because of this, samples for radiocarbon dating were collected from a few levels which, assumedly, had remained unaffected by redeposition of allochthonous vegetal matter. Of the two samples so obtained, the lower one is from pollenzone III which is dominated by reworked Tertiary elements (Fig. 4). For that reason, the vegetal remains were carefully checked on suitability for age determination. Selection of the material was based on two criteria, viz. i) freshness of appearance with a low degree of corrosion, and ii) autochthonous origin. The second criterion implies that the vegetal matter derives from species known to occur under Weichselian climatic conditions. Since the same procedure was not applied to the upper sample, it is proposed that only the radiocarbon age of the lower sample be considered valid. The upper sample probably suffered contamination by redeposited organic matter which was not recognized as such (Fig. 4).

Working from a 14C date of 21 230 + 490/- 460 BP for the lower sample, a Late Weichselian Pleniglacial age is attributed to section Börgermoor. Possibly, its aeolian upper part is of Weichselian Late Glacial age but positive evidence for this has not been found (see Fig. 5 for chronostratigraphy of the Weichselian).

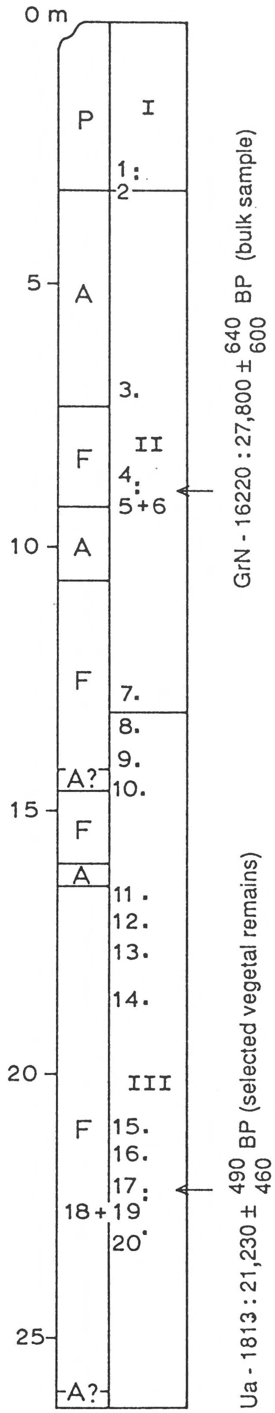

Fig. 4. Pollenzones and 14C dates of borehole section Börgermoor. Pollenzones: I = Holocene peat with in-situ pollen, II = Fluvial and aeolian sands with reworked pollen. Pollenassemblages consist exclusively of Weichselian elements, III = Fluvial and aeolian sands with reworked pollen. 80 to 90 % of pollen-assemblages consist of Tertiary elements. P = Peat, A = Aeolian unit, F = Fluvial unit, 1–20 = Pollen samples.

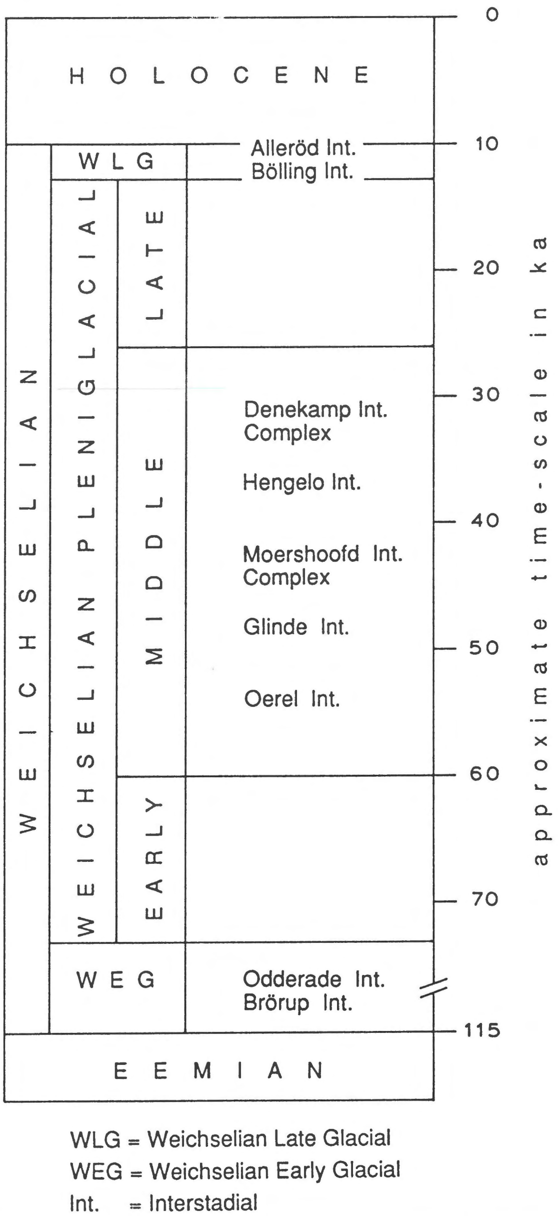

Fig. 5. Chronostratigraphy and geochronology of the Weichselian in northwest Germany. Based on Behre (1989) and Ran & Van Huissteden (1990).

(iv) Palaeo-environment: Tundra to polar-desert conditions prevailed in western Europe during the Late Weichselian Pleniglacial (e.g. Kolstrup 1980, Zagwijn 1991). Apparently, this ambiance did not preclude the episodic flow of rivers in the valleys and basins that surround the Geestplateaus. Nor did it prohibit seasonal growth of aquatic plants in stagnant water since it was on that very type of material that radiocarbon age determination Ua–1813 has been performed.

On the ground of lithologic and sequential similarity, site Dohren, 46 km to the south, is believed to occupy the same chronostratigraphic position as the section under discussion.

Nordlohne

Site Nordlohne is a sandpit in a fluvial to aeolian succession. The lower, fluvial part of the sequence represents a terrace of the Ems of unspecified Weichselian age which is overlain by Late Weichselian Pleniglacial through Weichselian Late Glacial aeolian sands. For a detailed discussion of exposure Nordlohne we refer to Schwan (1987).

Heavy-mineral data

The heavy-mineral data of the five studied sections are given in Figs 6 to 12. The legend of Figure 9 is the one used by the Geological Survey of the Netherlands.

Methods

The data in this text section are based on (i) percentage counts of standard species on 55 bulksamples, i.e. on samples in the 53–420 μm fraction, (ii) estimated abundances of glaucophane, glauconite and mica in the five reference sections, and (iii) percentage counts of standard species on the five fractions 53–74, 74–105, 105–149, 149–210 and > 210 μm of eleven fractionated samples.

Standard-type heavy minerals and glaucophane in grain mounts were identified with transmitted light on the basis of one hundred grains per slide. Glauconite and mica in bulksamples were identified with reflected light.

Mean grain-size is based on either 31 fractions in the 0–1 mm range or 33 fractions in the 0–2 mm range. The parameter was computed as first moment of the grouped data.

