

Grain surface characteristics of periglacial aeolian and fluvial sands

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Abstract

Surface features of quartz grains from periglacial aeolian and fluvial deposits from two areas in The Netherlands and adjacent Germany have been studied with a Scanning Electron Microscope. The relative abundance of the 29 distinguished characteristics is statistically analysed in an attempt to correlate the surface features with the regionally and genetically determined sediment types.

Frequencies of individual grain surface characteristics vary widely and are usually insufficient to separate the sediment types. This is partly due to the variable degree of surface pattern overprint caused by the polygenetic nature of the sediments concerned. However, linear combination of the sample variables (using principal component analysis) allows the discrimination of several distinct clusters, that show a fair correspondence with the macroscopically defined depositional groups. The regional and stratigraphical patterns observed, seem to be dominated by two factors: one which is related to the transport energy and the mode of deposition involved and perhaps connected with the prevailing wind regime; the other with chemical alterations, probably reflecting the source area of the sediment. New perspectives are opened for the genetical interpretation of sediments by grain morphoscopic analysis when combined with multivariate statistics.

Introduction

Quartz-grain surface features, as observed with a Scanning Electron Microscope (SEM), may reveal important aspects of the depositional environment (a.o. Krinsley & Doornkamp 1973; Le Ribault 1975; Smart & Tovey 1981; Pye & Sperling 1983; Culver et al. 1983; Baker 1976). Although the study of the morphoscopy of quartz grains in the Netherlands received some attention in the past decades (Kuenen 1959, 1960; Van der Waals 1967; Riezebos 1974) no systematic research has ever been carried out. This study is an attempt to establish the relation between morphoscopic surface characteristics and the sedimentary history of the deposit concerned as known from other sources such as sedi-

mentary structures, mineralogical composition and grain-size analyses. More specifically, an attempt is made to establish morphoscopic criteria to differentiate between fluvial and aeolian sediments. Next, variations in surface features within the aeolian realm are investigated in a genetic as well as in a stratigraphic and regional sense.

The material used in this study consists of Pleistocene aeolian and fluvial sands. A comparison is made between a locality in the southern part of the Netherlands (Goirle) and the Twente-Emsland area in the eastern part of the Netherlands and adjacent Germany (fig. 1). Both areas are situated in the coversand belt. This study forms part of a research project on the genesis and provenance of aeolian sediments.

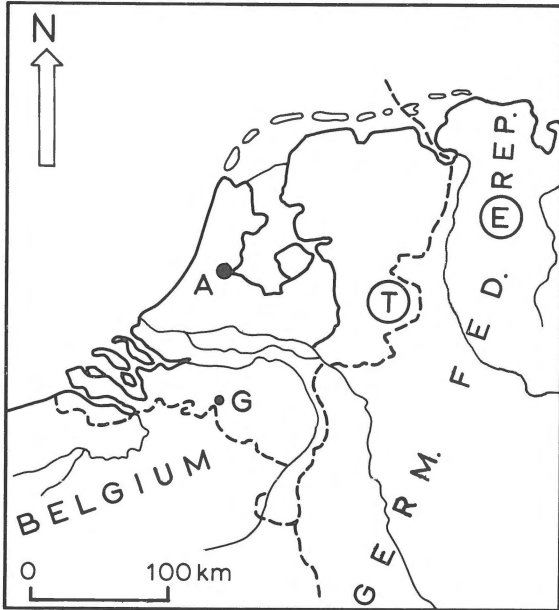


Fig. 1. Location map. A = Amsterdam, E = Emsland area, T = Twente area, G = Goirle.

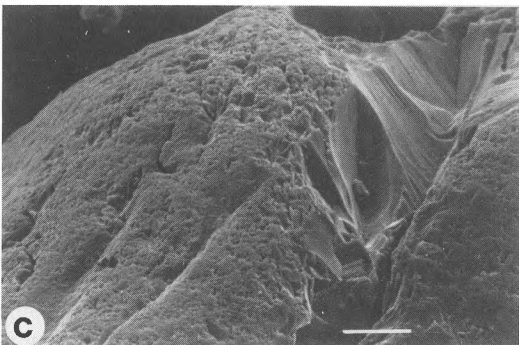
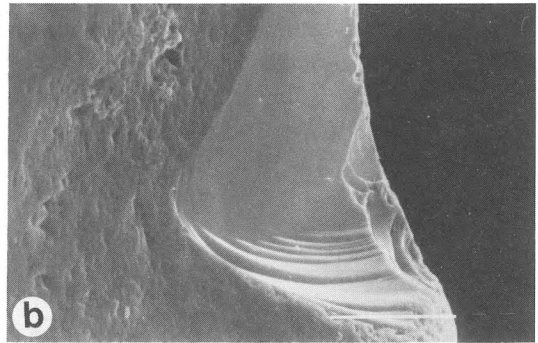
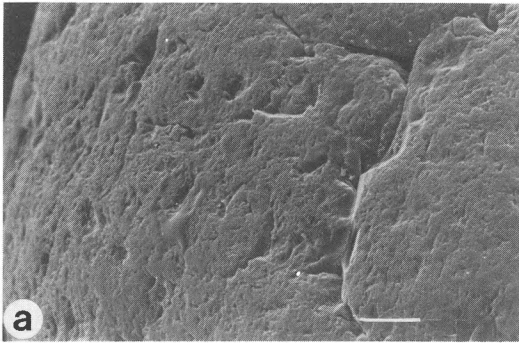
Characteristic grain surface features

A survey of the literature and the results of the present research have resulted in the distinction of 29 surface features, which are described below. They allow the characterisation of each grain surface and form the base for a genetic interpretation. Examples of the most striking surface features are given in Fig. 2.

Rounding (1) depends for the greater part on the degree of abrasion suffered by the sample concerned (Higgs 1979).

The High relief (2) of the quartz grain surface depends on the extent of mechanical and/or chemical modification of the surface since it was removed from the crystalline parent rock (Higgs 1979).