The Difference of Means Test was used to test hypotheses of significant difference and of no significant difference. In the first case, the test is one-tailed and in the second case it is two-tailed. In both cases the t-score having a Student's distribution with (N_1 + N_2 - 2) degrees of freedom served as a test statistic.

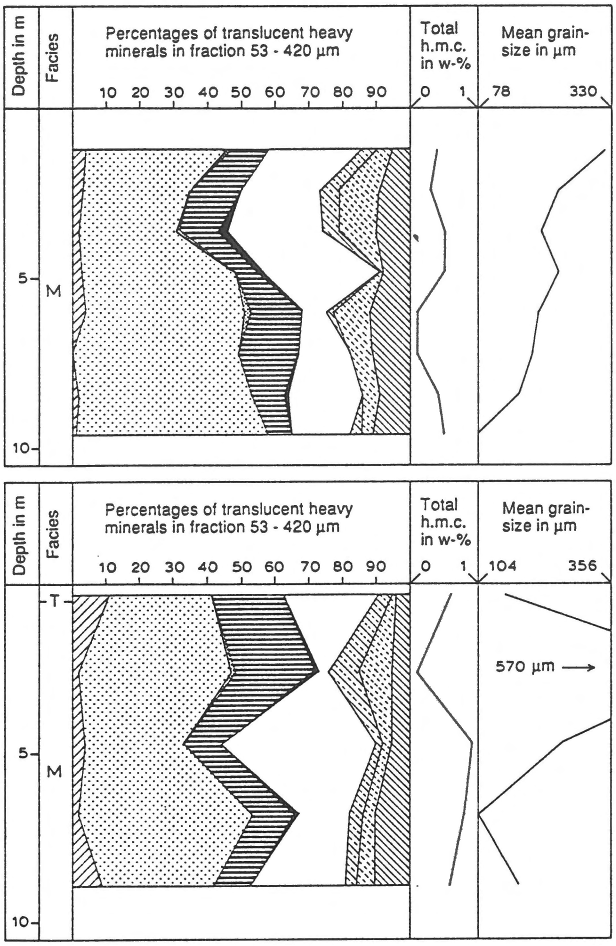

Fig. 6. Heavy-mineral composition of Saalian sections Breddenberg (above) and Wattberg (below). For legend see Fig. 9.

Mineral types

A brief comment is given on the following types of minerals:

(i) Epidote: This class includes also the minerals zoisite and clino-zoisite, both of which occur in minor amounts in the investigated samples.

(ii) Alterite: Here, the term alterite refers to grains which are alteration products of certain minerals, mainly epidote. A mineral has been classified as an alterite when it shows aggregate polarization between crossed nicols or a greyish colour resembling a 'mouse skin'. The first type is by far the most abundant and the relation with epidote is evident. Leucoxene grains which are slightly transparent between crossed nicols and are greyish due to high birefringence, are not counted as alterite but as opaque grains, since they are alteration products of ilmenite. Percentage counts of epidote and alterite, though constant in sum, may vary in proportion amongst different analysts, since the transition from the one to the other is gradual.

Hornblende alterite and augite alterite, as described by Van Andel (1950) and Boenigk (1983), were not found in our material.

Occasionally, heavy-mineral counts are published which do not include alterite though, from the context, its presence in the subject material must be presumed. In such cases the question arises of how the species has been classified and how its omission has affected inferences on provenance or correlation.

(iii) Hornblende: This group consists of green hornblende and, to a minor degree, tremolite.

(iv) Volcanic minerals: This class comprises minerals such as basaltic hornblende, pyroxenes, sphene

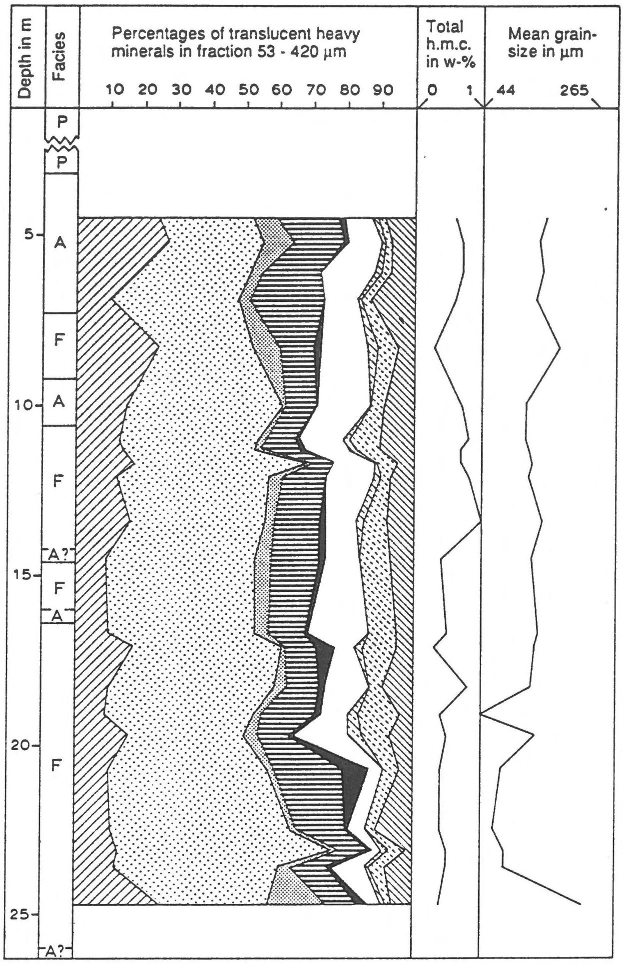

Fig. 7. Heavy-mineral composition of Weichselian in borehole section Börgermoor. For legend see Fig. 9.

(titanite) and olivine. Since most of these minerals may occur in volcanic as well as plutonic and high-grade metamorphic rocks, the group designation is not fully adequate but justified by the fact that in the Netherlands these minerals mainly derive from volcanic rocks in the Eifel Mountains. In the samples of the present study the main minerals of this group are augite and sphene. The 'volcanic minerals' generally occur in low percentages.

(v) Ultrastable minerals: Zircon and to a lesser extent rutile are the dominant components in this category which furthermore comprises the more rarely occurring minerals anatase, brookite and spinel. Tourmaline, though sharing the property of extreme stability, is represented separately.

(vi) Metamorphic minerals: This group consists of the aluminium silicates andalusite, kyanite and sillimanite. The other metamorphic minerals, garnet and staurolite, are both represented separately in the diagrams.

(vii) Trace minerals: Minerals not normally included in the diagrams because of their low frequencies are chloritoid, glaucophane and topaz. Percentages of the last species are only given in a few cases where its abundance warranted assignment to a separate class (Fig. 11). Whereas chloritoid does not seem to have any particular significance, glaucophane and topaz are important indicators of provenance as will be shown below.

Garnet, epidote, alterite, hornblende and the volcanic minerals are collectively referred to as unstable or weatherable minerals. The others come into the group of stable minerals.

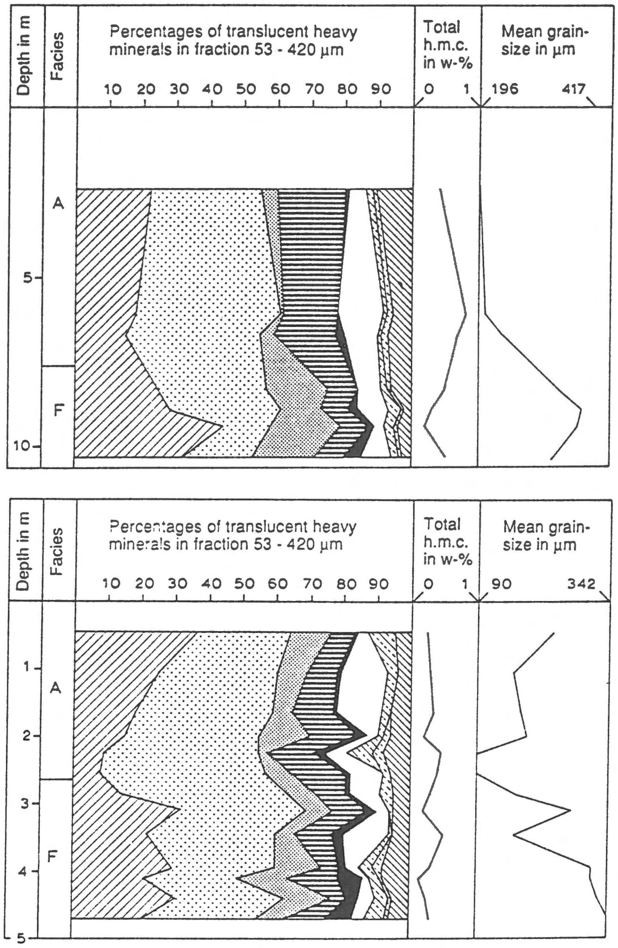

Fig. 8. Heavy-mineral composition of Weichselian sections Dohren (above) and Nordlohne (below). For legend see Fig. 9.

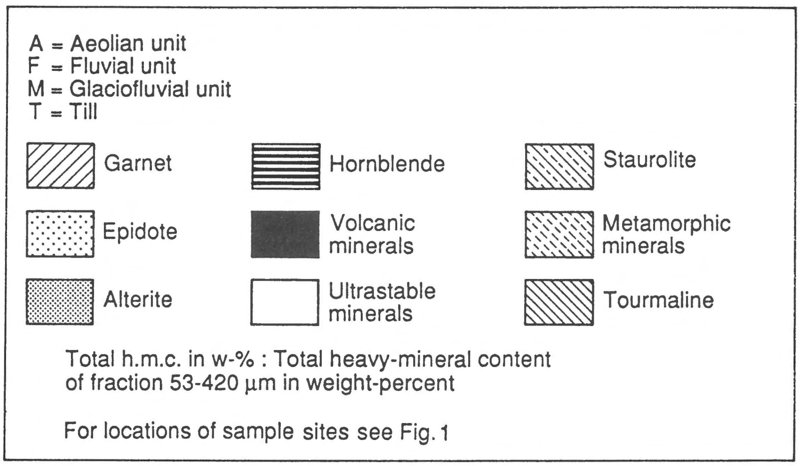

Fig. 9. Legend to heavy-mineral diagrams (Figs 6–8, 10).

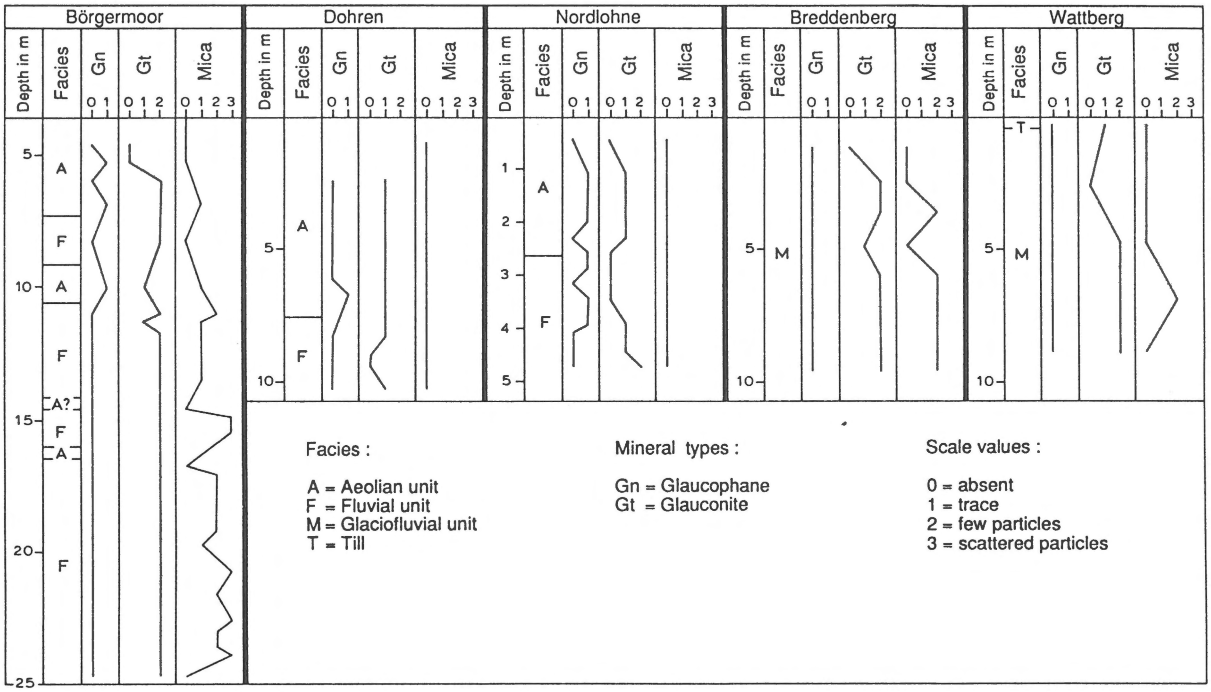

Fig. 10. Frequency estimates of glaucophane, glauconite and mica in the studied sections.

Results

Reviews of the factors that determine the composition of heavy-mineral assemblages and their time-dependent changes are given by Boenigk (1983), Krook (1987) and Van Huissteden (1990). Here, this matter will be approached by a systematic comparison of samples from different sedimentary environments.

Common characteristics. Three characteristics common to all the samples are discussed first. These are:

(i) a high content of unstable heavy minerals. For the Saalian glaciofluvial samples (N = 12) and the Weichselian aeolian and fluvial samples (N = 42) the mean percentages of garnet + epidote + alterite + hornblende are respectively 59 and 77,

(ii) presence of metamorphic minerals + staurolite with a mean abundance of seven percent (N = 55),

(iii) occurrence of the mineral topaz in trace quantities.

Occurrence of glauconite and mica. As shown in Fig. 10, the trace minerals glauconite and mica are found mainly in the Weichselian fluvial samples from Börgermoor and in the Saalian glaciofluvial samples (Breddenberg and Wattberg). Moreover, these two categories of samples share a comparatively high percentage of metamorphic minerals (Table 1). Along with the above features, the fluvial part of section Börgermoor has a pollen-assemblage that, below a depth of 13 m, is dominated by Tertiary elements (Fig. 4).