Conchoidal fractures (3) are caused by grain-to-grain collision in an aeolian and/or fluvial medium (Kransley & Funnell 1965). Higgs (1979) suggested conchoidal fractures are characteristic only of glacial environments and of material freshly lib-



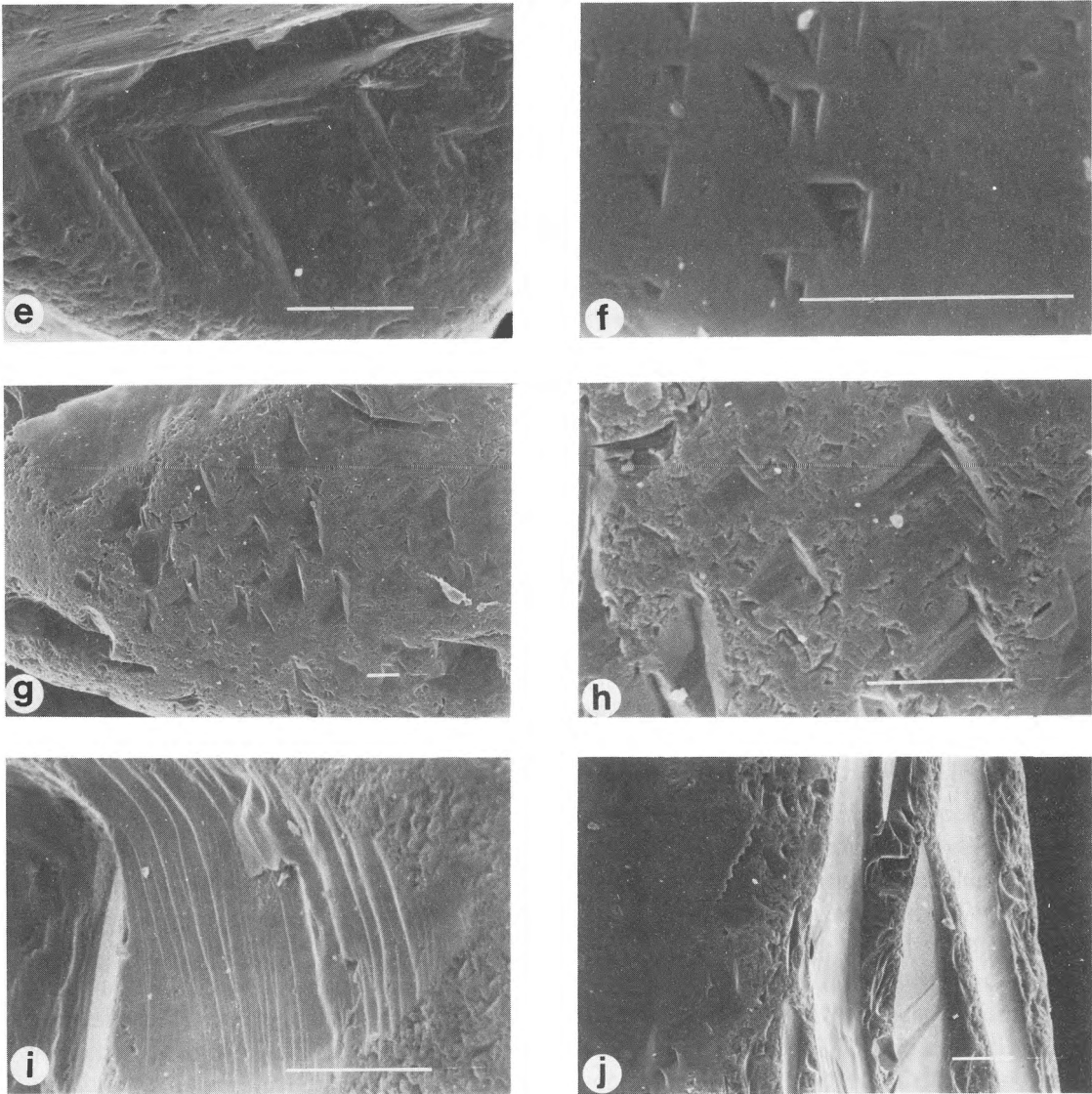


Fig. 2. Scanning electron micrographs of grain surface textures. Length of bar represents $10\ \mu\text{m}$. Numbers in brackets refer to grain surface features listed in Table 1. a: Straight scratches (7), curved scratches (8), scratches with satellite V's (9) and mechanical V-shaped pits (16). All these features result from grain-to grain collisions in air and water. b: Conchoidal fracture face (3) with arc-shaped steps (5). Some mechanical V-shaped pits (16) at the left. c: Conchoidal fractures (3) with semi-parallel steps (4), straight scratches (7), mechanical V-shaped pits (16) and irregular small fractures (21). These impact features occur on quartz grains deposited in high energy environments. d: Chattermarks (17). e + f: Oriented etch pits (23) formed by dissolution of quartz. g + h: Mechanical V-shaped pits (16) which have suffered dissolution. This process exposes the oriented crystal pattern. i: Semi-parallel steps (4) in a disc-shaped concavity (12) with orange-peel structure (28) to the right. This latter feature is characteristic of aeolian environments. j: Face of conchoidal fracture (3) with semi-parallel lines (6).

erated from a crystalline source. Therefore it is possible that many of the conchoidal fracture patterns are inherited from the source material and from earlier periods in the grain's transport history.

Semi-parallel steps (4) are closely allied to conchoidal fractures (3) and consequently characteristic only for the same environments. They have probably been caused by shear stress (Krinsley & Funnell 1965).

Arc-shaped steps (5) are a series of concentric shaped arcs on conchoidal breakage faces (Whalley & Krinsley 1974).

Semi-parallel lines (6) are parallel striations of varying length which are caused by the movement of sharp edges against the grains involved. This feature is especially characteristic of glacial environments (Krinsley & Funnell 1965).

Straight scratches (7) and *curved scratches* (8) of about 2–25 μm result from grain-to-grain collision and are therefore found in all environments characterised by grain motion (Higgs 1979). They are often associated with *mechanical V-shaped pits* (16), which may incorporate *satellite v's* (9) at intervals along their length (Higgs 1979).

Imbricated breakage blocks (10), which look like a series of steeply dipping hogback ridges are considered diagnostic for the glacial environment, but it has been shown that other modes of origin are possible (LeRibault 1975).

Single (11) and *Multiple disc-shaped concavities* (12), equidimensional as well as elongate, are commonly associated with conchoidal breakage patterns. Margolis & Krinsley (1971) considered them one of the most important features characterizing aeolian environments.

Meandering ridges (13) apparently result from the intersection of slightly curved conchoidal breakage patterns caused by grain-to-grain collision in an aeolian medium (Krinsley & Donahue 1968).

Faces, unaffected by diagenesis or weathering frequently include traces of another cleavage direction, represented by a series of parallel plates with depressions between them. These *upturned plates* (14) are usually irregular in height and extent and may consist of a series of disconnected individuals, all perfectly oriented in one direction. They possi-

bly display traces parallel to r(1011) and z(0112) (Wellendorf & Krinsley 1980).