Table 1. Mean contents of glauconite, mica and metamorphic minerals in Weichselian Talsand and Saalian glaciofluvial sand.

Mineral type	Mean content			
	Weichselian Talsand			Saalian glaciofluvial sand
	Bö.[1] N = 16	Do.[1] N = 4	No.[1] N = 7	N = 12
Clauconite[2]	1.9	0.5	0.7	1.5
Mica[2]	1.7	0.0	0.0	0.9
Metamorphic minerals[3]	6.3	1.0	1.6	6.5

[1] Bö = Börgermoor, Do = Dohren, No = Nordlohne
[2] expressed as mean scale value (Fig. 10)
[3] expressed as mean percentage.

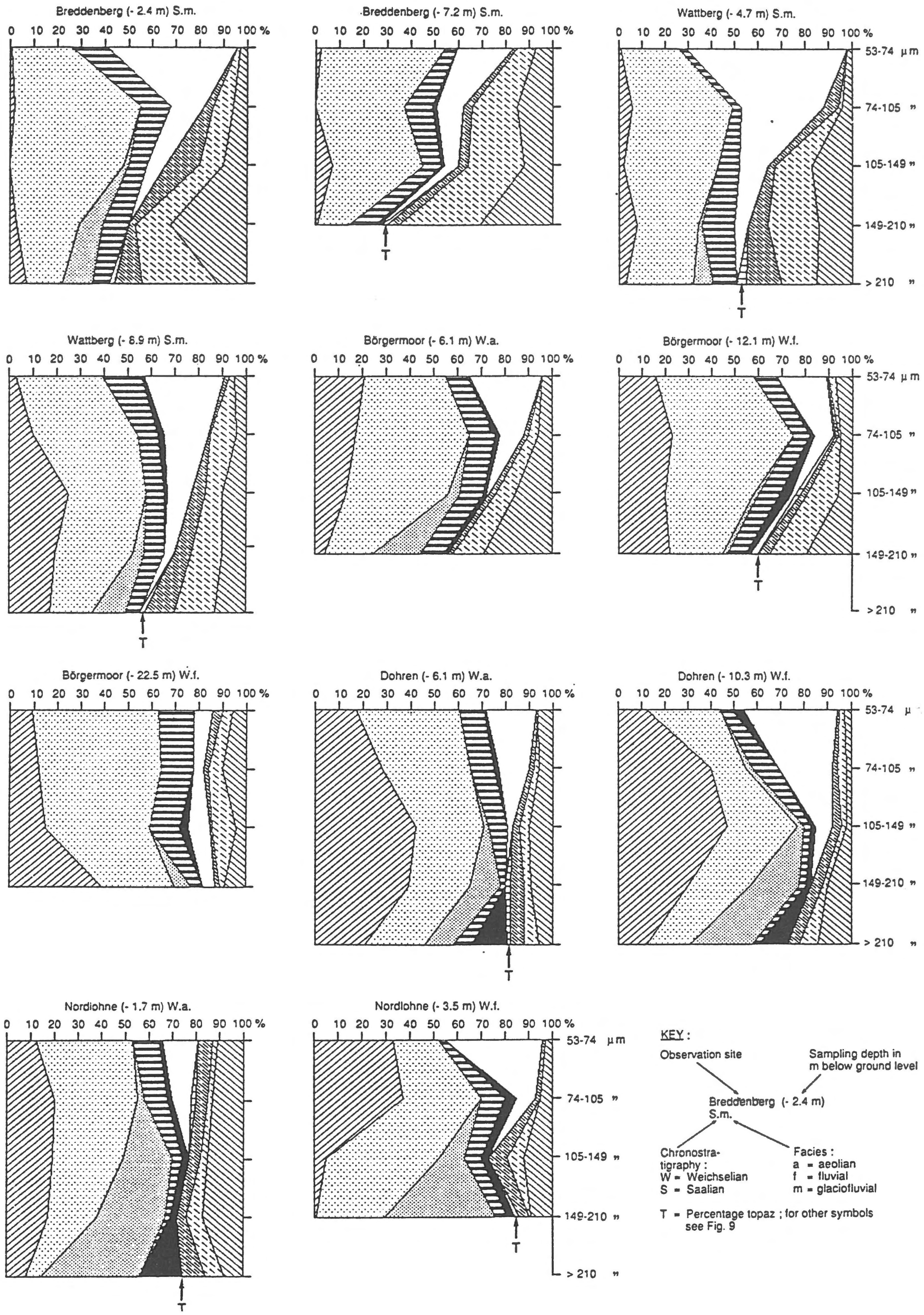

Fig. 11. Fractionated-sample diagrams for eleven selected samples from the five studied sections.