Graded arcs (15) appear in series, each with a progressively smaller radius towards the centre. They probably represent percussion fractures and are characteristic of aeolian environments (Whalley & Krinsley 1974).

Mechanical V-shaped pits (16) are due to impact and are formed in subaqueous and aeolian environments, particularly relatively high energy environments (Krinsley & Doornkamp 1973).

Chattermarks (17) appear in series of subparallel indentations averaging 0.5 μm in length; they are probably produced by grains skipping one another (Krinsley & Funnell 1965).

Irregular or polygonal cracks (18) almost invariably occur in association with an irregular *precipitation/solution surface* (24) and are probably shrinkage cracks (Cheng 1978).

Flat cleavage planes (19) are extremely flat areas formed by cleavage and are more commonly found on the smaller quartz grains. They are possibly inherited from the parent rock, but may also have formed mechanically in glacial and subaquatic environments.

Fresh cleavage planes (20) share a strong environmental association with conchoidal fractures and may therefore be genetically related (Higgs 1979).

Irregular small fractures (21) are impact features present on quartz grains from high energy environments. Along cleavage lines or other crystallographically oriented features *Precipitation of silica in the shape of upturned plates* (22) is possible (Krinsley & Doornkamp 1973).

Oriented etch pits (23) formed by dissolution of quartz, are characteristic of marine subaquatic and certain pedologic horizons (Cater 1984). The longer the grains are in contact with alkaline solutions and the less mobile they are the larger and more abundant are the resulting etch pits.

Chemical disintegration (25) takes place in highly aggressive chemical environments (Krinsley & Doornkamp 1973).

A smooth precipitation surface (26) is usually the result of rapid precipitation of silica which may be in optical continuity with the old surface and re-

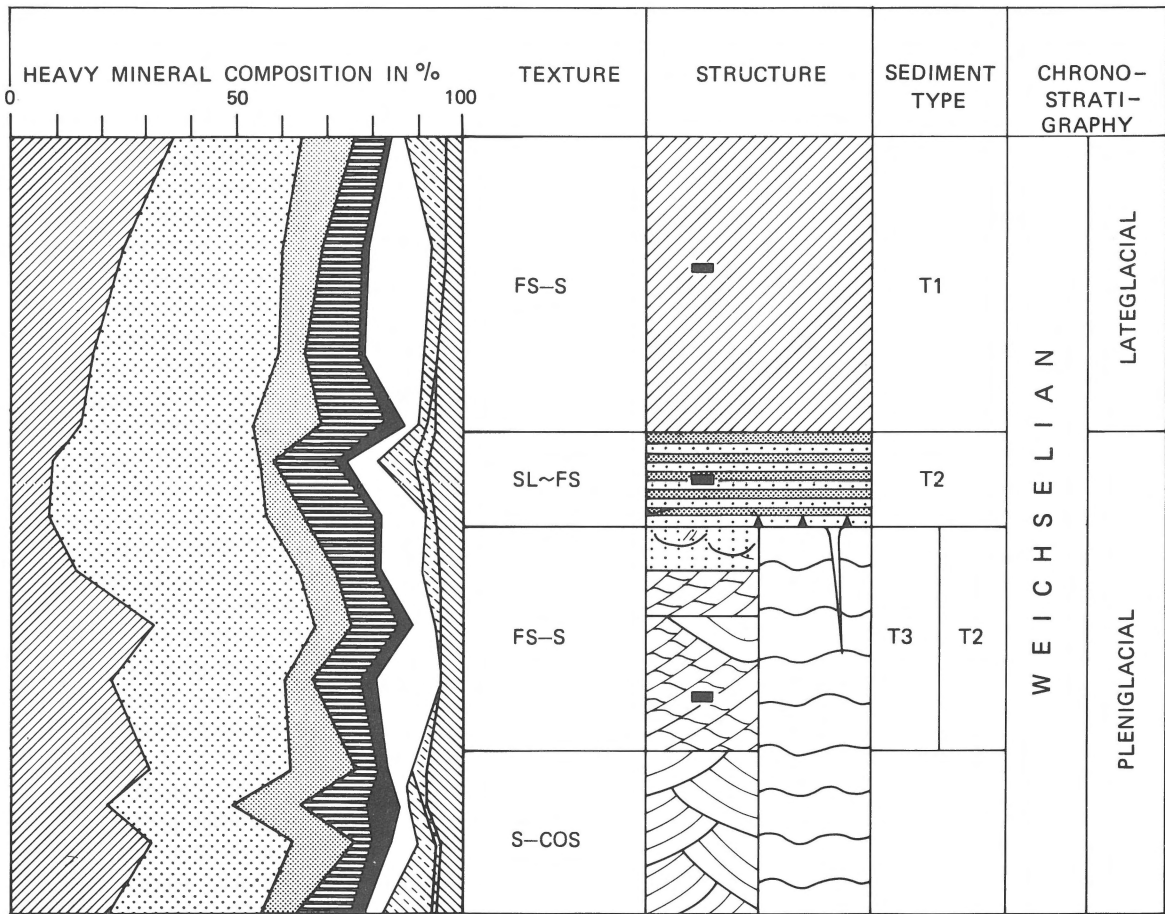


Fig. 3. Sediment types, texture and structure, heavy-mineral composition and chronostratigraphy of the synthetic profile of the Twente-Emsland area. The length of the profile is 4,3 m. For legend see Fig. 5.

flects underlying plate topography. This may occur in aeolian, glacial and fluvial environments (Krinsley & Doornkamp 1973). Under quiet conditions and slow silica precipitation *quartz crystal growth* (27) is possible (Cater 1984). A feature very indicative of aeolian environments is an *orange-peel structure* (28) formed by upturned plates which have been subject to solution/precipitation of silica and have been smoothed consequently (Krinsley & Doornkamp 1973). Each large individual plate is composed of a number of small ones, all oriented crystallographically. *Adhering particles* (29) may be found on grains from glacial and aeolian environments (Higgs 1979).

Description of the sediment types

The Twente-Emsland area

At nine representative sites in the Twente-Emsland area (Fig. 1) grain-surface texture samples have been collected from the sediment types T1, T2 and T3 (fig. 3-5).