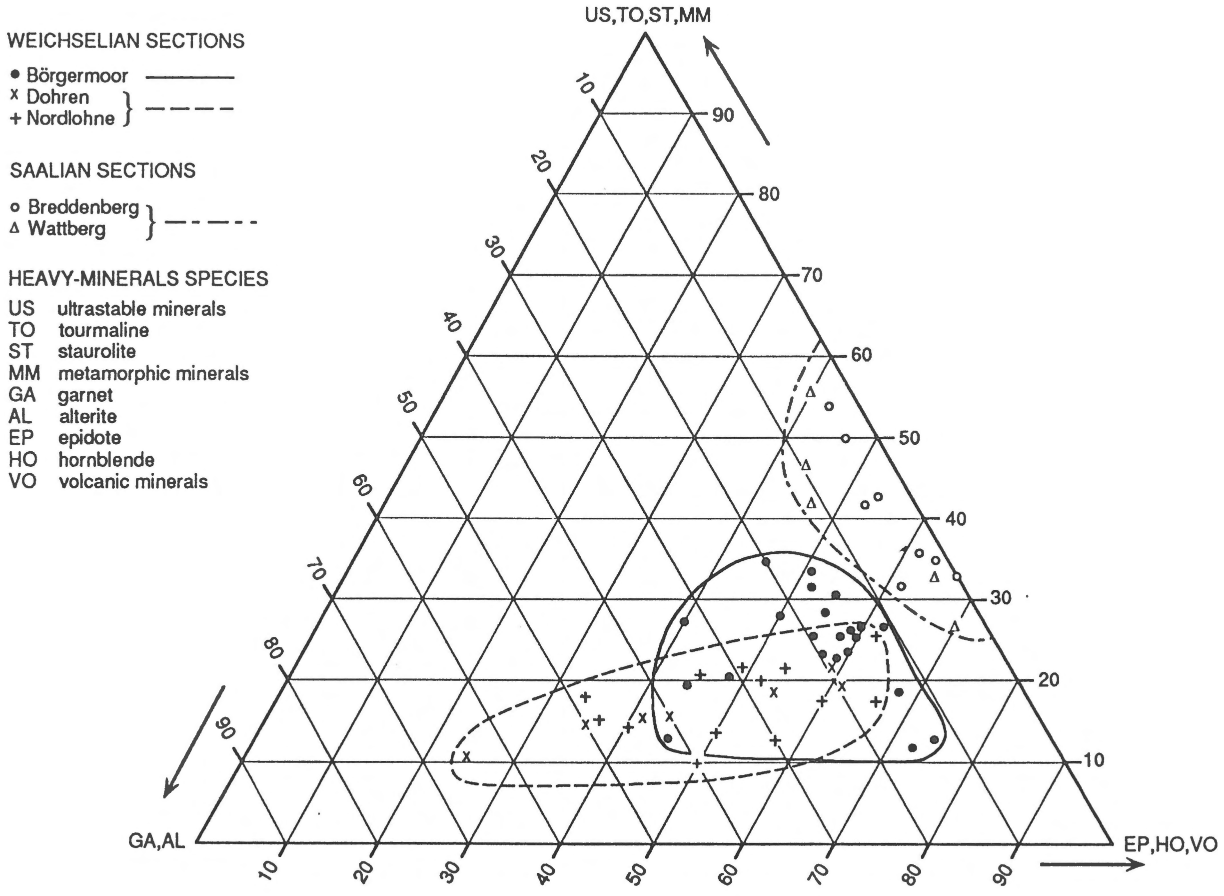

Fig. 12. Ternary diagram of heavy-mineral composition of the studied sections.

Saalian versus Weichselian samples. The conspicuous feature is the higher content in unstable heavy minerals of the Weichselian samples with respect to those of Saalian origin. Statistical testing shows that the mean percentages of garnet and alterite are significantly higher in the Weichselian sections at both 5% and 1% level of significance (Figs 6–8, 12).

In addition to the principal difference in heavy-mineral composition noted above, it was found that (i) most of the Weichselian samples contain variable though small quantities of the mineral augite whereas this species is altogether absent from the Saalian material, and (ii) the Saalian samples show a generally higher percentage of metamorphic minerals + staurolite than their Weichselian counterparts (Figs 11, 12).

Downstream compositional change. A clear contrast exists between the Weichselian fluvial samples from Börgermoor on the one hand and those from Dohren plus Nordlohne on the other (Fig. 12). Samples from the latter group (i) have a significantly higher mean percentage of garnet and alterite and a significantly lower mean percentage of epidote and metamorphic minerals at 5 and 1 % level of significance in both cases, (ii) contain smaller quantities of glauconite and lack altogether in mica (Table 1, Fig. 10), and (iii) have a generally coarser texture, greater roundness and higher augite content in their coarsest fraction (Fig. 11).

Fluvial versus aeolian samples. The fluvial and aeolian samples are all of Late Weichselian Pleniglacial to Weichselian Late Glacial age. At both 5% and 1% level of significance there is no significant difference between the mean percentages of unstable heavy minerals of the two categories. The only discriminating feature is the presence or absence of the mineral glaucophane as shown in Fig. 10. There, it can be seen that this species is absent from the Saalian sections and also from the lower, fluvial parts of the Weichselian sections Börgermoor and Dohren. It does occur, however, in the top of the fluvial part of section Nordlohne but from a detailed study by Schwan (1987) it is known that this zone is of mixed fluvial and aeolian character. Thus, the presence of glaucophane seems to be restricted to units that are of either pure aeolian or fluvio-aeolian origin.

Discussion

(i) The presence of metamorphic minerals, staurolite and trace quantities of topaz is a common characteristic of both Saalian and Weichselian samples. These features are attributed, mainly, to reworking of material laid down by the ancient north German rivers which, in part, constituted the precursors of the present rivers Elbe, Weser and Ems. In Late Tertiary to Middle Pleistocene times, the main trunk of this riversystem crossed the northern European lowland in an east to west direction and debouched in the North Sea basin. Its branches drained both the Baltic Shield from the north and the Hercynian Mittelgebirge from the south. The riversystem under consideration became inactive during the Elsterian Glacial or even earlier but, in any case, long before the Saalian ice sheet began to develop (Zagwijn 1975; Van Staalduinen et al. 1979).

Fibrolite was found as the dominant sillimanite variety in the coarsest fraction of one Saalian sample viz. Breddenberg – 7.2 m (Fig. 11). This supports the above view on the provenance of the metamorphic minerals + staurolite in the subject sediments (Zandstra 1971, Müller et al. 1988).

(ii) As already mentioned, the Weichselian Talsand of site Börgermoor and the Saalian meltwater sands of sites Breddenberg and Wattberg are remarkably similar with respect to their mean content of metamorphic minerals, glauconite and mica. This suggests that the two categories derive in part from the same sources. Whereas the relatively high percentages of metamorphic minerals are attributable to the deposits of the ancient north German riversystem, the presence of glauconite and mica suggests provenance from shallow marine beds. The latter type of beds, having a Tertiary or Pleistocene (mainly Holsteinian) age, is known to occur extensively in the subsoil of northwest Germany (Woldstedt & Duphorn 1974, Hinsche 1977a, 1977b, Institut für Angewandte Geodäsie 1984, Ziegler 1990).

It is likely that ice push during the Main Drenthe Advance has aided in exposing the above-mentioned units to erosion by the Weichselian Talsand-river. At the same time, the expanding ice sheet would have incorporated material from these pre-Saalian units and, during subsequent deglaciation, transmitted it to the meltwater deposits.

(iii) In view of the topographic position and similarity in grain-size, it might be supposed that the Weichselian fill of the Niederungen derives mainly from the Saalian meltwater sands which flank and underlie the Ems-Hase fluvial basin. However, this cannot be the case since, along with other differences, the Weichselian sands are significantly richer in garnet and alterite than their Saalian substrate. Though it is most likely that the closely adjacent Geest plateaus did contribute to the buildup of the Weichselian Talsand and overlying coversand, a considerable part of the material must have come from other sources that were relatively rich in garnet and alterite. Here, it is assumed that the contrast under consideration, rather than being due to chance, has a regional significance.

A relative enrichment in garnet and alterite was also found in the Middle Weichselian Pleniglacial fill of the Dinkel valley in the Netherlands (Fig. 1). All of the potential source rocks in the catchment of the Dinkel, including Drenthe–1 till, have a lower content in the above-mentioned heavy minerals than the sediments of the valley (Van Huissteden 1990).

The discussed feature might be explained by assuming that the Weichselian buildup of fluvial deposits in the glacial basins was preceded by a period of erosion caused by the low sea level of the last ice age. During this phase, the Weichselian precursor of the Ems and its tributaries would both extend their courses in an upstream direction and cut down into the headwater portion of their drainage basins. As a result, the subsequent infilling of the valleys was primarily by particles derived from Cretaceous and older rocks (Fig. 13) with the share of the Saalian substrate being subordinate only.