Type T1. The structure of this periglacial aeolian coversand is primarily characterised by both horizontal bedding and low-angle inclined bedding. Within beds, continuous parallel lamination prevails. This stratification type presumably corresponds to aeolian planebed lamination in the sense of Hunter (1977). Strings of granules or small pebbles

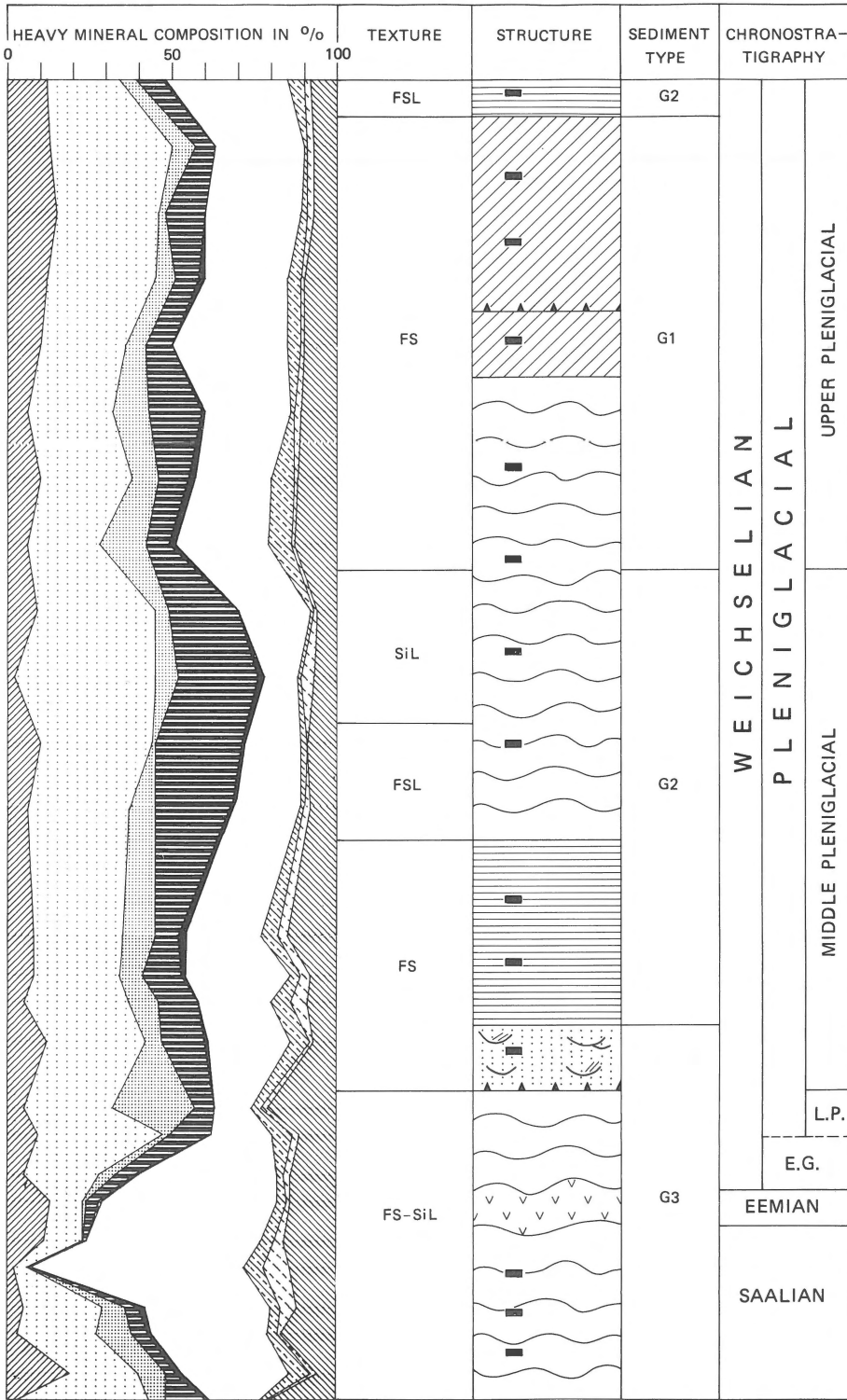


Fig. 4. Sediment types, texture and structure, heavy-mineral composition and chronostratigraphy of the Goirle profile. The length of the profile is 4 m. For legend see Fig. 5.

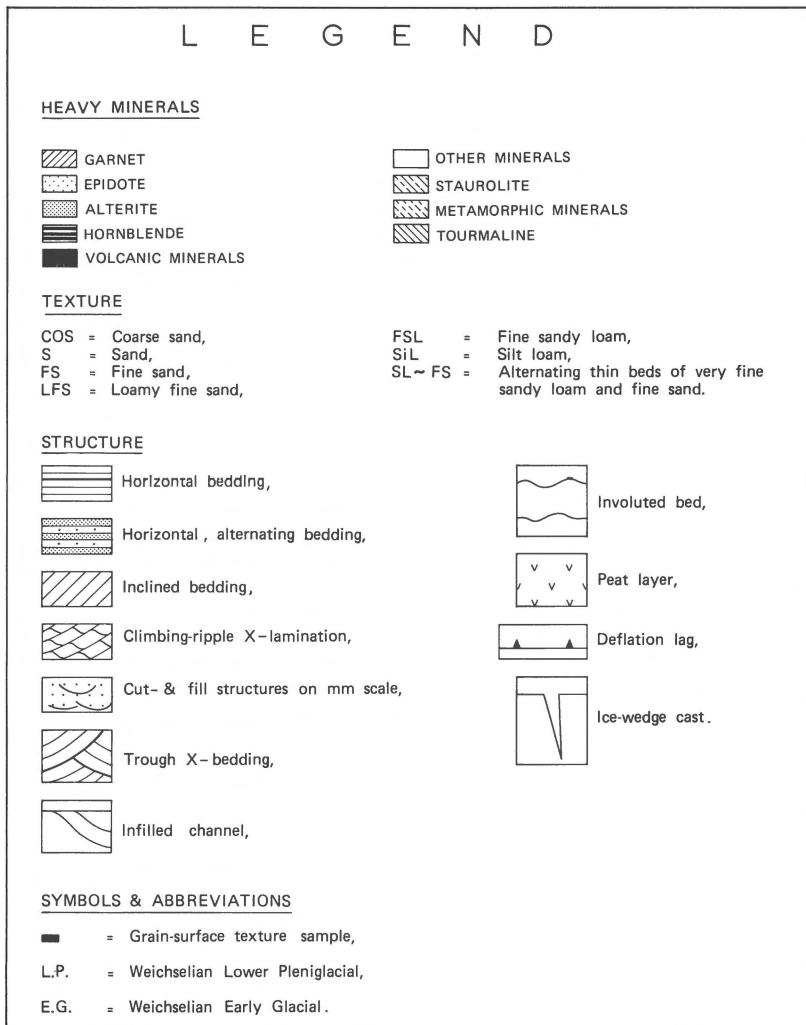


Fig. 5. Legend to Figs. 3 and 4.

bles, marking former deflation surfaces, occur with some regularity. Sediment type T1 has a generally homogeneous sandy texture and a gently undulating surface topography. It is closely similar to 'eolian subfacies A' described by Ruegg (1983).

Type T2. A more or less regular alternation of coarser and finer-grained beds is the principal characteristic of this periglacial aeolian coversand. Depending on their stratigraphic position, the beds are either horizontal and wavy, or strongly distorted by periglacial involutions. Sediment type T2 corresponds to 'eolian subfacies B' defined by

Ruegg (1983). Its genesis is discussed by Schwan (1986).

Type T3. This class comprises originally wind-borne coversand which has been reworked by current flow. Accordingly, in the Twente-Emsland region, thick units of type T3 are mainly found in the proximity of rivers such as the Dinkel and Ems. Much thinner intercalations of similar sediment, on the other hand, are not restricted to the sides of present watercourses. They are, in fact, fairly common in coversand regions and were locally formed by shallow and short-lived paleo-discharge-systems

(Ruegg 1983; Vandenberghe 1985)

The fluviatile character of the sediment type under discussion is evidenced by channel-fill structures, small-scale cross-lamination and in particular by abundant climbing-ripple lamination.

The Goirle-exposure (location on fig. 1)

Fig. 4 shows the general make-up of the Goirle-profile along with the levels which have been sampled for grain-morphoscopic analysis. G1, G2 and G3 are the three sediment types that could be distinguished in this exposure (see also Vandenberghe & Krook 1985).

Type G1. This unit is closely similar to the sediment type T1 (described above). It only differs from its counterpart in the Twente-Emsland area by a somewhat finer texture and by the fact that its lower part has been distorted by cryoturbation. This latter feature is associated with an older time-stratigraphic position (see Fig. 4).

Type G2. This sediment type is a periglacial wind-borne deposit. The lower G2-unit represents an aeolian fining-upward sequence as from bottom to top its texture changes from a coversand-like fine sand to a loess-like silty loam. Whereas the loamy top is uniquely characterised by horizontal even lamination, the sandy base shows an alternation of coarser- and finer-grained thin beds very similar to that of sediment type T2 in the Twente-Emsland region. To a large extent the originally horizontal stratification of sediment type G2 is deformed by periglacial involutions.

Type G3. This sediment type results from small-scale fluviatile reworking of aeolian deposits and as such it is similar to unit T3 in the Twente-Emsland region. From base to top unit G3 consists of a Saalian microfan deposit, an Eemian peat layer and a Weichselian bed that presumably was formed by surface runoff or sheet-flooding of snow-melt-water. Included in this last subunit is a desert pavement below which the strata are involuted. This level corresponds to the Weichselian Lower Plen-

iglacial chron with permafrost conditions (Vandenberghe 1985).

Morphoscopic analysis

From both regions two mutually comparable types of aeolian sediments are considered, as well as a group of sediments deposited under aquatic conditions. About 5 g of each sample was boiled for 10 minutes in concentrated hydrochloric acid, followed by thorough flushing with distilled water. Under a binocular 30 monocrystalline quartz grains were picked at random from each sample. This number is thought to be sufficient to represent the variability in a sample (Krinsley & Doornkamp 1973; Baker 1976). Only grains in the size range 105–210 μm were used in order to reduce the influence of grain size on the surface characteristics.

Fig. 6 shows the mean frequency of every surface characteristic for each of the regional-genetic classes. This graph does not reveal any obvious pattern. This is not surprising when the origin of the aeolian sands is considered. Indeed, it has been shown previously (Vandenberghe & Krook 1981) that the aeolian sands under consideration were deposited originally as fluvial sands. They were taken up by the wind and redeposited after transport over highly variable distances. Therefore, it may be expected that the original surface features are superposed by others in varying amounts, depending on the distance of wind transport, and it seems impossible to infer the mode of transport of a sand from the study of one sample. The same holds for the fluvial samples which were transported by small rivers over relatively short distances only.

The range of frequencies of several characteristics is rather wide. χ^2 tests have been performed on the raw data in order to establish the significance of the observed differences between groups of samples. Beforehand, the characteristics which are either rare (<20%) or abundant (>80%) in almost all the grains (>96%) of a sample are excluded. The results (Table 1) show that many of the above-mentioned characteristics are significant for the distinction between the fluvial and aeolian sands and between the different types of aeolian sands.