(iv) As noted before, there exists a distinct contrast between the fluvial samples from Börgermoor on the one hand and those from Dohren plus Nordlohne on the other (Fig. 12). The difference corresponds to a growing contribution to the depositional process of the headwater portions of the riversystem. The diagrams of Fig. 14 are based on our own observations supplemented with heavy-mineral analyses of drag samples from the river Lippe published by Van Andel (1950). Taking into account the steepest gradients only, it can be seen that garnet, alterite and volcanic minerals were provided in the first place by southern sources whereas

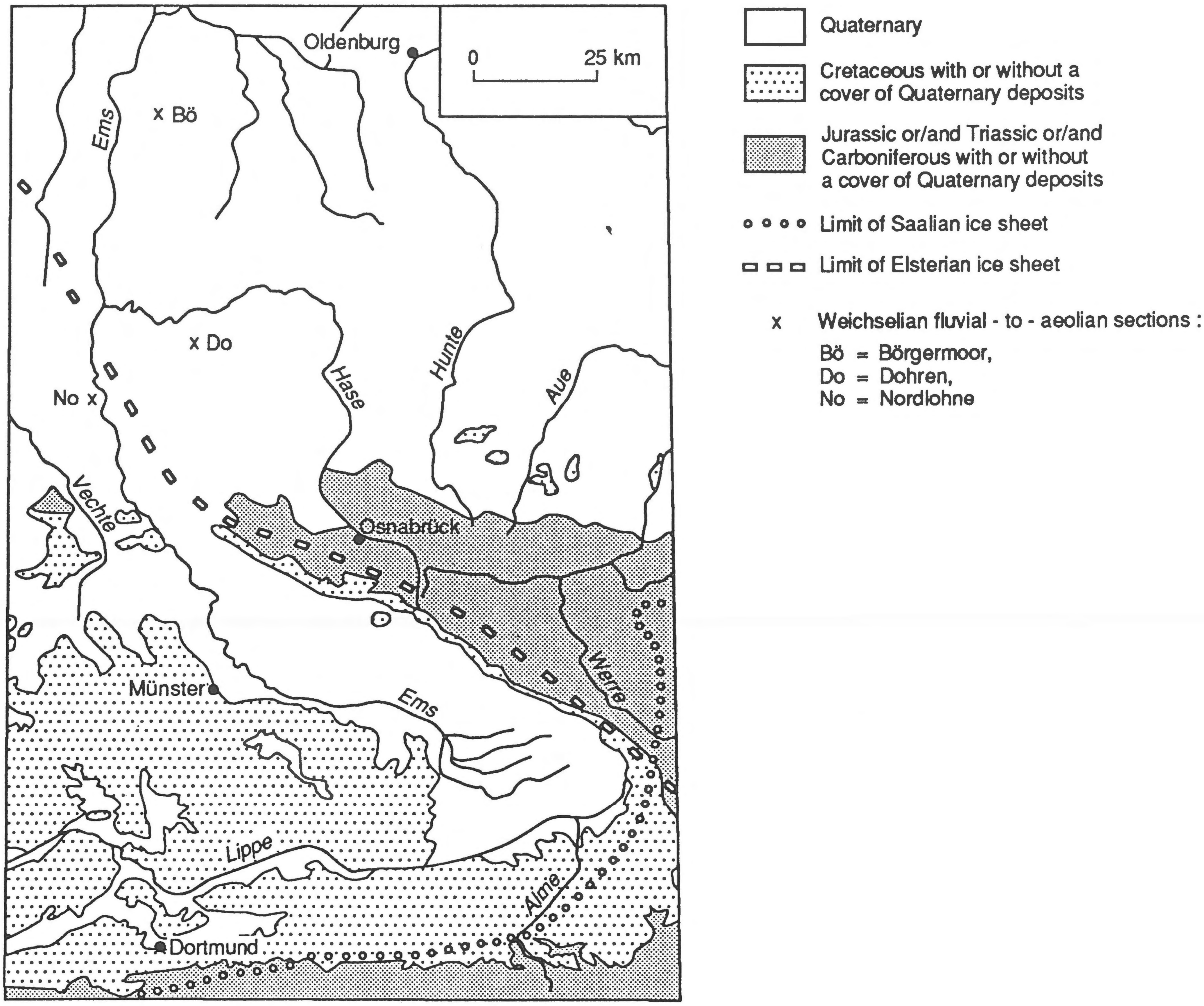

Fig. 13. Catchments of Ems and Hase. Based on Liedtke (1973) and Bundesanstalt für Geowissenschaften und Rohstoffe (1981).

epidote and to a lesser extent also metamorphic minerals should have a mainly northern origin. Moreover, the trend reversals in the diagrams of, mainly, garnet, epidote and alterite show that Ems and Hase have different source areas (Fig. 13). Thus, it might be presumed that the downstream trends in heavy-mineral composition of the fluvial deposits in the study area reflect changes in the subsoil: Cretaceous and older rocks in the south that give way to Cenozoic beds rapidly thickening in northern direction.

A closing remark on the southern source rocks regards the volcanic minerals. From the work of Lippolt (1983) it is known that Cenozoic volcanic activity of the West Eifel, located to the southwest of the Ems' headwaters, lasted until late in Weichselian times. It cannot be excluded, therefore, that the volcanic species in the Weichselian Talsand, rather than being eroded from a rock substrate, were dumped subaerially into the riversystem. Naturally, this implies that explosions and subsequent winds would have been strong enough to carry grains in the 53–420 μm fraction over the odd 180 km that separated source and receiving site.

(v) As already mentioned, the only difference between the Weichselian fluvial and aeolian deposits in the Ems-Hase floodplain is the occurrence of traces of glaucophane in the latter type of sediment.

The mineral glaucophane is regarded characteristic of Rhine sediments which occur over large areas in both the subsoil of the Netherlands and the southern North Sea basin where they form a surface deposit along