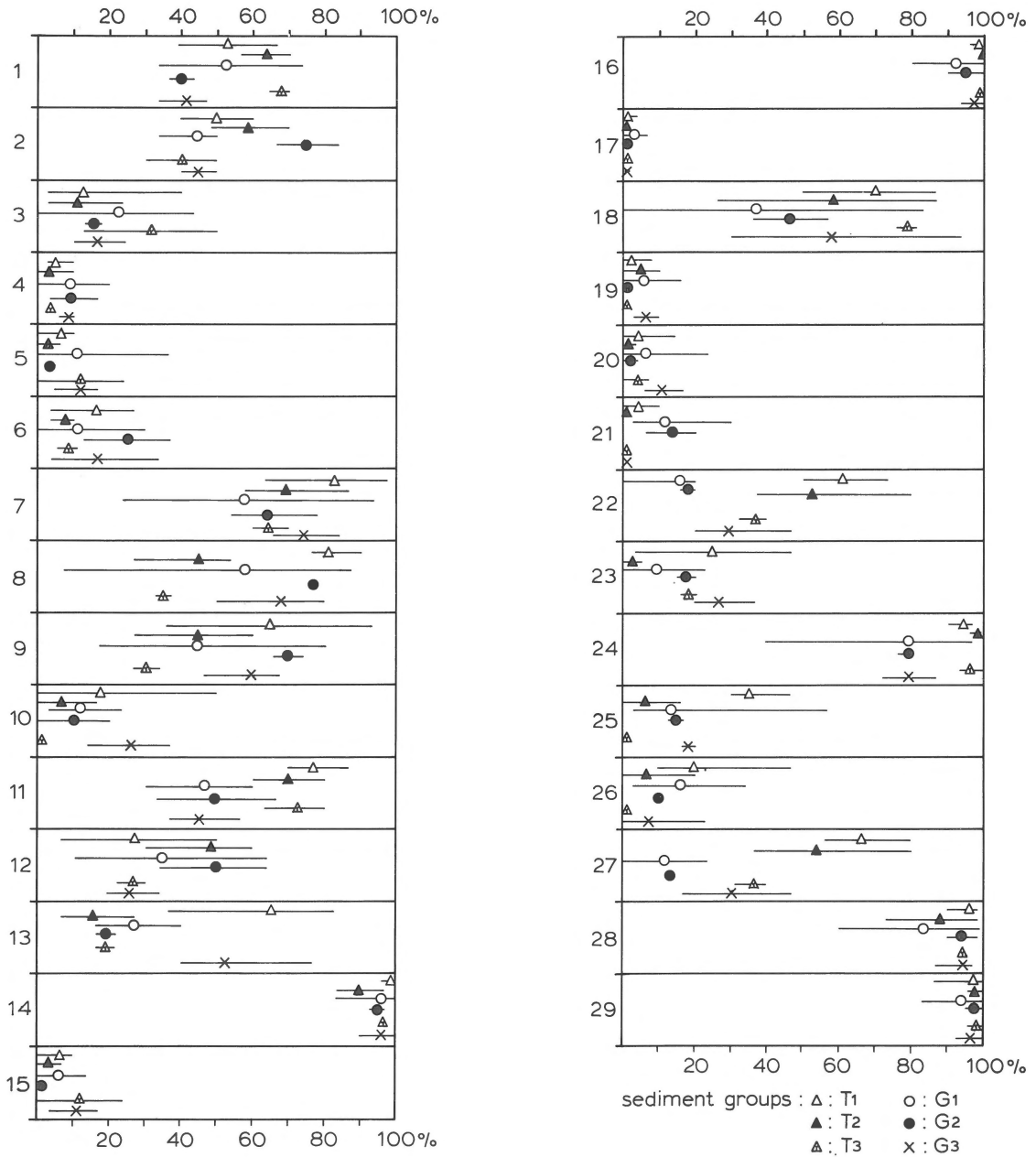


Fig. 6. Mean and range of the frequencies of the surface characteristics for the different sediment groups. The numbers of the surface characteristics refer to the description in the text.

However, since many characteristics investigated are correlated, a Principal Component Analysis (PCA) should reduce the dataset to a manageable small number of factors. As no a priori weight should be given to any of the individual grain characteristics the data set should first be con-

verted into a z-score matrix. It turns out that about 60% of the variance is explained by the first three eigenvectors (resp. 27%, 21% and 13% and nearly 50% by the first two eigenvectors. From Fig. 7 it is evident that no single characteristic is responsible for any of the eigenvectors. However, eigenvector

I is mainly determined by impact features (6-8-9-13), while eigenvector II weighs largely chemical precipitation or solution phenomena (27-24-22).

The sample scores of the PCA are plotted in twodimensional diagrams. This discussion will be limited to the plot on axes I-II since the diagrams with axes I-III and II-III reveal no new results. The most striking result of the PCA (Fig. 8) is the appearance of distinct clusters of genetically and spatially defined groups. An unambiguous distinction between the samples from the two regions is realized by a line perpendicular to axis II. Comparison of the aeolian and fluvial sands from Goirle shows their position to be determined mainly by the values of eigenvector II. The same might be valid for the Twente-Emsland area, although the number of fluvial samples is too low. The aquatic samples centre around zero on axis II. The wide range of values on axis I might suggest the unsuitability of this eigenvector to discriminate between the aeolian and the fluvial sands. Within the Twente-Emsland group very distinct clusters are formed by the aeolian sand types along axis I. The distinction between the sediment types G1 and G2

within the Goirle samples is also evident, although less pronounced than in the Twente-Emsland samples.

Discussion

Distinction between sediment types on the basis of a single characteristic is possible only in a few cases. For each sediment type the range of frequencies usually is wide. The PCA, however, shows that groups of characteristics enable a clear separation between sedimentary or regional groups. Below, the differences between these groups are discussed in some more detail. In spite of the clustering in a PCA-plot, the variable loadings (Fig. 7) demonstrate that none of the axes I and II is determined by a few surface characteristics only, but, on the contrary, by a combination of many such characteristics. In the discussion below on the differences between several sediment types, we therefore refer both to the general pattern revealed by the PCA and to the original raw data.

Table 1. Comparison of the frequencies of the surface characteristics for the different sediment groups by χ^2 -testing. All circles indicate a significance level of more than 0.05. In addition, black dots point to non-overlapping ranges of the raw data.

Sediment groups		G2/G1	G1-2/G3	T2/T1	T1-2/T3	G1-2/T1-2
Number of samples		5/5	10/4	6/5	11/2	10/11
Surface characteristics	1. predominantly rounded	○	-	-	-	○
	2. high relief	-	-	-	-	-
	3. conchoidal fractures	-	-	-	○	○
	6. semi-parallel lines	○	-	○	-	-
	7. straight scratches	○	○	○	-	○
	8. curved scratches	○	-	●	○	-
	9. scratches with satellite v-shaped pits	-	-	○	○	-
	10. imbricated breakage blocks	○	●	○	○	-
	11. single disc-shaped concavities	-	-	○	-	-
	12. multiple rounded disc-shaped concavities	-	-	○	-	-
	13. meandering ridges	-	●	●	○	○
	18. irregulr polygonal cracks	○	○	-	-	○
	22. upturned precipitation plates	○	○	-	○	●
	23. oriented etch pits	○	○	○	-	-
	24. precipitation/solution surface	○	-	-	-	○
	25. chemical disintegration	○	-	●	○	○
	26. smooth precipitation surface	-	○	○	○	-
27. quartz crystal growth	-	○	○	○	●	