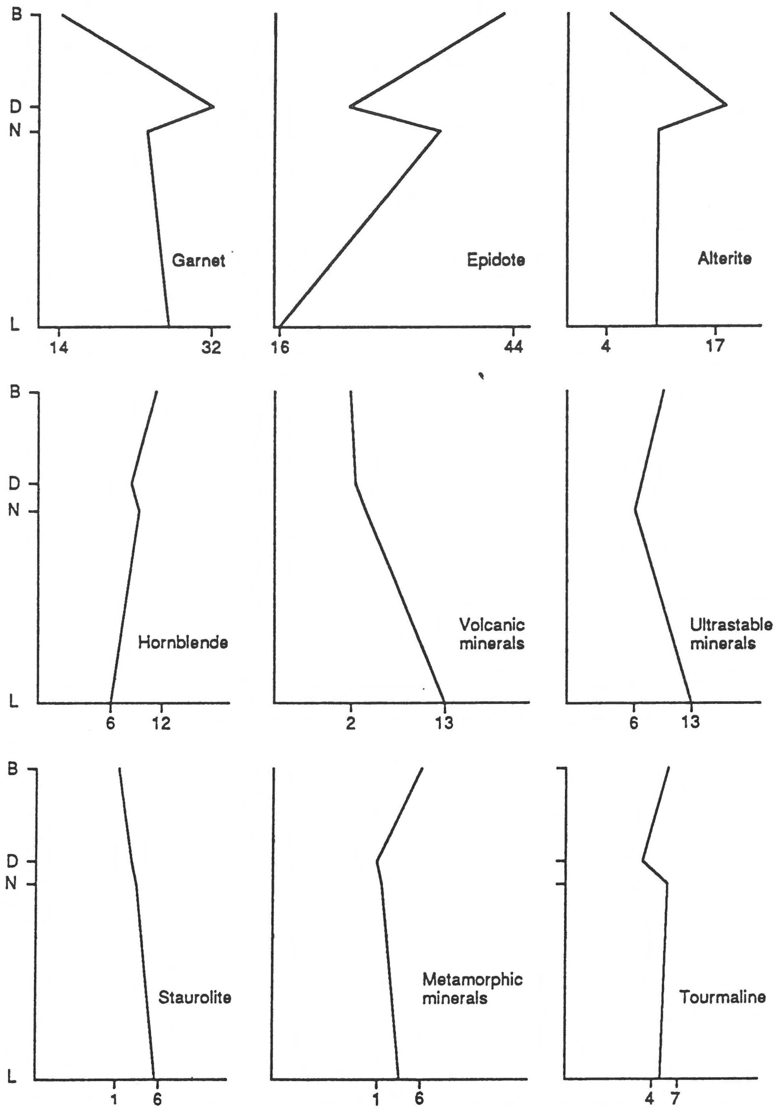

Fig. 14. South-to-north change in heavy-mineral composition of fluvial deposits in study area. Horizontal axis: mean percentage of species. Vertical axis: position to north of river Lippe. L = Lippe (N = 9); N = Nordlohne (N = 7); D = Dohren (N = 4); B = Börgermoor (N = 16).

with formations of different provenance (Baak 1936, Boenigk 1983, Kasse 1988). When the latter region fell dry during the Late Weichselian Pleniglacial, it acted as an important source of aeolian deposition downwind. In particular in the later part of that period, hyperaridity and strong windactivity with dominance of northwesterly or westerly winds prevailed in NW Europe (Kolstrup 1980, Schwan 1988, Meyer & Kottmeier 1989). On the basis of this, it is assumed that deflation from the formerly dry part of the North Sea floor contributed to the deposition of our coversands. This is not to say, however, that this faraway region was the principal source of the aeolian sedimentation. Rather, we feel that this process was in the first place a result of local reworking by wind of the Weichselian fluvial sands as is borne out by the data of the next paragraph. The long-distance transport of grains from the southern North Sea basin was, as it were, superimposed on the local depositional system and but for the admixture of glaucophane its effect remained unnoticeable.

A feature of interest, related to fluvial to aeolian sequences, can be deduced from the fractionated-sample data of Fig. 11. When the finest aeolian and fluvial fractions of site Nordlohne are compared, it is seen that the former has lower garnet and ultrastable mineral percentages and higher epidote and tourmaline percentages than the latter. This is accounted for by assuming that the aeolian unit had formed, largely, from local deflation of the fluvial substrate before this was entirely covered up by windborne sand. As a result, the fluvial source-material became depleted in the low-density minerals epidote and tourmaline and (relatively) enriched in the high-density species garnet and zircon. Concurrently, the reverse happened to the receiving site. This implies, that in the sense of Kuenen (1964) a deposit-repository relationship exists between the finest fractions of aeolian and fluvial sands.

A different behaviour is displayed by the light mineral muscovite which combines low density with a markedly tabular shape. In Fig. 10 it can be seen that in the fluvial to aeolian sequence Börgermoor the mica content decreases upwards. When, here again, local deflation of the fluvial substrate is assumed, this means that the mica flakes are removed from the system rather than being concentrated at the receiving site (cf. Moura & Kroonenberg 1990).

Conclusions

1. Common to all Saalian and Weichselian samples are: (i) high percentages of unstable species, (ii) a generally small percentage of metamorphic minerals + staurolite, and (iii) traces of topaz. The last two categories derive from deposits of the Late Tertiary to Elsterian north German riversystem.
2. The Weichselian Talsand of site Börgermoor and the Saalian meltwatersands of sites Breddenberg and Wattberg are mineralogically related and, in part, derive from the same sources. The relatively high percentages of metamorphic minerals are attributed to the deposits of the north German riversystem and the elevated glauconite and mica contents indicate provenance from shallow marine beds of Tertairy or Pleistocene (mainly Holsteinian) age.
3. The Weichselian heavy-mineral associations are significantly richer in garnet and alterite than the Saalian ones. This shows that the Saalian meltwater sands which flank and underly the Ems-Hase basin, did not significantly contribute to the Weichselian buildup of fluvial sediment. As an alternative it is proposed that this event was preceded by a period of erosion caused by the low sea level of the time. During this phase, the ancient riversystem extended its course upstream and cut into the headwater portion of its drainage basin. As a result, subsequent infilling of the valleys was mainly by material from pre-Cenozoic rocks. This source provided the minerals garnet and alterite in the quantities found in the Weichselian samples.
4. In heavy-mineral composition, there is a clear contrast between fluvial Talsand samples from the northern part of the study area (site Börgermoor) and those from its southern part (sites Dohren and Nordlohne). These data, supplemented with analyses of drag samples from the river Lippe by Van Andel (1950), reveal downstream trends in the mineralogy of the Weichselian fluvial sands. Garnet, alterite and volcanic minerals largely derive from southern sources whereas epidote and to a lesser extent also metamorphic minerals have a largely northern origin. These trends reflect changes in the sediment supply from Cretaceous and older rocks in the south to thick Cenozoic beds in the north.
5. The occurrence of trace quantities of the mineral glaucophane is restricted to Weichselian aeolian samples. This suggests that deflation from the formerly dry part of the North Sea floor contributed to the deposition of the aeolian coversands in the study area. The process had a minor effect only and the deposition of the Weichselian coversand resulted in the first place from local reworking by wind of the fluvial substrate. This follows from (i) the fact that there is no significant difference in unstable-species content between fluvial and aeolian samples, and (ii) the deposit-repository relationship that was found to exist between the finest fractions of both types.

Acknowledgements

We extend our thanks to the following persons: Mr. B. Deitermann, landowner at Dohren, and Mr. R. Diekmann, manager of Torfwerke Neuhaus GmbH at Sedelsberg, for permission to drill on their terrains, Dr. S. Bohncke for interpretation of palynological data and Dr. C. Kasse for useful suggestions, Drs. E. Dabroek, Mr. D. van Harlingen and Drs. M. Visser for participation in the fieldwork, and Prof. Dr. S. Kroonenberg for constructive criticism which substantially contributed to the improvement of the original manuscript.