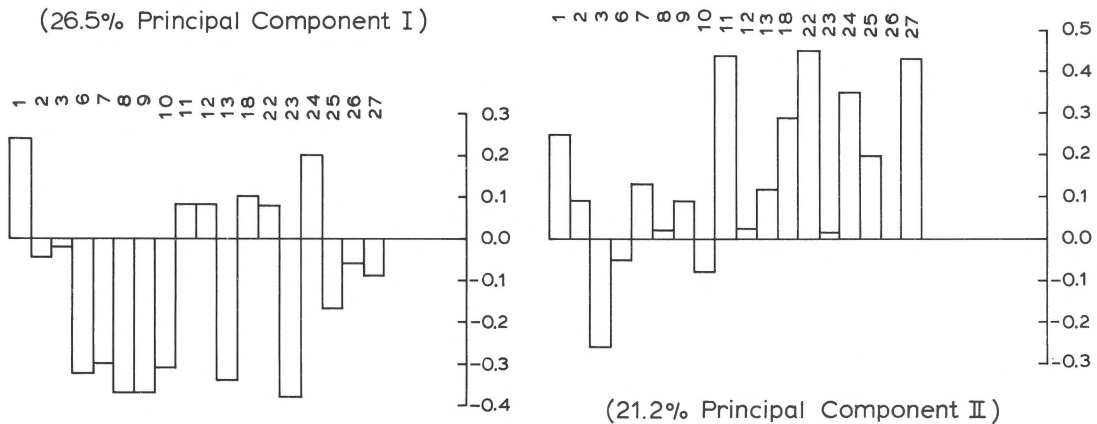


Fig. 7. Eigenvector loading of vector I and II on the original variables. Eigenvector I accounts for 26,5% and vector II for 21,2% of the variance. Eigenvector I mainly reflects conditions of energy while vector II is largely determined by features of chemical nature.

1) The sediments of the Goirle section versus those of the Twente-Emsland region

The clustering on the PCA-plot is well expressed by vector II which is mainly determined by surface features of a chemical nature. According to the present knowledge such features are not caused by mechanical processes of wind or river transport. As the post-depositional history of the Weichselian sediments in both regions is thought to be the same, it may be concluded that vector II reflects (partly) pre-depositional features. These features may be different for both groups because the sediments in the two regions were derived from different parent material.

Characteristics 7 (straight scratches), 11 (single concavities), 21 (irregular small fractures), 22 (precipitated upturned plates) and 27 (quartz crystal growth) apparently occur in different amounts. Their inheritance from the parent material is likely.

2) The aeolian sediment types

The two aeolian types of the Twente-Emsland region are clearly separated on the PCA-plot by their values on axis I. In contrast, the clustering of the aeolian sediment types of the Goirle section is less pronounced. This distinction on the basis of sediment type (grain size, structure) is not easily explained because the similar types T1 and G1 occur

at opposite positions along axis I and this is also the case for the resembling types T2 and G2.

From the mineral association of the Goirle section (Fig. 4) a common source material for the aeolian sand types G1 and G2 may be inferred. On the other hand, it is striking that most of the G1-sands are deposited during the very cold conditions of the Weichselian Upper Pleniglacial (Vandenberghe & Krook 1981, 1985), while the G2-sands have been deposited under the milder periglacial conditions of the Weichselian Middle-Pleniglacial (Vandenberghe 1985) or at the transition from Pleniglacial to Late Glacial (sample 1). The upper Pleniglacial was characterised by predominantly northern (Schwan 1986), or eastern winds (Gullentops et al. 1981), whereas it may be assumed that a northwestern component in the wind direction prevailed during the more temperate Middle Pleniglacial. As a hypothesis, the clustering into two groups in the PCA-plot may thus be attributed to a slightly different way of aeolian transport and sedimentation expressed by wind regimen or wind strength.

In the Twente-Emsland section (Fig. 3) the heavy mineral composition of the aeolian sands T1 is the same as that of the underlying fluvial beds. Apparently the T1-sediments were locally blown off this substrate. The strikingly low proportion of the relatively heavy garnet within sediment-type T2 is explained by differential transport over a long distance (Schwan 1986). Thus, in this region as well,

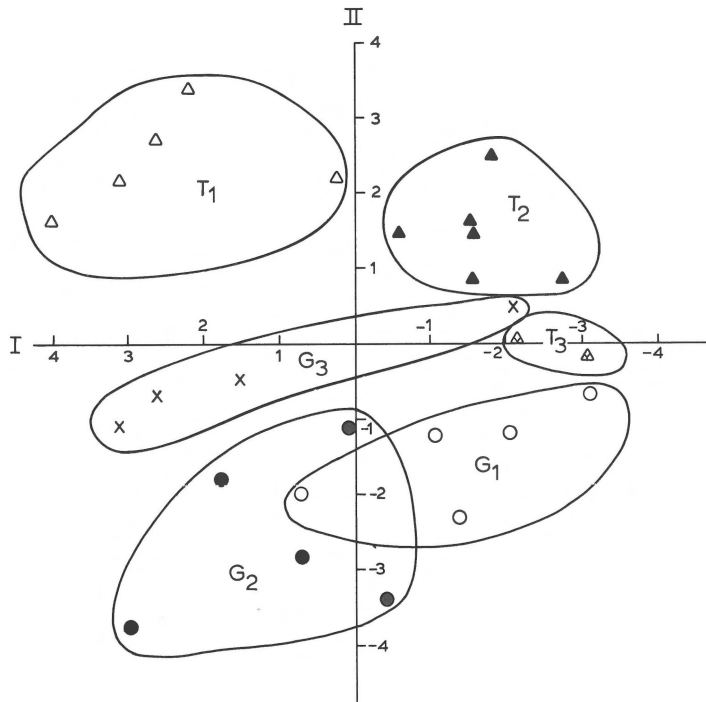


Fig. 8. Plot of the samples on eigenvectors I and II. The distinct clustering between the different sediment classes and especially between the regional groups is striking.

the mineralogy points to one and the same provenance for both sediment types. Besides, these sediments have been deposited during the Upper Pleniglacial by northern winds of unequal strength during the year, whereas the T1-sediments have been transported during the Younger Dryas by southwestern winds (Maarleveld 1960) of uniform strength (Schwan 1986).

Thus, different aeolian processes may be the cause for the clustering on axis I. In this respect it is striking that the Upper Pleniglacial sands in both regions occur in the same position along axis I and that both the Late Glacial and Middle Pleniglacial sands have a common position at the left side of the PCA-diagram

Meandering ridges, scratches, etchpits and V-shaped pits are more frequent within facies A than in facies B.

3) Aeolian versus fluvial sands

In the PCA-plot it appears that axis II mainly de-

termines the boundary between aeolian and fluvial sediments. As stated before, axis II reflects characteristics of the parent material. In the Goirle section the sedimentological composition indicates a southern provenance for the fluvial sediments as opposed to a northern and a western provenance (apart from the dominant local component) for the aeolian sediments. However, from the common provenance of the aeolian and fluvial sediments in the Twente-Emsland region it may be concluded that axis II is not only determined by the characteristics of the source material but also, to a certain extent, by the mode of deposition.

Irregular fractures (21) are a significant characteristic which is virtually absent in aquatic sediments but which commonly occurs in the aeolian group. The frequencies of 'upturned precipitation plates' (22) and 'quartz crystal growth' (27) are higher in the aquatic sediments than in the aeolian ones. However, as has been shown above, these three characteristics (21-22-27) of chemical nature are probably source properties. The striking 'oriented etch pits' (23) (Fig. 2ef) – a characteristic

determining axis I – are much more frequent in fluvial than in aeolian sands, which is in accordance with the subaquatic nature mentioned by Cater (1984). On the other hand, characteristics attributed classically to aeolian environments (concavities (11), meandering ridges (13), graded arcs (15) and orange-peel structures (28)) occur in equal amounts in the aeolian and fluvial sands or even more in the latter sediments.

Conclusions

From these analyses it follows that:

1. It is generally insufficient to rely on *individual* characteristics in order to differentiate between aeolian and fluvial sediments.

2. On the other hand, the *combination* of surface features allows discrimination between these two sediment groups and between different source areas. Different wind regimes might be the cause of specific patterns surface features.

3. Surface features may be attributed to specific processes only when the grains are fresh. Polygenic sediments have a much more complex surface texture because the various processes have left their specific imprint on the surface of the grains.

4. Since individual marks are not equally expressed on each grain, a statistical analysis is necessary.

5. The interpretation of the ultimate sedimentary process is complicated by the variation in the preceding depositional history of the particles.

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References

- Baker, H.W. Jr. 1976 Environmental sensitivity of sub-microscopic surface features on quartz sand grains – a statistical evolution – *J. Sed. Pet.* 46: 871–880
- Cater, J.M.L. 1984 An application of scanning electron microscopy of quartz sand surface texture to the environmental diagnosis of Neogene carbonate sediments, Finestrat Basin, south-east Spain – *Sedimentology* 31: 717–731
- Cheng, K.Ly 1978 Grain surface features in environmental determination of Late Quaternary deposits in New South Wales – *J. Sed. Pet.* 48: 1219–1226
- Culver, S.J., P.A. Bull, S. Campbell, R.A. Shakesby & W.B. Whalley 1983 Environmental discrimination based on quartz grain surface textures: a statistical investigation – *Sedimentology* 30: 129–136
- Gullentops, F., F. Paulissen & J. Vandenberghe 1981 Fossil periglacial phenomena in Belgium – *Biuletyn Periglacialny* 28: 345–365
- Higgs, R. 1979 Quartz grain surface features of Mesozoic-Cenozoic sands from the Labrador and Western Greenland continental margins – *J. of Sed. Petr.* 49: 599–610
- Hunter, R.E. 1977 Basic types of stratification in small eolian dunes – *Sedimentology* 24: 361–387
- Krinsley, D.H. & B.M. Funnell 1965 Environmental history of quartz sand grains from the lower and Middle Pleistocene of Norfolk, England – *Quart. J. Geol. Soc. London* 121: 435–461
- Krinsley, D.H. & J. Donahue 1968 Environmental interpretation of sand grain surface texture by electron microscopy – *Geol. Soc. Amer. Bull.* 79: 743–748
- Krinsley, D.H. & J.C. Doornkamp 1973 Atlas of quartz sand surface textures. Cambridge University Press: 91 pp.
- Kuenen, P.H. 1959 Experimental abrasion, 3. Fluvial action on sand – *Amer. J. Sci.* 57: 172–190
- Kuenen, P.H. 1960 Experimental abrasion, 4. Eolian action – *J. Geology* 68: 427–449
- Le Ribault, L. 1975 l'Exoscopie des quartz détritiques au microscope électronique à balayage – 9e Congrès Int. Sedimentol. (Nice) 1975 – *Sedimentology* 61–67
- Maarleveld, G. 1960 Wind directions and cover sands in the Netherlands – *Biuletyn Periglacialny* 8: 49–59
- Margolis, S.V. & D.H. Krinsley 1971 Submicroscopic frosting on eolian and subaqueous quartz sand grains – *Bull. Geol. Soc. Amer.* 82: 3395–3406
- Pye, K. & C.H.B. Sperling 1983 Experimental investigation of silt formation by static breakage processes: the effect of temperature, moisture and salt on quartz dune sand and granitic regolith – *Sedimentology* 30: 49–62
- Riezebos, P.A. 1974 Scanning electron microscopical observations on weakly cemented Miocene sands – *Geol. Mijnbouw* 53: 109–122
- Ruegg, G.H.J. 1983 Periglacial eolian evenly laminated sandy deposits in the Late Pleistocene of NW Europe, a facies unrecorded in modern sedimentological handbooks. *In*: Brookfield, M.E. & T.S. Ahlbrandt (eds.) Eolian sediment and processes, Elsevier (Amsterdam): 455–482

- Schwan, J. 1986 The origin of horizontal alternating bedding in Weichselian aeolian sands in N.W. Europe – *Sedim. Geology* 49: 73–108
- Smart, P. & N.K. Tovey 1981 *Electron microscopy of soils and sediments: examples* – Clarendon Press (Oxford): 177 pp
- Vandenberghe, J. 1985 Paleoenvironment and stratigraphy during the Last Glacial in the Belgian-Dutch border region – *Quat. Res.* 24, 23–38.
- Vandenberghe, J. & L. Krook 1981 Stratigraphy of the Pleistocene deposits at Alphen (Southern Netherlands) – *Geol. Mijnbouw* 60, 417–426
- Vandenberghe, J. & L. Krook 1985 La stratigraphie et la genèse de dépôts Pleistocènes à Goirle (Pays-Bas) Assoc. Fr. Etude Quat. Bull.1985/4–5: 57–65
- Van der Waals, L. 1967 Morphological phenomena on quartz grains in unconsolidated sands, due to migration of quartz near the earth surface – *Meded. Geol. Stichting* 18: 47–51
- Wellendorf, W. & D.H. Krinsley 1980 The relation between the crystallography of quartz and upturned eolian cleavage plates – *Sedimentology* 27: 447–453
- Whalley, W.B. & D.H. Krinsley 1974 A scanning electron microscope study of surface textures of quartz grains from glacial environments – *Sedimentology* 21: 87–107