References

Baak, J.A. 1936 Regional petrology of the southern North Sea – Ph. D. Thesis, Wageningen: 127 pp

Behre, K.E. 1989 Biostratigraphy of the Last Glacial Period in Europe – Quaternary Science Reviews 8: 25–44

Boenigk, W. 1983 Schwermineralanalyse – Ferd. Enke Publ., Stuttgart, 158 pp

Boigk, H., C. Dietz, H.-O. Grahle, K. Hoffmann, W. Hollstein, F. Kühne, W. Richter, H. Schneekloth & R. Wager 1960 Zur Geologie des Emslands – Beih. Geol. Jahrb. 37: 419 pp

Bundesanstalt für Geowissenschaften und Rohstoffe 1981 Geologische Karte der Bundesrepublik Deutschland und benachbarter Gebiete 1:1.000.000 – Hannover

Duphorn, K., F. Grube, K.-D. Meyer, H. Streif & R. Vinken 1973 Area of the Scandinavian Glaciation: Pleistocene and Holocene. In: E. Schönhals & R. Huckriede (eds.): State of Research on the Quaternary of the Federal Republic of Germany – Eiszeitalter u. Gegenwart 23/24: 222–250

Hinsch, W. 1977a Basis des glaziären Pleistozäns in Schleswig – Holstein bzw. Oberkante des Präquatertärs (einschliesszlich Kaolinsand und autochthone Schollen) bezogen auf NN. Maszstab 1:250.000 – Geologisches Landesamt Schleswig-Holstein, Kiel

Hinsch, W. 1977b Karte des präquartären Untergrundes in Schleswig-Holstein. Maszstab 1:250.000 – Geologisches Landesamt Schleswig-Holstein, Kiel

Institut für Angewandte Geodäsie 1984 Das jüngere Tertiär in Nord- und Nordostniedersachsen. Präquartärer Untergrund. Maszstab 1:200.000 – Frankfurt a. M

Kasse, C. 1988 Early-Pleistocene tidal and fluviatile environments in the southern Netherlands and northern Belgium – Ph.D. Thesis, Vrije Universiteit, Amsterdam: 190 pp

Kolstrup, E. 1980 Climate and stratigraphy in northwestern Europe between 30,000 B.P. and 13,000 B.P. with special reference to The Netherlands – Meded. Rijks Geol. Dienst 32–15: 181–253

Krook, L. 1987 An introduction to the study of heavy minerals – Internal Rep. Fac. of Earth Sc., Vrije Universiteit, Amsterdam: 52 pp

Kuenen, Ph. H. 1964 Pivotability studies of sand by a shape-sorter. In: L.M.J.U. van Straaten (ed.): Deltaic and shallow marine deposits. Developments in sedimentology, Vol. I. Elsevier Publishing Cy, Amsterdam: 464 pp

Liedtke, H. 1973 Die nordischen Vereisungen in Mitteleuropa. Geologische Karte Maszstab 1:1.000.000 – IVIS-Verlag, Berlin

Lippolt, H.J. 1983 Distribution of Volcanic Activity in Space and Time. In: K. Fuchs, K. von Gehlen, H. Mälzer, H. Murawski & A. Semmel (eds.): Plateau Uplift. The Rhenish Shield – A Case History – Springer Verlag, Berlin: 441 pp

Meyer, K.-D. 1983 Zur Anlage der Urstromtäler in Niedersachsen – Z. Geomorph. N.F. 27(2): 147–160

Meyer, H.H. & Chr. Kottmeier 1989 Die atmosphärische Zirkulation in Europa im Hochglazial der Weichsel-Eiszeit abgeleitet von Paläowind-Indikatoren und Modellsimulationen – Eiszeitalter u. Gegenwart 39: 10–18

Moura, M.L. & S.B. Kroonenberg 1990 Geochemistry of Quaternary fluvial and eolian sediments in the southeastern Netherlands – Geol. Mijnbouw 69: 359–373

Müller, A., R. Ortmann & L. Eissmann 1988 Die Schwerminerale im fluviatilen Quartär des mittleren Saale-Elbe-Gebietes – Altenbg. nat. wiss. Forsch., Altenburg, Heft 4: 70 pp

Ran, E.T.H. & J. van Huissteden 1990 The Dinkel Valley in the Middle Pleniglacial: dynamics of a tundra river system – Meded. Rijks Geol. Dienst 44–3: 209–220

Schröder, E. 1978 Geomorphologische Untersuchungen im Hümmling – Göttinger Geogr. Abhand., Heft 70, Verlag E. Goltze KG, Göttingen: 111 pp

Schwan, J. 1987 Sedimentologic characteristics of a fluvial to aeolian succession in Weichselian Talsand in the Emsland (F.R.G.) – Sediment. Geol. 52: 273–298

Schwan, J. 1988 The structure and genesis of Weichselian to Early Holocene aeolian sand sheets in western Europe – Sediment. Geol. 55: 197–232

Schwan, J. & J. Vandenberghe 1991 Weichselian Late Pleniglacial fluvio-aeolian deposits and cryogenic structures. In: Excursion Guide Symposium Periglacial Environments in relation to Climatic Change, Maastricht/Amsterdam, 3–6 May, Vrije Universiteit, Amsterdam: 68–77

Van Andel, Tj.H. 1950 Provenance, transport and deposition of Rhine sediments – Thesis Wageningen: 129 pp

Van den Berg, M.W. & D.J. Beets 1987 Saalian Glacial deposits and morphology in The Netherlands. In: J.J.M. van der Meer (ed.) Tills and Glaciotectonics, Proc. INQUA Symposium on Genesis and Lithology of Glacial Deposits, Amsterdam, 1986. A.A. Balkema, Rotterdam: 235–251

Van Huissteden, J. 1990 Tundra rivers of the Last Glacial: sedimentation and geomorphological processes during the Middle Pleniglacial in Twente, eastern Netherlands – Meded. Rijks Geol. Dienst 44–3: 3–138

Van Staalduinen, C.J., H.A. Van Adrichem Boogaert, M.J.M. Bless, J.W.Chr. Doppert, H.M. Harsveldt, H.M. Van Montfrans, E. Oele, R.A. Wermuth & W.H. Zagwijn 1979 The geology of The Netherlands – Meded. Rijks Geol. Dienst 31–2: 9–49

Woldstedt, P. & K. Duphorn 1974 Norddeutschland und angrenzende Gebiete im Eiszeitalter. Koehler Verlag, Stuttgart: 500 pp

Zagwijn, W.H. 1975 De palaeogeografische ontwikkeling van Nederland in de laatste drie miljoen jaar – Kon. Nederl. Aardrijksk. Gen., Geogr. Tijdschr. IX (3): 181–201

Zagwijn, W.H. 1991 Colleges vegetatiegeschiedenis van het europese Kwartair, dl. 3 – Internal Rep. Fac. of Earth Sc., Vrije Universiteit, Amsterdam/Geol. Survey of the Netherlands, Haarlem: 50 pp

Zagwijn, W.H., D.J. Beets, M. van der Berg, H.M. van Montfrans & P. van Rooijen 1985 Atlas van Nederland, dl. 13: Geologie – Stichting Wetenschappelijke Atlas van Nederland, Staatsuitgeverij, Den Haag: 23 pp

Zandstra, J.G. 1971 Geologisch onderzoek in de stuwwal van de oostelijke Veluwe bij Hattem en Wapenveld – Meded. Rijks Geol. Dienst, N.S. 22: 215–260

Ziegler, P.A. 1990 Geological Atlas of Western and Central Europe; 2nd and completely revised edition – Shell Intern. Petroleum Mij. B.V., The Hague: 239 pp